healthcare

Special Issue Reprint

The 10th Anniversary of *Healthcare*—TeleHealth and Digital Healthcare

Edited by
Daniele Giansanti

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Editor

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About the Editor

Daniele Giansanti

Dr. Giansanti received an M.D. in Electronic Engineering at Sapienza University, Rome, in 1991; a Ph.D. in Telecommunications and Microelectronics Engineering at Tor Vergata University, Rome, in 1997; an academic specialization in Cognitive Psychology and Neural Networks at Sapienza University, Rome, in 1997; and a specialization in Medical Physics at Sapienza University, Rome, in 2005.

Dr. Giansanti was in charge of the Design of VLSI Asics for DSP in the Civil Field (1991–1997) during his M.D. and Ph.D., and he served as a CAE-CAD-CAM system manager and Design Engineer in the project of electronic systems (Boards and VLSI) for the Warfare at Elettronica S.p.A. (1992–2000), one of the leaders in the military field.

More importantly, he also conducts various research at ISS (the Italian NIH) (2000–today) in the following fields:

1) Biomedical engineering and medical physics with the development of wearable and portable devices (three national patents).

2) Telemedicine and e-Health: technology assessment and the integration of new systems in the fields of telerehabilitation, domiciliary monitoring, digital pathology, and digital radiology.

3) Mhealth: recent interest in the integration of smartphones and tablet technology in health care, with particular interest in the opportunities and the relevant problems of risks, abuse, and regulation.

4) Acceptance of and consensus on the use of robots for assistance and rehabilitation.

5) Challenges and acceptance of the use of artificial intelligence in digital radiology and digital pathology.

6) Cybersecurity in the health domain.

Dr. Giansanti is a Professor at Sapienza and the Catholic University in Rome and a tutor of theses. He is a Board Editor and reviewer for several journals. He has 171 publications indexed on Scopus and numerous scientific contributions, such as monographies, chapters, congress papers, and special issues.

Preface

The TeleHealth and digital healthcare domains have undergone a remarkable evolution in recent years, marked by groundbreaking advancements and transformative innovations. This progress has been propelled by the continuous evolution of digitization processes, both in mobile and fixed technologies. Furthermore, the standardization and integration of these developments within the health domain have played a pivotal role in facilitating these advancements.

Undoubtedly, the COVID-19 pandemic served as a significant catalyst, propelling these fields forward at an unprecedented pace. It provided a unique testing ground, fostering the rapid growth and consolidation of existing technologies while also paving the way for the exploration of new applications.

In the present landscape, TeleHealth and digital healthcare leverage an array of emerging technologies, including robotics, virtual reality, augmented reality, and artificial intelligence. Additionally, various assistive technologies have found ample opportunities within this sector, further enhancing its scope and impact.

In recognition of the ongoing developments and the 10th anniversary of *Healthcare*, a Special Issue entitled "The 10th Anniversary of Healthcare—TeleHealth and Digital Healthcare" was introduced. This initiative aimed to comprehensively outline the current state of affairs, share established experiences, explore future prospects, and highlight persisting challenges in this dynamic field.

The Special Issue represents a significant milestone, featuring 26 contributions that have garnered the attention of a vast community of authors. These contributions span across various formats, including introductory editorials, scientific articles, reviews, perspectives, and systematic reviews, providing a comprehensive overview of the latest research and advancements in TeleHealth and digital healthcare.

As we embark on this journey through the pages of this reprint, we invite readers to delve into the diverse perspectives, insights, and innovations presented within. It is our hope that this compilation serves as a valuable resource for researchers, practitioners, policymakers, and anyone interested in shaping the future of healthcare through technology.

My sincere thanks to Vicky Luo, MDPI's managing editor, who provided exceptional support in every phase of the creation of this collection.

Daniele Giansanti

Editor

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Editorial

Joint Expedition: Exploring Telehealth and the Digital Healthcare Landscape as a Team Integration

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1. The Joint Expedition Exploring Telehealth and the Digital Healthcare Landscape

The TeleHealth and digital healthcare domains have witnessed remarkable advancements in recent years (Contribution 1), propelled by the evolution of digitization processes, both in mobile [1,2] and in fixed technologies [3,4]. Additionally, the standardization and incorporation of the developments within the health domain [5,6] have played a crucial role in facilitating these advancements. A significant impulse in this field was the pandemic, which was a significant catalyst, providing an unprecedented growth stimulus and acting as a testing ground for the consolidation of existing areas and exploration of new applications [7,8].

Presently, the dominions of TeleHealth and digital healthcare leverage emerging technologies such as robotics [9], virtual reality [10], augmented reality [11], and artificial intelligence [12]. Even assistive technologies employed in various applications find ample opportunities within this sector [13]. In light of these considerations, we introduced a Special Issue entitled The 10th Anniversary of *Healthcare*—TeleHealth and Digital Healthcare https://www.mdpi.com/journal/healthcare/special_issues/4R7KYJ9CAJ (accessed on 20 February 2024) to coincide with the 10th anniversary of *Healthcare*. The objective was to comprehensively outline the ongoing developments, share established experiences, explore future prospects, and highlight persisting challenges in this dynamic field.

The Special Issue has successfully achieved a significant milestone, featuring 25 contributions (excluding this editorial) (Contribution 1–Contribution 25), attracting the attention of 26,701 authors at the time of writing. The published papers, according to the selected categories (Figure 1), encompass 1 introductory editorial (Contribution 1), 16 full scientific articles (Contribution 2–Contribution 17), 6 reviews (Contribution 18–Contribution 23), 1 perspective (Contribution 24), and 1 systematic review (Contribution 25).

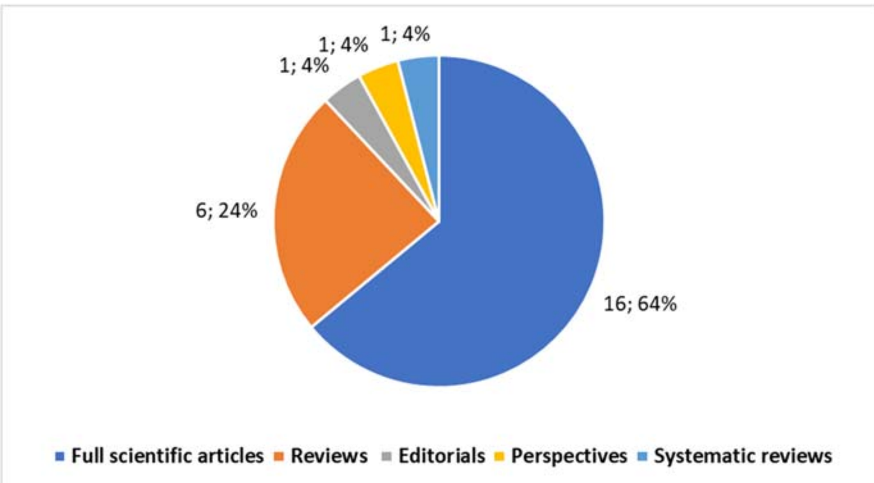

Figure 1. Published articles categorized.

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The Editorial by Giansanti D. (Contribution 1) introduced the aims of the SI and reflected on the progress and status of telehealth and digital healthcare over the past decade. The focus was on assessing the current state of telehealth and digital healthcare and exploring their evolution over the past ten years. It covered the historical context, technological advancements, adoption rates, patient outcomes, challenges, and future prospects in these fields.

2. Conclusive Discoveries: A Closer Look at Scientific Article Outcomes

2.1. An Overview of the Contributions

The 16 articles covered various topics of interest to the SI. Below, the focus and a brief excerpt of the content are detailed.

Ouédraogo et al.'s work (Contribution 2)—*Acceptability of Telerehabilitation*:

This study investigated the acceptability of telerehabilitation (TR) among individuals with stroke and their caregivers. Employing a qualitative approach and the UTAUT-2 model, the research revealed positive experiences with TR, showcasing improvements in functional abilities. Actors considered the technology easy to use, with prior experiences and support playing crucial roles in acceptance. On the one hand, the pandemic further acted as a catalyst in this field. On the other hand, technology, Internet instability, and lack of feedback emerged as barriers. Despite these challenges, the study emphasizes TR's potential for effective stroke rehabilitation, urging the need to address obstacles to widespread adoption.

Shalom et al.'s work (Contribution 3)—*Evaluation of Telephone Visits in Primary Care*:

As telehealth, particularly telephone visits, becomes increasingly prevalent, this study explored family physicians' and pediatricians' perceptions of three key aspects: quality of care, safety, and satisfaction. A survey involving 342 participants was conducted, along with subsequent in-depth interviews. The outcome of the involved physicians highlighted a high acceptance/satisfaction with the telephone-based visits. The parameters related to the safety and the quality of the procedure received a comparatively lower assessment. Notably, 80% recommended combining face-to-face and telephone visits, and 51% acknowledged challenges in decision-making due to the inability to closely examine patients. The study emphasizes the importance of careful implementation, patient selection, technological upgrades, and patient education to enhance the effectiveness of telephone visits in healthcare.

Stara et al.'s work (Contribution 4)—*The Impact of a Multicomponent Platform Intervention on Older Adults*:

This study delves into the realm of gerontechnology, a cross-disciplinary field merging gerontology and technology to address age-related physical and cognitive decline in older adults. Focused on a multicomponent platform integrating ambient sensors, wearable devices, and a cloud application, the research evaluates its impact on self-efficacy, acceptance, well-being, and quality of life in a sample of elderly people. Utilizing a mixed-methods approach, the study indicates positive participant engagement with the integrated platform. Results highlight favorable usability and acceptance, particularly for the smartwatch, with a slight improvement in overall well-being and stable self-efficacy. The study underscores the readiness of such technology for mainstream use, offering valuable insights for developers targeting the aging population.

Rossi et al.' s work (Contribution 5)—*Social Media Perspectives on the Inspire Upper Airway Stimulation System*:

This study delves into the landscape of sleep surgery, focusing on the Inspire® Upper Airway Stimulation (UAS) device, a popular treatment for obstructive sleep apnea, and its representation on social media platforms (Instagram, Facebook, TikTok). Analyzing 423 public posts, the study identifies images (67.4%) and videos (28.1%) as dominant content, with physicians contributing over a third of the posts. Notably, 40% are advertisements, and patient experiences constitute 34.5%. TikTok exhibits higher engagement, with posts averaging 152.9 likes, compared to Instagram and Facebook at 32.7 and 41.2 likes, respectively. The findings emphasize the importance of healthcare professionals providing clear, evidence-based information in the evolving landscape of healthcare on digital platforms. Collaborative efforts are crucial to ensure accurate health information dissemination in the realm of medical innovations like the UAS device.

Litvinova et al.'s work (Contribution 6)—*Patent and Bibliometric Analysis of Pulse Oximeters in Digital Medicine*:

This study comprehensively examined pulse oximeters' evolution in digital medicine through patent and bibliometric analysis. Key countries dominating pulse oximeter patents include the United States, China, the Republic of Korea, Japan, Canada, Australia, Taiwan, and the United Kingdom. The analysis highlighted a consistent growth trend, underscoring the increasing significance of pulse oximeters in digital medical practices. Utilizing a specific software, six primary research clusters were identified, spanning measurement accuracy, IoT integration, diverse pathology applicability, telemedicine, AI and deep learning, and usage in critical care settings. The findings suggest promising applications of digital technologies in pulse oximetry across various medical fields, with identified technical solutions to enhance accuracy, validity, and clinical use and incorporate machine learning.

Giannopoulou et al.'s work (Contribution 7)—*RODI mHealth app Insight for Neurodegenerative Disorder Detection*:

This study focuses on addressing the global health concern of Neurocognitive Disorders (NCDs) by developing the RODI mHealth app. Conducted from July to October 2022 with 182 participants (both with NCDs and healthy individuals), the study aims to assess performance differences, identify critical features for outcome prediction, and utilize machine learning to unveil patterns associated with NCDs. The analysis prioritizes tasks within RODI based on their alignment with NCD criteria, revealing that tasks related to visual working memory are most significant in distinguishing between healthy individuals and those with an NCD. The study provides a blueprint for future mHealth apps, guiding the enhancement of digital indicators for disorders and related conditions.

Mustapoevich and Kim's work (Contribution 8)—*Machine Learning Applications in Sarcopenia Detection*:

This study focuses on sarcopenia, a condition characterized by muscle mass loss, stamina decline, and reduced physical performance, with a specific emphasis on its detection and management using modern technologies. The review explores the lack of global consensus on sarcopenia's definition and the diverse techniques for measuring its parameters. It discusses criteria from the European and Asian Working Groups, highlighting challenges in result comparison. The paper delves into machine learning applications for sarcopenia detection, emphasizing issues like data accessibility and feature selection. Wearable devices, blockchain technology, and edge computing are also explored for monitoring, data security, and healthcare information management. While recognizing potential benefits, the review underscores limitations and calls for further research to address standardization and data management challenges and optimize technology use in sarcopenia detection and management.

Gallè et al.'s work (Contribution 9)—*Introducing Telemedicine in Italy: Citizens' Awareness*:

This study investigates the awareness and attitudes toward telemedicine in the Italian adult population, particularly considering sociodemographic factors and regional differences in service implementation. Conducted between October 2022 and February 2023, the questionnaire-based research reveals that less than half of the respondents were aware of telemedicine services in their region. Among those who were aware, limited usage was attributed to preferences for in-person visits or a perceived lack of need. Over 90% of users expressed satisfaction with telemedicine services. Notably, a negative attitude toward telemedicine was more prevalent among older adults. The study emphasizes the need for increased awareness and the utilization of telemedicine in Italy despite its active presence.

Pennestrì and Banfi's work (Contribution 10)—*Primary Care improvements*:

The contribution starts highlighting the importance of the allocation of European funds in the Italian digitalization processes related to the health domain. While national guidelines emphasize telemedicine as a key innovation, this paper delves into the specific contributions that digital health and telehealth can play in primary healthcare modernizations. The study explores how digital solutions can support effective stratification, prevention, and management of chronic patient needs. It addresses key areas involving population health management, chronic care management, clinical groups, anticipatory healthcare, quality and outcome frameworks, patient-reported outcomes, and patient-reported experience. The paper highlights the potential benefits of digitalization while acknowledging the associated risks and limitations that need to be considered in the implementation process.

Cho and Hong's work (Contribution 11)—*Electronic Sharing of Health Information and Costs*:

This study explores the impact of the electronic sharing of health information on hospital costs and identifies circumstances leading to changes in overall hospital performance. Utilizing data from sources including the American Hospital Association, Center for Medicare and Medicaid Services, and Census Bureau, the research finds a considerable decrease in hospitalization costs by sharing the information internally but not outside. Interestingly, the study reveals that despite challenges such as lack of incentives and capabilities, sharing health information can still lead to cost savings for hospitals. The implication suggests that overcoming obstacles in information sharing is crucial for hospitals to realize the anticipated advantages. The study recommends policymakers target hospitals facing challenges in information sharing, emphasizing a need for strategic approaches to address specific obstacles and improve policy efficiency.

Yang et al.'s work (Contribution 12)—*Kinesio Taping and Virtual-Reality-Based Upper Extremity Training for Stroke Patients*:

This study investigates the impact of combining hand motion training based on virtual reality using the Kinesio Taping (KT) system on stroke. Forty-three stroke patients were randomly assigned to either an experimental group receiving both KT and VRT or a control group receiving only VRT over 30 sessions spanning 6 weeks. Evaluation tools included the Wolf Motor Function Test (WMFT), the Fugl–Meyer Assessment of the Upper Extremity (FMA-UE), the Motor Activity Log (MAL), and the Self-Efficacy Scale (SEF). The experimental group demonstrated statistically significant improvement in FMA-UE, WMFT, MAL, and SEF compared to the control group. The study concludes that the combined intervention of VRT with the KT technique positively impacted the upper limb recovery in the involved patients, suggesting that the stability provided by KT to the wrist extensor muscles contributed to more effective improvement than VRT alone.

Vintilă et al.'s work (Contribution 13)—*Digital Healthcare Communication for Urologists' Surveillance of Lithiasis Patients*:

This paper addresses the impact of the COVID-19 pandemic on lithiasis patients, particularly those requiring internal stents. Two studies were conducted: a clinical study evaluating the bacterial urinary colonization prevalence in patients with obstructive urolithiasis and internal stents and a quantitative study using multiple linear regression to gauge urologists' opinions on leveraging digital technologies for improved communication. The clinical study found a 35% prevalence of urinary colonization, affected by infection in combination with the SARS-CoV2 virus. The outcome indicated urologists' openness to employing online technologies for communication with patients. The results provide valuable insights for healthcare practitioners, emphasizing factors influencing the communication process and suggesting considerations for hospital managers when implementing online communication technologies.

Gatica et al.'s work (Contribution 14)—*Teledermatology Evaluation and Feedback Systems*:

This study evaluates Chile's teledermatology system by analyzing 243 consultations. It focuses on basic specifiers' fulfillment, revealing strong adherence to core teledermatology functions. Significant correlations are found between patient destination, pharmacological prescription, drug coverage, and physician education. Primary health center consultations exhibit higher pharmacological prescription rates, mostly involving government-covered drugs, compared to face-to-face referrals. The study emphasizes targeted evaluations for education and prescriptions to enhance teledermatology quality.

Niculescu et al.'s work (Contribution 15)—*Challenges of Integrating New Technologies for Orthopedic Doctors*:

This research explores the intention of orthopedic doctors to adopt new medical technologies, particularly during the pandemic era. The study, encompassing 145 orthopedic doctors, utilized a questionnaire for data collection and employed a multiple linear regression model for analysis. The findings highlight that doctors' intention to embrace new medical technologies is influenced by perceived advantages and disadvantages, risks, technology quality, experience in usage, and receptivity to digital tools. The results provide valuable insights for hospital managers and authorities, shedding light on key factors influencing the adoption of emerging technologies in orthopedics.

AlAli et al.'s work (Contribution 16)—*Usage of Digital Health Mobile-Based Applications among Saudi Population*:

This cross-sectional study investigates the adoption of digital health mobile applications among the Saudi population to guide the Saudi Ministry of Health and the government in scaling up digital health initiatives. The research explores the extent of usage, affordability of smart devices, app presence, perceived benefits, and barriers to adoption. Findings reveal that while many participants can afford smart devices and recognize the benefits of medical apps, limited understanding of usage, difficulties in downloading, and ethical concerns hinder widespread acceptance. The study emphasizes the need for additional efforts from authorities to promote the uptake of digital health in Saudi Arabia.

David et al.' work (Contribution 17)—*Mobile Health Interventions on Lifestyle and Anthropometric Characteristics*:

This randomized controlled trial aimed to evaluate the effect of mHealth procedures on subjects with hypertension without control. Participants received lifestyle counseling and were randomly assigned to different mHealth interventions or usual clinical treatment (control). The mHealth group, which included an automatic oscillometric device for blood pressure measurement and personalized text messages, showed a significantly higher likelihood of achieving lifestyle goals at six months. Additionally, there were clinically relevant reductions in body fat, segmental trunk fat, and waist circumference in the mHealth group compared to the control, emphasizing the positive impact of mHealth on hypertension management and lifestyle adherence.

2.2. Common Message

The combination of digital technologies and healthcare has ushered in transformative advancements, as evidenced by a comprehensive exploration of 16 scientific article studies (Contribution 2–17). From the widespread acceptance of Telehealth interventions (Contribution 2–3) to the impactful integration of multicomponent platforms for older adults (Contribution 4), the studies underscore a paradigm shift in healthcare delivery. Insights from social media perspectives (Contribution 5) emphasize the need for accurate information dissemination, reflecting the evolving landscape of healthcare on digital platforms.

Technological innovations, such as machine learning applications (Contribution 8), mHealth apps for neurodegenerative disorder detection (Contribution 7), and pulse oximeter evolution in digital medicine (Contribution 6), reveal promising prospects for the future. The studies collectively highlight the potential benefits of digital technologies in addressing healthcare challenges.

Public awareness and acceptance of telemedicine, as explored in Italy (Contribution 9), and the forward-looking approach to primary care innovations in Italy (Contribution 10), underscore the critical role of technology-driven policies in shaping healthcare. The exploration of the electronic sharing of health information (Contribution 11) provides strategic insights for policymakers, emphasizing the importance of overcoming obstacles for hospitals to realize anticipated advantages. Innovative healthcare approaches in diverse regions, such as Saudi Arabia (Contribution 16), showcase the potential for digital health adoption while acknowledging challenges. The impact of mobile health interventions on lifestyle and anthropometric characteristics (Contribution 17) points to the positive influence of digital solutions on hypertension management.

Studies delving into specialized healthcare domains, such as the combined intervention for stroke patients (Contribution 12), digital communication in urologists' surveillance (Contribution 13), and teledermatology evaluation (Contribution 14), reveal targeted applications of technology in critical medical areas.

2.3. Key Emerging Themes

As a whole, these studies (Contribution 2–17) reflect a dynamic landscape where technology, carefully implemented, holds the promise to enhance healthcare accessibility, quality, and patient outcomes. The collective findings call for collaborative efforts among healthcare professionals, policymakers, and technologists to navigate challenges and leverage the full potential of digital healthcare innovations (Contribution 2–17). The articles embraced various themes, with each article encompassing different ones. Focusing on the dominant theme, Table 1 illustrates the key emerging dominant themes along with the corresponding articles.

Table 1. Dominant emerging theme by article.

Themes	Description	Studies
Telehealth and Digital Interventions	Acceptability of Telerehabilitation. Evaluation of Telephone Visits in Primary Care	(Contribution 2) (Contribution 3)
Impact of Digital Platforms on Healthcare	Impact of a Multicomponent Platform on Older Adults Social Media Perspectives on Healthcare Devices	(Contribution 4) (Contribution 5)
Technological Advancements in Medicine	Patent and Bibliometric Analysis of Pulse Oximeters mHealth App Insight for Neurodegenerative Disorders Machine Learning Applications in Sarcopenia Detection	(Contribution 6) (Contribution 7) (Contribution 8)
Telemedicine and Public Awareness	Introducing Telemedicine in Italy: Citizens' Awareness Primary Care of the (Near) Future	(Contribution 9) (Contribution 10)
Specialized Healthcare Domains	Combining Virtual-Reality-Based Training for Stroke Patients Digital Healthcare Communication for Urologists' Surveillance Teledermatology Evaluation and Feedback Systems	(Contribution 12) (Contribution 13 (Contribution 14)
Innovative Healthcare Approaches	mHealth Interventions on Lifestyle and Anthropometric Characteristics Usage of Digital Health Mobile-Based Applications in Saudi Arabia	(Contribution 17) (Contribution 16)
Health Information Sharing and Technology Adoption	Various Medical Technologies Adoption by Orthopedic Doctors Electronic Sharing of Health Information and Costs	(Contribution 15) (Contribution 11)

3. Conclusive Discoveries: A Closer Look at the Reviews and the Perspective

3.1. An Overview of the Contributions

The seven reviews, including the systematic reviews, provide a significant contribution to the exploration of more stabilized emerging themes proposed in the collection (Contribution 18–23,25). The perspective included in this collection helps us look toward the future (Contribution 24) of this discipline. Below, the focus and a brief excerpt of the content are detailed.

Holl et al.'s work (Contribution 18)—*Mobile Apps for COVID-19: A review of Reviews*.

This study conducts an overview of mobile applications (apps) used during the COVID-19 pandemic. Analyzing 24 eligible studies, the review covers the period from January 2020 to April 2022. Key findings highlight that most reviews focused on apps from the USA, the UK, and India, leaving a gap regarding apps from many African and Middle and South American countries. The categorization reveals four main groups: security and privacy, App overview, MARS rating, and miscellaneous. The study aims to offer a high-level overview, identify factors contributing to app success, and pinpoint gaps in the current literature, providing valuable data for future analyses and research.

Alghamdi's work (Contribution 19)—*Effective Telehealth Solutions for COPD: A Narrative Review*.

This paper explores Telehealth (TH) solutions as promising interventions for managing Chronic Obstructive Pulmonary Disease (COPD). Conducting a literature review up to October 2023, the study identifies 30 papers presenting TH solutions for COPD management. TH and digital health solutions are considered interchangeable, both aiming to enhance care, accessibility, and quality of life. The content of TH solutions encompasses symptom management, physical activity promotion, and psychological support. Mechanisms are influenced by factors like content, delivery mode, strategy, and intensity. Common outcomes include treatment adherence, health status, and quality of life. Effective implementation requires consideration of patient needs, technology familiarity, healthcare professional support, and data privacy, emphasizing patient engagement for optimal effectiveness.

Simeoni al.'s work (Contribution 20)—*Assistive Tech Impact in International Web Portals*.

This study explores the role of assistive technologies (ATs) in supporting individuals with disabilities and frailties, focusing on the initiatives of the UN, UNICEF, and WHO. Using a dual-method approach, the research involves a direct search of institutional websites and a literature review. The findings reveal initiatives aimed at tailoring ATs based on guidelines, monitoring their introduction through surveys, and disseminating AT culture and recommendations. The study indicates a growing interest in ATs, with international institutions playing a vital role in monitoring, disseminating, and improving access to ATs. However, persistent challenges need to be addressed to enhance the success of these initiatives.

Almufareh et al.'s work (Contribution 21)—*Motor Imagery Rehabilitation for Individuals with Disabilities: A Review*.

This manuscript provides a comprehensive analysis of the significance of motor imagery in neuro-rehabilitation, emphasizing its non-invasive and cost-effective nature. It explores the fundamental mechanisms, applications across various disability conditions, and potential benefits for enhancing motor functionality. The document also discusses existing challenges and highlights the need for ongoing research and innovative technologies to maximize the potential of motor imagery in aiding individuals with disabilities.

Borna et al.'s work (Contribution 22)—*A review on AI Models in Health Information Exchange*.

This review explores the utilization of AI models in Health Information Exchange (HIE) to predict clinical outcomes, addressing a gap in current research. The study, following PRISMA guidelines, analyzed 11 shortlisted publications out of 1021 identified through databases. The findings reveal a notable preference for machine learning models, particularly in oncology and cardiac failures, showcasing commendable predictive proficiency with varying metrics. While AI in HIE holds transformative potential for healthcare, the study emphasizes the need for a well-rounded approach to ensure the delivery of trustworthy and effective AI-augmented healthcare solutions.

Morone et al.'s work (Contribution 23)—*Assistive Technologies in Spinal Cord Injury: A Narrative Review*.

This narrative review of reviews explores the integration of assistive technologies (ATs) in the context of Spinal Cord Injury (SCI). Conducted through a search on PubMed and Scopus, the review identifies the evolution of ATs, emphasizing their role as products, services, or standalone or networked devices. It underscores the potential of innovative technologies to enhance the quality of life and reduce healthcare costs in SCI. However, the review identifies gaps in addressing ethical and regulatory aspects, emphasizing the need for comprehensive studies focusing on multiple domains to facilitate integration into the health domain.

Calvache-Mateo et al.' work (Contribution 25)—*Respiratory Telerehabilitation in Long COVID-19: A Systematic Review*.

This systematic review and meta-analysis focused on exploring the use of telerehabilitation for supporting Long COVID-19 rehabilitation. The review included controlled trials comparing respiratory telerehabilitation interventions with various controls. The analysis, encompassing 10 studies, revealed significant positive outcomes for telerehabilitation in improving quality of life, reducing dyspnea, and enhancing strength both in respiratory muscles and lower limb muscles while improving the functional capacities of the involved subjects. The study did not show a significant difference in adverse outcomes between comparator groups and telerehabilitation groups. The findings highlighted both the effectiveness and safety of the methodology for Long COVID-19 patients.

Cruz-Panesso et al.'s work (Contribution 24)—*Training Physicians for Telehealth Competencies*.

This perspective study highlights the increasing prevalence of telehealth in North America, emphasizing a 40% rise between 2019 and 2020, stabilizing at 40% in 2021. It underscores the challenges in integrating telehealth curricula due to a shortage of experienced faculty and limited time. To address these issues, the article recommends rethinking traditional learning models and suggests telesimulation as an effective method for training telehealth competencies, providing practical experiences for technical and interpersonal skills.

3.2. Common Message

Across diverse healthcare reviews, a unified message resonates—the urgent need for ongoing innovation, adaptive strategies, and a patient-centric paradigm within the evolving healthcare landscape (Contribution 18–25). The discourse spans specific domains like mobile apps, telehealth solutions, assistive technologies, motor imagery rehabilitation, AI in health information exchange, and respiratory telerehabilitation. The emerging focus is on:

Innovation and Patient-Centricity:

The reviews and the perspective collectively advocate for leveraging cutting-edge technologies (Contribution 18–23, 25), including mobile apps, telehealth solutions, AI models, and assistive technologies, to address healthcare challenges. The common thread emphasizes the importance of tailoring interventions to meet individual patient needs, fostering engagement and adherence, and considering diverse requirements.

Global Perspective and Challenges:

Certain reviews offer a global outlook, stressing the role of international institutions and the challenges in disseminating assistive technologies globally (Contribution 20, 23). Identifying existing challenges and gaps, whether in the analysis of mobile apps from specific regions or integrating assistive technologies ethically, is a recurring theme.

Efficacy, Safety, and Evidence-Based Practices:

Systematic evaluations, such as respiratory telerehabilitation in Long COVID-19, consistently underscore the efficacy and safety of interventions (Contribution 24). The common discourse prioritizes evidence-based practices, positive patient outcomes, and the integration of proven strategies into healthcare protocols.

Call for Ongoing Research:

All the contributions (Contribution 18–25) advocate for sustained research and development. Whether in motor imagery rehabilitation, AI models, or telehealth competencies, there is a shared call for continuous exploration, improvement, and adaptation to emerging healthcare needs.

3.3. Key Emerging Themes

In essence, the collective discourse revolves around embracing innovation, prioritizing patient well-being, acknowledging global perspectives and challenges, ensuring efficacy and safety, and advocating for continuous research and improvement within the dynamic healthcare landscape.

The contributions embraced various themes, with each one encompassing different themes. Focusing on the dominant theme, Table 2 illustrates the key emerging dominant themes along with the corresponding study.

Table 2. Dominant emerging theme by study.

Themes	Description	Studies
Assistive Technology	Assistive Tech Impact in International Web Portals Assistive Technologies in Spinal Cord Injury Integration	(Contribution 20) (Contribution 23)
Physician training in digital health	Training Physicians for Telehealth Competencies: The perspective in North American territory	(Contribution 24)
Rehabilitation and digital health	Respiratory Telerehabilitation in Long COVID-19: A Systematic Review Motor Imagery Rehabilitation for Individuals with Disabilities: A Comprehensive Review	(Contribution 25) (Contribution 23)
AI Integration	AI Models in Health Information Exchange: Clinical Implications	(Contribution 22)
Effectiveness of telehealth solutions	Effective Telehealth Solutions for COPD: A Narrative Review	(Contribution 19)
Mobile Apps	Mobile Apps for COVID-19: A Comprehensive Review	(Contribution 18)

3.4. In Conclusions

Recent technological innovations, including AI, and the COVID-19 pandemic have spurred a formidable acceleration in research and development within digital health, significantly propelling mHealth and eHealth. The Special Issue gathered important contributions in various domains, identifying both emerging and well-established themes and outlining intriguing directions for future developments. The initiative also underscores the significance of these tools as a focal point for scholarly exchange and discussion among researchers worldwide.

Conflicts of Interest: The authors declare no conflict of interest.

List of Contributions

1. Giansanti, D. Ten Years of TeleHealth and Digital Healthcare: Where Are We? *Healthcare* **2023**, *11*, 875. https://doi.org/10.3390/healthcare11060875.
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Editorial

Ten Years of TeleHealth and Digital Healthcare: Where Are We?

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1. Digital Healthcare and TeleHealth

Due to the development of the technological innovation of devices, availability of increasingly performing networks, improvement of the digitization processes, and the push to greater diffusion determined by the COVID-19 pandemic, Digital Healthcare (DH), also referred to as Digital Health [1–4], and Telehealth (TH), also referred to as Telemedicine [5–8], have undergone an impressive development in recent years. Technological innovation concerns with sensorization, monitoring, control, and communication electronics. The push to miniaturization of the realization processes and the increasingly performing processing has increased accessibility of portable and/or wearable devices to everyone, and these devices can be used integrated with mobile technology. However, technological innovation also concerns with the mechanics of electronic and computer science integration within mechatronic devices intended for the health domain. Computer science has never delayed development, having a leading role in both the functioning of the devices, and the new and innovative solutions distributed throughout health services. This field is additionally able to rely on the development of new algorithms, based on artificial intelligence (AI). As a result of the technological innovations of information and electronics of communications, networks have become increasingly widespread, accessible, fast, and competitive, regarding both fixed and mobile networks. The digitization processes have become increasingly simplified and inexpensive, and large volumes of data, or commonly, Big Data, have been made available. Access, management, processing, and the exchange of clinical data between professionals (including images, remote monitoring, the exchange of bidirectional information between citizens and health services, and many other processes within the health domain) have become a lot simpler and more routine. The COVID-19 pandemic heavily contributed to the push towards TH and DH. In the need for social distancing and the optimization of care processes, two cardinal elements within the health domain have been identified, in both TH and DH. COVID-19 has significantly facilitated advancement of both the research, and policies and regulations of the TH and DH fields. Following the acute phases of the COVID-19 pandemic, both DH and TH have entered common language in the relationship between citizens and the health system, certainly in the most developed countries.

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2. TeleHealth and Digital Healthcare Today

With technological evolution, DH and TH have occasionally adapted their field of intervention. DH and TH are two interconnected fields of the health domain, whereby the first includes the latter. DH refers to all the activities encompassing the digitization of medicine and healthcare, whilst TH is an element included in DH, allowing the patients to participate in remote computer-based consulting with doctors, or providing the professionals an opportunity to interact with patients to exchange data information and/or perform collaborative diagnoses.

Beyond TH, today, DH [1–4,9] includes portable and wearable devices, mobile health, personalized medicine for individuals, health information technology (IT), such as in-hospital information systems and radiology information systems. Digitization is revolutionizing DH owing to the applications in both eHealth and mHealth, and the decision-based support software based on AI.

Currently, TH utilizes a healthcare provider (HCP), avoiding the in-person doctor/specialist interaction [5–8,10,11]. eHealth utilizes the internet based on personal computer solutions, and mHealth does so based on smartphones, or tablets. This allows real time monitoring of the patient by the HCP, using portable or wearable devices. DH allows for various interactions with a HCP, including cybersecure emails, messages or file exchange, participating in a phone or video call consultation, collaborating with professionals in teleconsulting and decisions regarding diagnosis.

TH, for example, permits: (a) mental health therapy and treatment, (b) dermatology self-monitoring, (c) accessing to clinical results, (c) follow-up after hospital dismissison, (d) management of medical prescriptions, (e) remote rehabilitation and assistance, (f) self-monitoring and self-therapy, in the case of diabetology or cardiology, for example, (g) emergency interventions, and (h) telemonitoring and teleconsulting.

3. The Evolution and Trends of the Scientific Production

A simple analysis conducted via Pubmed allows us to make some considerations on the development of TH and DH, as much research appears among scientific publications of the last decade.

A search of studies focusing on TH, with the "telehealth [Title/Abstract]" keyword, was carried out simultaneously with the production of this editorial [12]. The following results were found:

- A total of 12,892 papers, of which 1837 are reviews [13].
- A beginning of scientific dissemination in 1978.
- In the last decade, the number of papers produced was 11,448 [14], equivalent to 88.8% of the entire historical production. Of these papers, 1662 are reviews [15].
- In the most recent period, commencing from the outbreak of the COVID-19 pandemic to date, 8482 papers, equating to 65.8% of the entire scientific production, have been published [16].

A search of studies focusing on DH, with the "digital healthcare [Title/Abstract]" Keyword, was carried out simultaneously with the production of this editorial [17]. The following results were found:

- A total of 340 papers, of which 91 are reviews [18].
- A beginning of scientific dissemination in 2003.
- In the last decade, the number of papers produced was 336 [19], equivalent to 98.8% of the entire historical production. Of these papers, 90 are reviews [20].
- In the most recent period, commencing from the outbreak of the COVID-19 pandemic to date, 265 papers, equating to 77.9% of the entire scientific production, have been published [21].

This brief overview, before all, highlights that DH, formally including TH, has a less voluminous and decidedly more recent history of scientific dissemination, which both follows the consolidation of the upsurge in digital development with mHealth in the health domain, and the evolution and/or adaptation of the terminology.

Furthermore, this overview also shows the great growth that has taken place in the last ten years in scientific production both in DH and in TH. This growth has even become impressive in the three years immediately following the outbreak of the Covid-19 pandemic.

4. The Impact of COVID-19 in This Field

In the most recent period, commencing from the outbreak of the COVID-19 pandemic, scientific production has undergone a further acceleration in both fields, regarding technology, employment, and policies and regulation [22,23].

The COVID-19 pandemic has presented a real training ground in this field and an unexpected growth stimulus never experienced before, with the consolidation of ancient areas and the exploration of new areas. Furthermore, even in TH and DH, one can currently count on the use of emerging technologies, such as robotics [24–27], augmented reality [28], virtual reality [29], and artificial intelligence [30,31]. Moreover, assistive technologies have played a strategic role during the pandemic as they were consolidated in the context of different applications and disabilities relating communication and motion [32–41].

In addition to the consolidated applications in this sector, new ones have been activated. An application that has exponentially developed in this period has been digital contact tracing for control, monitoring, and epidemic alerting through mobile apps and mHealth solutions [42–48]. TH and DH have also been integrated in the use of artificial AI tools in the diagnosis and treatment of COVID-19. Digital radiology, digital pathology, and digital dermatology, as brief examples, have explored new potential in health care [49–51]. Big Data have played a strategic role in overcoming the pandemic [52]. Assistance for the disabled has tested new solutions [24–27], such as the social robot, which has played an innovative role as a support and/or mediator between a therapist and a patient [24,25,27]. In this case, the therapist have experienced a radical change in their role. For example, following the pandemic, the professional figure of augmented physiotherapist or digital physiotherapist are being considered. Many mobile apps bordering medical devices and non-medical devices, for physical wellness, including psychological wellness (e.g., gymnastics, walking, nutrition, emotional support, nutrition) have undergone important development [53]. COVID-19 has also stimulated the improvement the use of DH and TH through policy interventions and improvement of regulations, as exemplified by Italy, where the rules of engagement were not initially adequately defined [54]. Approximately a year after the outbreak of the pandemic, the TH and DH sector could rely on 215 search optimization keywords (SEO) reported in [55].

COVID-19 has also lead to bottlenecks. The digital divide represents a major obstacle for the use of TH and DH [56–61]. Literacy with IT tools (essential for interacting with DH and TH) is often inadequate and opportunities are lost, even in wealthy countries. In the poorest countries, the component of the digital divide also remains due to access to technology, for economic reasons or due to lack of infrastructure.

The regulatory aspects must also be perfected and internationalized. An example of this is the drive towards technological innovation being followed by regulatory consolidation, related to the trustworthiness of the AI regarding digital radiology integrated with AI [62]. The increase in the use of digital technologies with TH and DH also has important implications for cybersecurity, which must be particularly considered, even in emerging sectors, such as the use of mobile technologies and robotics in healthcare (for example, social robotics), where new risks are present for professionals and citizens [27,53,63].

Attention to strategic aspects of remote interaction must be maximized, taking into account all phases of the connection, even the preliminary aspects, such as informed consent, with its important legal and administrative implications [64]. It will also be necessary to make an optimal use of the opportunities that DH offers with the integration of Big Data, by deriving the maximum benefit from this and inheriting the fruitful experience in the field of digital radiology [65].

5. Conclusions and Final Reflection

In the last decade, DH and TH have undergone a rapid acceleration in terms of application of use, as documented by the growth of the number of scientific publications. In the period following the outbreak of the pandemic, this growth has been impressive. New applications, additionally integrated with AI, have had an important development in diagnostics, therapy, assistance, epidemiology, and other sectors. Bottlenecks have also emerged in this recent period, such as: (a) the digital divide into the two components due to literacy and access to infrastructure, (b) the adjustment of the regulations, which must remain updated with technological innovation and the trustworthiness of the AI, and (d) cybersecurity applied to new devices operating in the health domain.

It is necessary to start from the recently consolidated experiences and from the problems persisting in TH and DH, and make a map point in scientific research. Researchers and stakeholders have a strategic role in this. With the special issue opened on the occasion of the tenth anniversary of the healthcare journal [66] (https://www.mdpi.com/journal/healthcare/special_issues/4R7KYJ9CAJ accessed on 31 January 2023), we intend to make a contribution in this direction.

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Article

Acceptability of Telerehabilitation: Experiences and Perceptions by Individuals with Stroke and Caregivers in an Early Supported Discharge Program

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Abstract: Introduction: Telerehabilitation (TR) is a promising method for facilitating the delivery and access to post-stroke rehabilitation services. Objective: The aim of this study was to explore the acceptability of TR and factors influencing its adoption by individuals with stroke and caregivers. Methods: A qualitative descriptive approach was used. Six individuals with stroke and three caregivers participated in individual online interviews. An abductive thematic analysis was employed to analyze the qualitative data, using the Unified Theory of Acceptance and Use of Technology 2 (UTAUT-2) model. Results: Participants reported positive experiences with TR, resulting in improvements in functional abilities, such as manual dexterity, balance, and positive interactions with therapists. They found the technology easy to learn and use, facilitating engagement in TR. Participants' prior experiences with technology, along with support from caregivers and therapists, facilitated acceptance and the use of TR. The COVID-19 pandemic also motivated participants to accept TR. However, technical issues, unstable internet connections, and lack of feedback were barriers to the use of TR. Conclusion: Despite existing obstacles, TR can be used to provide rehabilitation services for individuals with stroke. Addressing these barriers is necessary to promote the widespread and effective use of TR in the context of stroke recovery.

Keywords: telerehabilitation; stroke; technology; early supported discharge; home-based; Canada

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1. Introduction

Stroke impacts millions of people worldwide annually [1], resulting in residual effects that, when interacting with the physical and social environment, can lead to restrictions in social participation [2]. Rehabilitation aims to optimize functional recovery and social participation [3]. A supportive environment, including easy access to rehabilitation care, home modifications to facilitate mobility, and emotional support from caregivers, can significantly enhance the chances of recovery [3]. In Canada, rehabilitation services can be provided in various settings, including hospitals and homes [3]. Evidence has shown that home care is associated with significant improvements in participation in activities of daily living compared to hospital care [4]. Indeed, individuals receiving rehabilitation care in hospital settings are inactive for three-fifths of their waking hours, which is not in concordance with the recommendation for the intensity of treatment and stimulation for post-stroke rehabilitation [4]. On the other hand, home care allows for more opportunities for training in functional tasks in individuals with stroke's natural environment, facilitating their return to performing daily life activities [4].

The Early Supported Discharge (ESD) program consists of offering home-based intensive rehabilitation services to people who have had a stroke and are discharged once medically stabilized [3,5]. It has the potential to reduce costs and is recommended as a solution to optimize functional recovery in individuals with stroke [3] since past studies have shown that ESD can lead to improvement comparable to inpatient rehabilitation for individuals with stroke [6,7]. For instance, a systematic review with meta-analysis of 17 randomized controlled trials, including 2422 individuals with stroke with moderate disability, demonstrated that ESD programs were associated with decreased morbidity and limitations, as well as greater improvement in performance in activities of daily living and higher satisfaction at the end of the scheduled follow-up after six months in comparison to conventional care [7]. Moreover, numerous studies have indicated that patients generally prefer to be discharged from the hospital earlier and to receive rehabilitation at home [8–10]. However, various obstacles related to environmental conditions can hinder the ESD rehabilitation professionals' ability to provide quality services that are in line with guidelines, including intensity of treatment, to persons with stroke in their homes [9,10]. For example, costs associated with frequent travel may act as barriers for rehabilitation professionals to provide home care [9,10]. Additionally, safety and accident risks, such as fall hazards due to weather conditions like snowstorms or rain, can pose additional obstacles for rehabilitation professionals [9,10]. Furthermore, even though the risk of disease transmission is lower at home compared to in a hospital, there is still the potential for contagion when rehabilitation professionals visit individuals with stroke at their residence [11,12]. Therefore, since the COVID-19 pandemic, telerehabilitation (TR) has been increasingly offered to allow rehabilitation professionals to deliver effective and safe home care that is acceptable for them as well as for individuals with stroke and their caregivers [11,12].

TR uses communication technologies, such as wearable devices, the internet, virtual reality, tablets, and phones, to remotely provide rehabilitation services to individuals in their homes and, as such, could be a complementary strategy to traditional in-person rehabilitation [13]. Past studies indicated that TR could lead to improvement similar to that of traditional rehabilitation approaches for individuals with stroke regarding performance in the activities of daily living and quality of life [13–17]. TR has shown to be applicable by rehabilitation professionals, and individuals with stroke perceived that TR was effective [11,15]. Furthermore, it has been shown that individuals residing in rural or remote areas often face difficulties in accessing specialized rehabilitation services that are not locally available [11]. Therefore, through TR, these individuals could benefit from these services, which is particularly advantageous in a vast country like Canada [11,13]. As a result, TR could favor equity between individuals with stroke regardless of their location, which is in concordance with the World Health Organization's goal of ensuring equal access to high-quality healthcare services [18].

Although TR was shown to be applicable in previous studies, the scientific literature is limited regarding individuals with stroke and their caregivers' acceptability of TR [16,19]. Applicability in our study is defined as the extent to which TR can be successfully used or applied by rehabilitation professionals and individuals with stroke [11], while acceptability is defined as the extent to which individuals with stroke, their caregivers, and rehabilitation professionals perceive TR as satisfactory, appropriate, and effective for delivering rehabilitation services remotely [11]. Additionally, using rehabilitation technologies in the home environment can be associated with certain barriers, such as complexity of use, limited access to reliable internet and appropriate equipment, and the loss of tactile and kinesthetic aspects of rehabilitation [20–22]. A more complete understanding of individuals with stroke and caregivers' experiences during their rehabilitation when using TR is integrated into the rehabilitation process is essential to ensure quality care is provided for all.

Moreover, few studies have explored the acceptability of TR when used in the home environment of individuals with stroke as part of a rehabilitation follow-up [16,19]. Furthermore, we recently explored the factors influencing the implementation of TR in an ESD program, involving clinicians and managers, and it revealed that numerous factors motivated clinicians to adopt TR [23]. Considering that the perspective of individuals with stroke and their caregivers is lacking, it is imperative that a study exploring their experiences with TR in an ESD program be conducted to better meet their needs. Thus, in alignment with the World Health Organization's call for more research to improve TR services for individuals with stroke [24], the objective of this study was to explore the acceptability of TR as part of the ESD program and the factors influencing its adoption in individuals with stroke and caregivers.

2. Materials and Methods

2.1. Research Design

This study was conducted using a descriptive qualitative design [25] that allowed the data analysis to be representative of participants' own experiences and perceptions on the research subject [26]. The description of this study is presented in accordance with the Consolidated Criteria for Reporting Qualitative Research (COREQ) checklist [27].

2.1.1. Theoretical Framework

Two theoretical frameworks were used, namely the Consolidated Framework for Implementation Research (CFIR) [28] and the Unified Theory of Acceptance and Use of the Technology 2 (UTAUT-2) model [29]. While the CFIR [28] was used to develop interview guides during data collection, as it combined multiple factors that could impact technology adoption, the UTAUT-2 model [29] was used for data analysis, as it allowed us to better understand the relationship between the factors specifically related to technology acceptance.

The UTAUT-2 model was used to determine the behavioral intention to use technology [29]. It is a modified version of the UTAUT model [30] that extends applicability to diverse individuals, such as users, consumers, and customers [31–33]. The UTAUT-2 model comprises seven key constructs, with their definition, as follows: (1) "Performance expectancy" pertains to the perceived benefits of using technology; (2) "Effort expectancy" relates to the perceived simplicity of using technology; (3) "Social influence" involves the influence of significant individuals on technology adoption; (4) "Facilitating conditions" involve perceiving available resources and support for behavior; (5) ''hedonic motivation" refers to the pleasure derived from using a technology; (6) ''price value" represents the balance between technology benefits and financial cost; and (7) ''habit" denotes the automaticity of a behavior [29,30]. These constructs are believed to influence the behavioral intention to use technology [30]. Additionally, the model incorporates the moderating effects of age, gender, and experience on the seven key constructs, as well as behavioral intention [30]. The UTAUT-2 model has been applied in various fields related to mobile technologies, including healthcare technologies [34–37] and TR [19]. To improve the rehabilitation process for individuals with stroke and their caregivers, it is essential to understand the acceptability of TR and the factors that influence its use. The UTAUT-2 model is presented in Figure 1.

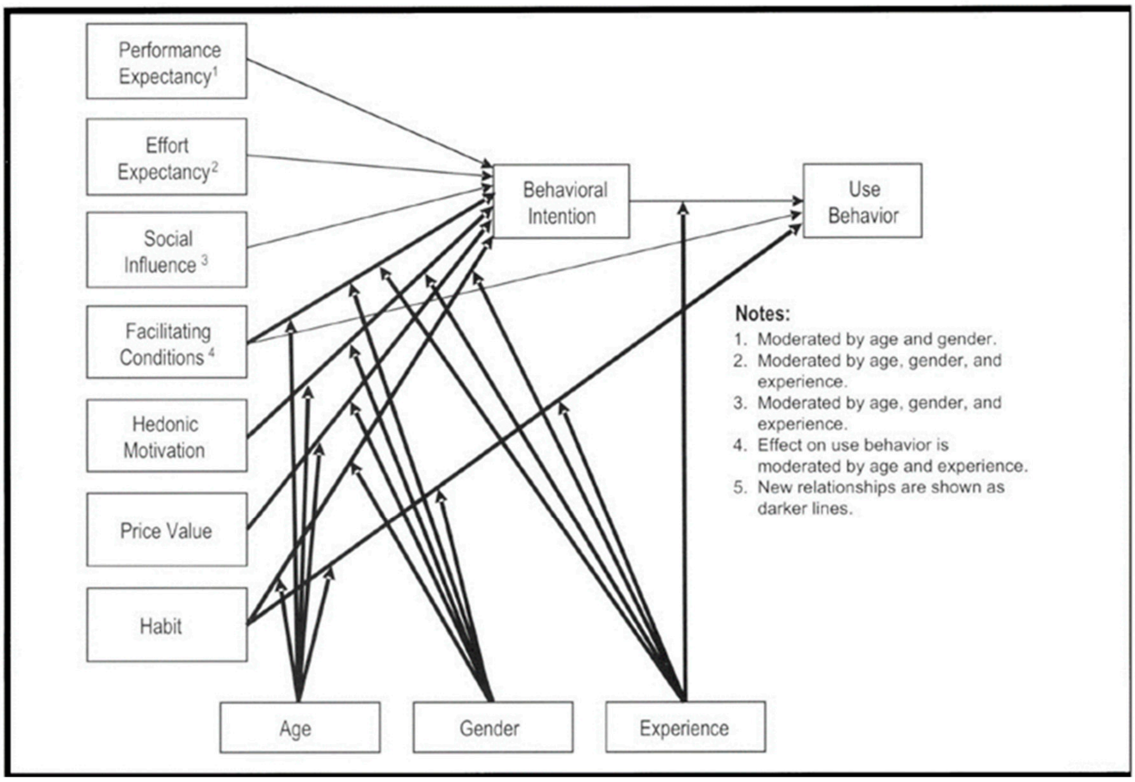

Figure 1. The Unified Theory of Acceptance and Use of Technology 2 (UTAUT-2) model from Venkatesh et al. 2012 [29] (permission to use the figure granted by the author: Viswanath Venkatesh). Note: The lighter arrows in Figure 1 show the original UTAUT domains.

2.1.2. Population and Recruitment

Participants in this study were individuals with stroke and their caregivers, as they often play an important role in the support and care of individuals with stroke. Including both individuals with stroke and their caregivers (when applicable) in the study allowed for a more diverse range of perspectives and insights. To be eligible for participation, participants were required to speak French or English, to have completed their ESD follow-up, and to have received TR interventions as part of the rehabilitation services the ESD program provided them within the past year. Individuals with stroke with severe cognitive and/or communication impairment that could have limited their participation in the data collection were excluded from the study. Participants were recruited using purposeful sampling [38] among clients from an urban rehabilitation center in Canada offering ESD as part of its stroke rehabilitation program. The aim was to recruit as many participants as possible from those who received TR services in the ESD program.

2.1.3. Intervention

The ESD Program

The ESD program provided treatment to individuals in the subacute stroke phase (typically 10 to 20 days post-stroke) who had mild to moderate deficits. These individuals were discharged home once they were medically stable and received the same level of intensive treatment as in an inpatient rehabilitation program [3]. In this current study, participants underwent the ESD program shortly after their hospital discharge, specifically between 7 and 10 days post-discharge. In the ESD program, clients received home-based intensive rehabilitation from an interdisciplinary team following discharge from acute care. The team consisted of an occupational therapist, physiotherapist, speech-language pathologist, social worker, clinical nurse, and special care counselor. The rehabilitation services were tailored to the specific needs of each client and were offered up to five days a week for a duration of five to six weeks. If necessary, clients could be referred to other disciplines, such as nutrition and psychology, to address additional needs. The components of this program were provided remotely to participants using TR. A coordinator facilitated communication between the interdisciplinary team, individuals with stroke, and their caregivers.

Telerehabilitation

Before starting remote rehabilitation, members of the interdisciplinary team visited the participants' homes to assess the environment and provided recommendations regarding suitable spaces for each TR intervention. The intervention proposed during remote rehabilitation was customized to meet the specific needs of each client and included daily life activities. In this study, TR was conducted using various technologies. Clinicians used their workstations (laptops or desktop computers with external camera and microphone). Individuals with stroke and their caregivers used personal cellphones, computers, or iPads. Zoom software version 5.6.5 (823) was used throughout TR sessions.

2.1.4. Data Collection Procedure

Sociodemographic and Clinical Characteristics

Sociodemographic characteristics, such as age, level of education, and clinical data, including the professionals from the interdisciplinary team that were involved in their care, the number of TR session for each discipline, and session duration were collected for each participant using an online survey. Additionally, the duration of participation in the ESD program with TR, the date and type of stroke, and time since stroke were extracted from participants with stroke' medical file.

Acceptability and Influencing Factors of Usability

Semi-structured interviews were held remotely in French and recorded using the Zoom Pro platform. These interviews were conducted by the third author, an experienced interviewer and occupational therapist, and lasted 30 to 45 min. The interviewer received guidance from both the second and the last authors. The interview guide was developed based on the CFIR model [28] and consisted of nine main open-ended questions, each accompanied by two to five probes, and was reviewed by the research team, which included experts in rehabilitation as well as knowledge translation, implementation science, and qualitative research. The main themes addressed in these questions revolved around participants' experience with TR (e.g., could you describe your experience with TR?), the accessibility of the technology (e.g., how did the process unfold to access the technology you needed for TR?), the technology functionality and complexity (e.g., was the technology relatively simple or rather complex to use?), and the interaction with therapists (e.g., how did you find the interaction with your therapists during TR?). The recordings of all interviews were transcribed verbatim by a research assistant and anonymized using pseudonyms. The verbatim transcripts were uploaded to the QDA Miner software version 6.0 to facilitate organization and coding.

2.1.5. Data Analysis

Sociodemographic and clinical data were analyzed using descriptive statistics (means, standard deviations, frequencies, and proportions).

An abductive thematic analysis, which aimed to transcend inductive and deductive approaches, was conducted [39]. Initially, a predefined coding scheme was developed based on the UTAUT-2 constructs. The interview verbatim transcriptions were coded using the predetermined codes, and where relevant, new codes were defined for extracts that were not represented in the initial codes. Finally, the new codes were reviewed with the research team and represented either as sub-themes related to the UTAUT-2 model or as new themes.

2.1.6. Ethical Considerations

Ethical approval for this study was obtained from the Rehabilitation and Physical Impairment Research Ethics Committee (CER RDP) of the Centre intégré universitaire de santé et de services sociaux du Centre-Sud-de-l'Île-de- Montréal (CCSMTL) (Project #2019-1058, CRIR-1347-0618). All participants provided informed consent before taking part in this study and were free to withdraw at any time.

3. Results

3.1. Description of Sample

A total of six individuals with stroke and three caregivers participated in the study. The mean age of the individuals with stroke was 67.7 $\pm$ 10 years, ranging from 50 to 77 years. The mean age of the caregivers was 61.7 $\pm$ 17.9 years, ranging from 42 to 77 years. Half of the participants had a university-level education, and 5/9 of them were males. The duration of TR sessions ranged from 45 min to 1 h. The disciplines in the ESD program (e.g., physiotherapy, occupational therapy) that were offered to individuals with stroke depended on their needs (Table 1), and the disciplines that were offered using only TR are mentioned in Table 1. The participants' strokes occurred between 2020 and 2021, which was during the COVID-19 pandemic when sanitary restrictions were imposed. Table 1 provides details of the participants characteristics.

Table 1. Participants' IDs and personal characteristics.

Participants ID	Age (Years)	Genre	Level of Education	Type of Stroke	ESD Duration with TR Modality (Weeks)	Rehabilitation Disciplines Involved	Disciplines Using only TR/Number of TR Session/Week	Time Since Stroke at the Time of the Interview (Months)
Individuals With Stroke (IWS)								
IWS-1	76	Male	University	Ischemic	5	PT, OT, SLP, SW; nurse, Psy	- OT/5/week - PT/5/week - SLP/5/week	12
IWS-2	77	Female	University	Ischemic	5	OT, kinesiology	- OT/3/week - Kinesiology/3/week	11
IWS-3	65	Male	Secondary	Ischemic	5	Psy, PT, SLP	- SLP/3/week	12
IWS-4	72	Male	University	Ischemic	6	OT, SLP, SW, psy, PT	- OT/3/week - PT/3/week - SLP/3/week - SW/2/6weeks	12
IWS-5	50	Female	College-level	Hemorrhagic	5	OT, PT, nurse, SW, art therapy	- OT/5/week - PT/5/week - Art therapy/5/week - Nurse/2/5weeks	7
IWS-6	66	Male	University	Ischemic	4	OT, PT, SW	- OT/3/week - SW/3/week	8
Caregivers (C)								
C1 (IWS-5)	42	Male	Secondary	N/A	N/A	N/A	N/A	N/A
C2 (IWS-2)	66	Female	University	N/A	N/A	N/A	N/A	N/A
C3 (IWS-4)	77	Female	Vocational diploma	N/A	N/A	N/A	N/A	N/A

Note: PT: physiotherapy; OT: occupational therapy; SLP: speech language pathology; SW: social worker; Psy: psychology/neuropsychology; N/A: not applicable.

3.2. Acceptability and Factors Influencing Usage of Telerehabilitation

Six main themes following the UTAUT-2 model were identified (Figure 2), which are presented and described in this section: (1) performance expectancy; (2) effort expectancy; (3) facilitating conditions; (4) social influence; (5) hedonic motivation; and (6) habit. Table 2 summarizes the results in terms of facilitators of and barriers to the acceptance and use of TR.

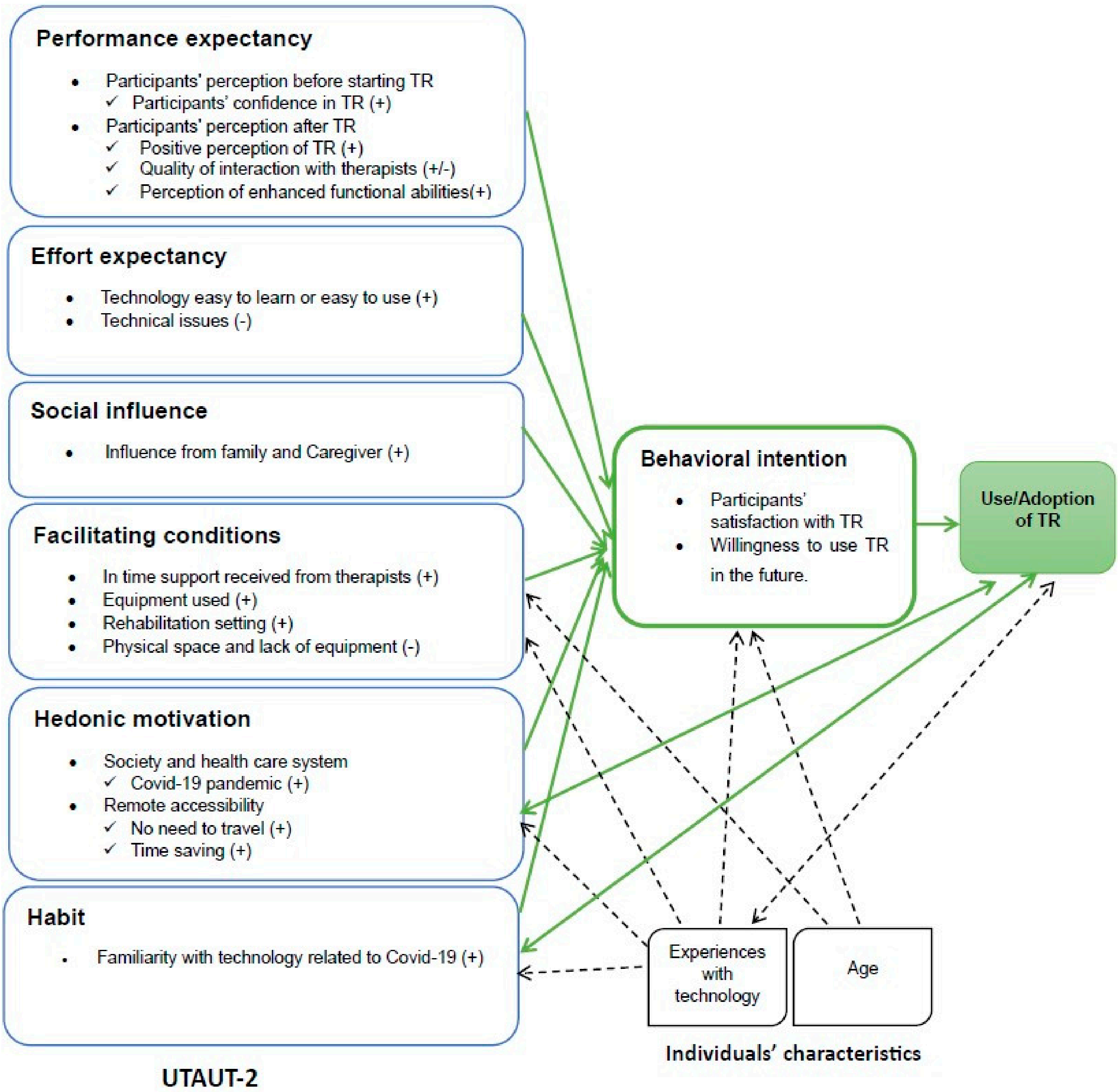

Figure 2. Acceptability and perceived factors influencing the use of TR based on the UTAUT-2 model. Note: + indicates a facilitator; − indicates a barrier; double-sided arrows (↔ ↔) show a dynamic, reciprocal relationship between two constructs, indicating influence in both directions. One-way arrows (→ - - →) depict a unilateral relationship, emphasizing that one construct can impact the other without direct reciprocity.

Table 2. Facilitators of and barriers to the acceptance and use of TR.

Factors Facilitating the Acceptance and Use of Telerehabilitation	Barriers to the Acceptance and Use of Telerehabilitation
• Participants' confidence in TR. • Positive perception of TR. • Quality of interaction with rehabilitation professionals. • Improvement in functional abilities. • Technology that is easy to learn or easy to use. • Support from family and caregivers. • In-time support received from therapists. • Familiarity with the equipment used for telerehabilitation (their own computer, iPad, tablet). • Familiarity with the rehabilitation setting (in their home environment). • No need to travel. • Time-saving. • Prior experience with Zoom or other technologies.	• Technical issues (audio configuration issues, relocating devices to different spaces, adjusting camera angles, and addressing general lighting concerns). • Instability of the internet connection. • Need for ample space to perform certain interventions (physiotherapy and occupational therapy). • Lack of equipment. • Lack of human contact. • Lack of feedback.

3.2.1. Performance Expectancy

For this theme, two sub-themes emerged: participants' perceptions (1) before starting TR and (2) after TR.

Participants' Perception before Starting TR

This sub-theme addressed participants' confidence in TR.

Participants' confidence in TR: Before starting TR, most participants had no prior experience in using technology for remote rehabilitation sessions. However, they were confident in achieving their rehabilitation goals. "*Before starting, I didn't have any apprehension, so I went for it [. . .] Since it was the first time [. . .] But in the end, I didn't have a bad experience, no. It went well*" (IWS-6).

Some participants were confident due to their previous positive experiences with technology and believed it was feasible. Ultimately, the results exceeded their expectations. "*Oh! I had no reservations. I work with technology [. . .] And I knew it was something that could be used [. . .] There were interventions* via *Zoom, and there were things that made progress*" (IWS-3).

Participants' Perception after TR

This sub-theme addressed three key points: (1) positive perception of TR, (2) quality of interaction with rehabilitation professionals, and (3) perception of enhanced functional abilities.

Positive perception of TR: All participants expressed a positive perception of the technology's use. Their overall experience was marked by significant benefits. The participants found the technology to be reliable and effective, greatly enhancing communication and collaboration with the stakeholders involved in the study. For instance, a caregiver expressed his perspective: "*There were no technological issues, and it allowed for improved communication with various stakeholders in different ways. It was excellent*" (C3). By providing remote rehabilitation services, TR filled a gap in post-stroke care, granting patients continuous access to healthcare professionals and specialized resources. For an individual with stroke, TR had a positive impact on his rehabilitation by providing quick access to treatments. He said: "*It (TR) allowed for faster and more frequent sessions, resulting in a significant benefit for me*" (IWS-3). TR was a valuable and appreciated experience, enabling them to receive the necessary rehabilitation care conveniently and efficiently. ESD, including when provided by TR, was widely perceived in a positive manner, eliciting positive reactions from participants.

Quality of interaction with rehabilitation professionals: All participants appreciated the interactions with the therapists. Despite being remote, the therapists were able to meet the participants' expectations. Patience, kindness, and availability were the words used by the participants to describe their appreciation of the therapists and to express their satisfaction with the quality of the interactions. For example, in response to the question, "How did you find the contact with the therapists when TR was used? Did you feel a sense of trust developed?" an individual with stroke expressed: "*I found it great! The ladies* *were great! Super friendly, kind, young. I liked the contact [. . .] they were available [. . .]. I have absolutely no criticism to make, really*" (IWS-2). A caregiver confirmed this by stating: "*I found all the therapists extremely kind and caring! They wanted to make sure things were going well. They wanted to make sure we were doing well. That's something very positive that I want to emphasize*" (C2). The TR experience was characterized by a good quality interaction with the therapists, which proved to be positive. However, four participants expressed regret regarding the lack of human contact during their TR sessions. They believed that this absence of contact could lead to negative repercussions on the feedback for certain interventions, particularly the challenges in demonstrating different angles to the camera during physiotherapy and occupational therapy sessions. One individual with stroke articulated this concern: "*In terms of physiotherapy, not having someone walking beside you and making corrections as you go along [. . .] it was less, I felt like there was less potential for feedback in terms of physiotherapy*" (IWS-3).

Improvement in functional abilities: All participants mentioned that they had achieved their rehabilitation goals set at the beginning according to their needs. They all reported a significant improvement in their physical condition after TR. Some participants noted an improvement in their manual dexterity, while others mentioned an improvement in their balance. For example, an individual with stroke expressed his success in regaining hand dexterity: "*It was really targeted. Exactly what I needed. Dexterity, the hand. I really succeeded*" (IWS-2). As for a caregiver, her spouse was unable to climb stairs upon leaving the hospital, but he could do so after TR. She expressed: "*On the first day he left the hospital, it took two people on each side to climb the six steps and enter the house. And in the end, he could go up and down all the steps and take a shower on their own*" (C3). ESD, including when provided by TR, has allowed participants to regain their functional abilities in a more effective and efficient manner.

3.2.2. Effort Expectancy

This theme referred to the degree of ease associated with using the system. Two sub-themes related to the technology easy to learn or easy to use and technical issues were identified.

Technology easy to learn or easy to use: All participants expressed their satisfaction with the ease of learning and using the technology. Even those who were using Zoom for the first time found it very easy to learn and use, requiring minimal effort and being well-suited to their abilities. For instance, an individual with stroke stated: "*It was the first time I did it, and it's easy*" (IWS-2). A caregiver confirmed these remarks, adding, "*It was the first time. We were wondering how it would go. But in the end, it was quite simple*" (C1). The technological tool, Zoom, has proven to be a solution in the context of TR, offering ease of learning and use.

Technical issues: Five participants mentioned technical difficulties, primarily related to their own devices (tablets, laptops, cameras). These difficulties primarily involved audio configuration issues, moving devices in different spaces, camera angles sometimes required for physiotherapy and occupational therapy intervention, and general lighting. For instance, an individual with stroke mentioned issues with the configuration of his tablet, which led to sound problems. He stated: "*I hadn't properly set up my tablet. So, my tablet had sound and other issues, that were technical problems*" (IWS-6).

Additionally, the stability of the internet connection was mentioned by three participants as one of the technical issues. The quality and smoothness of the audio and visual transmission during TR sessions were influenced by the reliability of the internet connection. However, this technical problem did not hinder the TR sessions, as users generally had a sufficiently good connection to conduct the sessions. For instance, a caregiver emphasized: "*There may have been an internet connection issue at some point, but I don't have any significant memory of it, generally, everything went well*" (C2).

Despite the technical constraints encountered during TR sessions, participants demonstrated remarkable perseverance and resilience, enabling them to continue their sessions without impediment. No interruptions were observed in the TR sessions due to these technical issues.

3.2.3. Social Influence

This theme pertains to the participants' perception of the individuals in their lives thoughts about the use of the technology for their rehabilitation. One sub-theme related to family and caregiver influence was identified.

Influence from family and caregivers: Some participants (n = 3) highlighted social influence when using the TR system. In addition to caregivers, family members played a prominent role in exerting social influence. For instance, for one caregiver, she and her daughter formed a strong team to positively influence the TR sessions of their parent. She expressed this by stating, "*We were also a team at home, my husband and his daughter (my daughter too). Thus, it has been an experience that helps people recover and feel comfortable in a familiar environment*" (C3). These participants emphasized the importance of their caregivers' influence in their therapy using technology. For example, an individual with stroke highlighted: "*I'm fortunate that my spouse is more knowledgeable about technology than I am*" (IWS-5). Another caregiver, due to his mastery of technological knowledge, indicated that he exerted an influence on the technology adoption of his spouse. He stated, "*Fortunately, my own computer knowledge made it happen easily. Because if it had depended solely on my spouse, she wouldn't have understood anything*" (C2).

Being able to receive support from their caregivers and family facilitated their therapy using technology.

3.2.4. Facilitating Conditions

This theme focuses on the participants' perceptions regarding the resources and support that were accessible to them during their use of TR. Three sub-themes emerged: (1) in-time support from therapists; (2) equipment used and rehabilitation setting; and (3) physical space and lack of equipment.

In-time support received from therapists: All participants emphasized that they had access to therapist support whenever needed to address technical issues or overcome any other difficulties that could hinder the smooth progress of their TR sessions. This facilitated the tasks during TR sessions. For instance, a caregiver mentioned, "*The first time, she (therapist) always arrived 5 min early to ensure she could assist us with the connection*" (C2). The involvement and availability of the rehabilitation professionals were essential in alleviating concerns and frustrations related to the use of technology, enabling participants to fully focus on their remote rehabilitation process.

Equipment used and rehabilitation setting: All participants used their own equipment, such as computers, iPads, and cameras, during the rehabilitation sessions. They were familiar with these tools and therefore did not need to learn how to use another device, which could have caused additional stress. For example, an individual with stroke used his own tools that he usually used in his professional activities. He stated, "*I have a tablet, a computer. And I used to own a small business that I left maybe a year ago, to retire. So, we were really into technology, we were working with a lot of tools*" (IWS-1).

Furthermore, the fact that the rehabilitation sessions took place at home allowed the participants to feel comfortable and relaxed, eliminating the stress associated with an unfamiliar environment. An individual with stroke expressed his comfort at home by saying, "*It took away the stress of being in a different environment, it puts me in my own environment. There, I could rest as I wanted, I could... I was at home! it says, 'There's no place like home'*" (IWS-6). The use of a familiar environment and familiar technological tools by participants undoubtedly facilitated TR by providing them with comfort and autonomy.

Physical space and lack of equipment: Most participants (n = 6) mentioned the need for ample space to perform certain interventions, particularly in occupational therapy and physiotherapy. Some had to rearrange furniture, while others had to move to different rooms depending on the intervention. For example, an individual with stroke highlighted: "*The kitchen is too small, so we used the dining room*" (IWS-4).

Despite these spatial constraints, all participants, in collaboration with the rehabilitation professionals, demonstrated great resilience and managed to find solutions to successfully carry out the TR sessions. One caregiver stated, "*She (rehabilitation professional) told us, look, we'll do this exercise in that room, and we can do this exercise in this area. To assess things, that's what she did—she looked at how our home was arranged. Then she conducted tests with certain interventions. And she said, okay, it works here, it doesn't work here because we need more space, and here it's safe*" (C1). In conclusion, the limitations arising from space constraints did not prove to be a significant obstacle impeding the smooth progress of TR.

Moreover, some participants (n = 4) highlighted the lack of equipment as an obstacle that can make TR more challenging. For instance, according to one participant, having basic equipment is necessary to engage in TR: "*Nothing too specific, but it definitely requires a foundation. If you don't have a laptop, it means you're confined to a single space*" (IWS-5). However, the participants managed to overcome this issue by acquiring the necessary equipment for their TR. For example, an individual with stroke said: "*I had to find my own tools and accessories*".

3.2.5. Hedonic Motivation

This theme focuses on the pleasure or entertainment derived from the use of TR. Two sub-themes were found related to: (1) society and the health care system and (2) remote accessibility emerged.

Society and the Health Care System

This sub-theme addressed the point related to the COVID-19 pandemic.

COVID-19 pandemic: Participants benefited from this intervention (ESD program in the form of TR) during a critical period between 2020 and 2021, while the COVID-19 pandemic was raging. The COVID-19 pandemic and its multiple repercussions on the healthcare system have led to increased difficulty in accessing healthcare services in Quebec. "*We talk about a pandemic because it was during the pandemic [. . .] I couldn't go to the clinics because they refused due to the virus.*" (IWS-2). Participants quickly realized that TR represented a better option for receiving care, despite the challenging healthcare context, and were motivated to use it. For instance, an individual with stroke did not hesitate to accept TR because of COVID-19, stating: "*I was asked if I wanted to do it* via *Zoom. Given the COVID situation, I said yes*" (IWS-1). Some participants perceived TR as a relief, "*For me, it was a good way to... I wouldn't leave the house; I wouldn't have someone come over. I didn't have access to anyone. We could do exercises and joke around, so it was lighthearted.*" (IWS-5), while others adopted it out of necessity, due to the lack of other available choices, "*We talk about a pandemic because it was during the pandemic. I didn't have a choice* "(IWS-2).

Remote Accessibility

This sub-theme addressed two key points: (1) no need to travel and (2) time-saving.

No need to travel: Most participants (n = 6) emphasized that the absence of travel for both individuals with stroke and rehabilitation professionals made TR more convenient and suitable. For instance, a caregiver emphasized that TR, by eliminating travel, is advantageous for all stakeholders: "*there are benefits to using this technology for the benefit of everyone in terms of travel*" (C3). Furthermore, for one of the participants, the use of TR proved to be an opportune strategy to reduce the risks of virus transmission: "*And with the times (COVID-19 and all), she (the therapist) is safe, and so am I*" (IWS-6). The absence of travel in the context of TR motivated the participants by providing them with a practical solution that is tailored to their specific needs, reduces virus transmission, and overcomes geographical barriers.

Time saving: According to some participants (n = 4), TR allowed them to save a considerable amount of time. For example, for an individual with stroke, TR reduced waiting times and provided a more efficient and convenient means of accessing a diverse range of rehabilitation services within the same day. He expressed it in the following way: "*The virtual approach brings certain advantages, as you can consult multiple specialists in a single day without wasting time on the road*" (IWS-5). TR provided flexibility and allowed individuals with stroke to see a greater number of specialists per day. As perceived by participants, these advantages contributed to optimizing time utilization and improved access to care.

3.2.6. Habit

This theme focuses on the extent to which people tend to engage in behaviors automatically. Two sub-themes related to (1) experience with zoom or other technology and (2) the familiarity with technology related to COVID-19 emerged.

Experience with Zoom or other technologies: All participants had previously used technological tools such as Skype, FaceTime, and even Zoom. Their prior experience boosted their confidence in virtual communication skills, making them more comfortable and willing to use TR. For example, an individual with stroke testified, saying, "*I didn't really have any doubts because I had already used Skype or similar tools*" (IWS-3). One of the caregivers added, "*We are professionals, and even before COVID, we worked with Zoom, teamwork, or meetings, things like that. We are very familiar with technology. And my spouse (IWS-4) too*" (C3). Overall, the participants' prior technological experiences played a positive role in their acceptance and successful utilization of TR and had a significant impact on mitigating the influence of advanced age on TR acceptance. Although, some participants (n = 2) pointed out that advanced age, coupled with post-stroke complications like reduced manual dexterity and visual or auditory impairments, could present obstacles to the adoption of technologies, "*For me, everything was complex [. . .], an elderly person who is not accustomed to technology [. . .] I think it would be challenging*" (IWS-5). The other participants did not mention advanced age as an obstacle, possibly due to their previous experience with technology.

Familiarity with technology related to COVID-19: The COVID-19 pandemic significantly expanded participants' relationships with technology. Most participants (n = 6) gained familiarity with technological tools such as Zoom during the pandemic and continue to use them regularly. One of the participants stated, "*In the context of my work, I used Skype a lot before Zoom came along [. . .]. It was here in Canada that I discovered Zoom because it's brand new*" (IWS-6). Over the past few years, technology has gradually become an integral part of lives, but the pandemic has accelerated this process dramatically.

3.2.7. Behavioral Intention

Regarding the participants' behavioral intention to use TR in the future, two sub-themes emerged: (1) participants' satisfaction with TR and (2) willingness to use TR in the future.

Participants' satisfaction with TR: All participants were satisfied with TR. They appreciated the opportunity to receive rehabilitation sessions in the comfort of their own homes. Additionally, some participants mentioned that using the technology helped reduce the stress associated with travel and allowed them to adhere to social distancing measures imposed by COVID-19. For example, for caregivers, TR with the ESD program, involving an interdisciplinary team, provided them with great strength. As mentioned by a caregiver, "*So, through the technology [. . .], it was very beneficial for me as a caregiver. I had a whole team around me that gave me a lot of strength*" (C3). An individual with stroke described TR as a positive experience, stating: "*I was very happy to use this system. It relieved me of a lot of stress... It was a quite... let's say, positive, very positive experience*" (IWS-2). Another participant, an individual with stroke, positively appreciated TR in these words: "*I am amazed and always grateful! So, at no point in any report, I want to see that I have been... No. Everything has been* *positive, more than positive*" (IWS-6). In conclusion, the participants thoroughly enjoyed the TR.

Willingness to use TR in the future: Overall, all participants reported an improvement in their functional abilities using TR. Consequently, most participants expressed their intention to use the system in the future. For example, for one participant, using TR would pose no problem. She stated, "*So for me, I found that if it had to be done again, I would do it without any problem*" (IWS-2). Similarly, one caregiver affirmed, "*It's excellent, I wouldn't change that. There are advantages to using this technology for the benefit of everyone in terms of travel*" (C3).

However, four participants expressed a preference for a hybrid model, combining remote and in-person rehabilitation sessions. For instance, one participant emphasized: "*In my case, since technology is not an issue, I would say it would have been a mix, maybe 90% Zoom and maybe 10% in-person sessions*" (IWS-1). As for caregivers, the hybrid model is seen as necessary: "*Yes, there are advantages to both. Then, I think that if it were used in a hybrid formula for physical rehabilitation, I believe it's something important to be able to guide more easily. I think that the majority can be done through TR*" (C2).

4. Discussion

The objective of this current study was to explore the acceptability of TR and the factors influencing the adoption of TR among individuals with stroke and their caregivers while receiving services from an ESD program. To our knowledge, this study is among the first to have explored the dimensions of TR in an ecological context of the participants and during traditional home-based rehabilitation. The results revealed that various factors related to the majority of UTAUT-2 domains played a significant role in the acceptability and adoption of TR.

First, the findings regarding participants' perceived performance expectancy revealed that, despite participants' initial unfamiliarity with TR, they displayed a favorable disposition towards its inclusion/integration in their rehabilitation. Moreover, factors such as improvements in physical abilities, like manual dexterity attributed to TR, and the positive perception of engagement and rapport with therapists positively influenced TR acceptability and its use. These results echoed the conclusions drawn by a qualitative study with 13 individuals with stroke who highlighted improvements in physical abilities and emotional well-being among participants through TR. Another qualitative study with five individuals with total knee arthroplasty conducted by Kairy et al. [40] revealed that participants also appreciated their interactions with physical therapists during their remote rehabilitation sessions, highlighting the importance of a therapeutic relationship for successful rehabilitation [41]. Given these positive results, the majority of participants expressed their satisfaction with TR and indicated their intention to use it in the future, corroborating findings from previous studies where participants similarly reported contentment with TR [40,42,43]. However, some participants reported receiving limited feedback during specific TR interventions, such as physiotherapy and occupational therapy, preferring a hybrid model that combines in-person rehabilitation with a remote component. Previous studies reported similar results, reinforcing the challenges of providing rehabilitation services solely through TR [23,40]. The use of a hybrid model could prove to be a more efficient approach and ensure access to care. Thus, clinicians could choose between face-to-face or TR interventions when appropriate throughout the ESD rehabilitation care episode. However, in countries that do not provide an ESD program, the use of the hybrid model could also help rehabilitation by increasing the frequency of rehabilitation sessions, either individually or potentially in groups. For example, rehabilitation professionals could schedule in-person sessions for comprehensive physical assessments while also offering TR sessions for regular follow-ups. This approach could provide increased flexibility in managing session schedules. Thus, the hybrid model could play a significant role in optimizing rehabilitation care for individuals with stroke, especially in contexts where resources are limited. In summary, these findings demonstrate the acceptability of TR in enhancing the functional abilities of individuals with stroke, as well as the potential to maintain a high-quality therapeutic relationship with healthcare professionals, despite geographical separation, therefore contributing to a favorable performance expectancy for TR and an increased behavioral intention to use it.

Secondly, participants' perceived effort expectancy underscored that technology-related factors significantly influenced acceptance and the use of TR. Specifically, the Zoom platform used in TR by the ESD program was lauded by participants for its ease of learning and utilization, which has been shown to be a relevant characteristic for the acceptability of TR [42]. However, technical issues and an unstable internet connection presented obstacles, but they did not interrupt the TR sessions. These results could be explained by the fact that the study took place in an urban environment in an industrialized country with excellent internet connectivity or because participants were tolerant of these issues. However, it is worth noting that challenges related to internet access may be even greater in rural areas and/or in developing countries [44]. In comparison to previous studies [23,42], technical problems and internet connection difficulties resulted in visibility issues and poor sound quality during TR sessions. These difficulties led to the cancellation of scheduled sessions and caused subsequent planning problems, which could affect the intensity of therapy for individuals with stroke and could have a negative effect on their rehabilitation [23,42]. Even though individuals with stroke in this current study appeared to be more tolerant of these technical issues, as also noted by a randomized controlled trial with 21 individuals with stroke, conducted by Woolf et al. [45], clinicians would be less so. For example, in their study on the implementation of TR before and during the COVID-19 pandemic, involving six clinicians and two managers, Auger et al. [23] indicated that clinicians had a relatively poor tolerance for technical difficulties and wanted to discontinue TR when these occurred, especially before COVID-19. While technical issues did not disrupt TR for individuals with stroke and caregivers participating in this current study, addressing these concerns should be a priority to ensure a seamless experience for future users. In conclusion, these results emphasize the importance of technology reliability and stability in maintaining the quality and effectiveness of TR programs for individuals with stroke.

Third, participants' environmental factors (social influence and facilitating conditions) were key for the acceptability of TR, especially regarding caregiver availability, equipment used for the TR, and TR setting. Indeed, individuals with stroke noted that the support provided by their caregivers encouraged them to use and engage with TR more effectively, especially during the early stages of stroke recovery when residual stroke consequences, like fine motor skills problems, visual impairments, and auditory impairments, could add complexity to using the technology. Caregivers played a pivotal role in providing technical assistance, such as device setup and camera adjustment for better visibility, as well as resolving any technical issues, which compensated for individuals with stroke impairments. Additionally, they acted as intermediaries, facilitating communication between individuals with stroke and rehabilitation professionals during TR therapies. Therefore, the presence of caregivers emerged as a significant facilitating factor in the acceptance of TR, aligning with previous studies that confirmed its important and supportive role [43,46,47]. However, not all individuals with stroke in this study had caregivers; yet, they did not report distinct challenges without one, highlighting the acceptance of TR even for those who were alone. Furthermore, participants' familiarity with their own devices (computers, tablets, cameras) and the TR setting at home facilitated stress reduction and improved the ease of using TR. This aligns with a mixed method study that included seven individuals with stroke, three caregivers, and six clinicians [48] that found that the familiarity of individuals with stroke with the equipment facilitated the adoption of TR. In summary, our evidence illustrates the importance of caregivers being present during TR sessions and equipment familiarity as key factors for successful TR adoption.

Regarding hedonic motivation, the health context related to the COVID-19 pandemic played an important role in motivating the acceptance of TR. Notably, this study focused on individuals who had experienced a stroke between 2020 and 2021, a period that coincided with the height of the COVID-19 pandemic and the corresponding preventive measures, such as social distancing. TR provided these participants with a solution that allowed them to receive rehabilitation care while adhering to social distancing protocols aimed at minimizing the risk of infection. Previous studies have similarly demonstrated that TR served as a practical approach to ensuring continuous care amidst the constraints imposed by the COVID-19 pandemic [49–51]. While the initial impact of the pandemic prompted many individuals to adopt TR [52], it also created an environment conducive to widespread familiarity with technologies, particularly platforms like Zoom© and Microsoft Teams© in Canada, and the exploration of their numerous benefits [52]. Therefore, participants' earlier experience with these technological tools facilitated TR use, aligning with Kruse et al.'s systematic review [53] of 30 studies that highlighted how a lack of technological experience and computer literacy acted as significant barriers to telemedicine adoption. Similarly, Auger et al. [23] observed that, before to the COVID-19 pandemic, clinicians' and managers' limited experience with the telemedicine platform imposed on them at that time impeded TR adoption. However, as reported in the same study [23], during the COVID-19 implementation phase, the fact that clinicians and managers themselves chose to use Zoom© because it was easier, and their familiarity with this platform, facilitated the adoption of TR. In summary, COVID-19 prompted participants to recognize certain advantages of TR, such as security, convenience, and accessibility. It would be important for TR to continue playing a significant role in post-stroke rehabilitation to ensure equitable access to rehabilitation services. Future studies could help to better learn from individuals with stroke and caregivers' experiences to provide essential guidance for clinical practice and policymaking.

5. Strengths and Limitations

This study has methodological strengths that enhance the scientific rigor of its findings. First, the use of two robust theoretical frameworks, namely the CFIR [28] and the UTAUT-2 [29] models, significantly bolstered the credibility of this research. Indeed, the incorporation of CFIR [28] enabled us to meticulously construct interview guides, comprehensively probing various facets influencing the adoption of TR within the ESD program. Meanwhile, the application of the UTAUT-2 model [29] during thematic analysis facilitated a profound and exhaustive exploration of the data, aligning with the objectives and unveiling the intricate interplay between identified themes. This deliberate approach amplified the credibility and relevance of this study. In order to ensure the transparency of the methodology, we adhered to the COREQ checklist, reinforcing the transferability of the outcomes. Furthermore, the inclusion of two distinct participant groups, individuals with stroke and caregivers, enriched the diversity of perspectives in this study, thereby reinforcing its credibility.

However, it is important to acknowledge certain limitations inherent in this research. The restricted sample size and homogeneity of participants drawn solely from a single ESD program limited the spectrum of perspectives obtained. This uniformity poses challenges in extrapolating these findings to other post-stroke rehabilitation programs incorporating TR, particularly in varying ESD contexts. However, contextual and personal details were documented and provided in order to allow the transferability of results where relevant. It is also important to acknowledge the presence of selection bias, given that we only had access to a sample of individuals monitored by the ESD program who received TR; this could have led to the collection of generally more positive perceptions. Thus, caution is necessary when attempting to generalize the findings to encompass all individuals with stroke and caregivers. Nevertheless, the meticulous presentation of both methods and results facilitates their adaptability across different settings [54].

6. Conclusions

The results of this qualitative study suggest that TR was accepted by individuals with stroke and their caregivers. Perceived benefits, such as improved performance, ease of technology use, and facilitative conditions, including support from caregivers and healthcare professionals, as well as the hedonic motivation associated with the COVID-19 pandemic, were factors that contributed to the acceptability of TR and its adoption among participants. TR is a promising intervention method for stroke rehabilitation by ESD programs, as it has been found to be convenient, accessible, and likely to be adopted in the long term by individuals with stroke and caregivers. However, barriers such as technical issues, unstable internet connections, and lack of feedback could limit the acceptance and use of TR. Thus, the use of a hybrid model combining in-person and remote rehabilitation can help overcome some of the challenges of TR and better address the needs of individuals with stroke and their caregivers. Future research is needed to further deepen our understanding of the needs and responsibilities of individuals with stroke and their caregivers.

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Article

Evaluation of Telephone Visits in Primary Care: Satisfaction of Pediatricians and Family Physicians and Their Perceptions of Quality of Care and Safety

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Abstract: Telehealth has accelerated since the outbreak of the COVID-19 virus. As telephone visits become more common, it is important to examine the challenges involved in using this modality of care. In this study, we examined family physicians' and pediatricians' perceptions regarding three aspects of the use of telephone visits: quality of care, safety of care, and physicians' satisfaction. A total of 342 family physicians and pediatricians responded to an online survey. Respondents were asked to rate their degree of agreement with 17 statements inquiring about quality, safety, and satisfaction with telephone visits on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). This was followed by in-depth interviews between January and April 2023 with 26 physicians. Participants expressed satisfaction (3.66 ± 0.80) with the use of telephone visits and lower assessments of safety (3.03 ± 0.76) and quality (2.27 ± 0.76) of care using the telephone modality. Eighty percent of the respondents think combining a face-to-face visit with a telephone visit is recommended, and 51% noted that the inability to examine patients closely affects and impedes a physician's decision making. Most interviewees indicated that telephone visits are safe only with former patients they had already seen in the clinic. The findings shed light on the perceptions of family physicians and pediatricians regarding telephone visits. The lower assessments of quality and safety compared to the assessment of satisfaction underscore the need for careful use of telephone visits in healthcare. A proper and balanced selection of patients, implementing technological upgrades to the modality, and performing patient education practices are recommended.

Keywords: telemedicine; telehealth; telephone visit; safety; quality; satisfaction; service assessment

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1. Introduction

Telemedicine delivers healthcare services using information and communication technology to remotely diagnose, treat, and prevent disease or injuries, conduct research, and provide evaluations and education for healthcare providers and their communities [1]. The COVID-19 pandemic changed patterns of operation in the healthcare system, including a transition to providing medical care through remote encounters. This proved central in preventing the transmission of the coronavirus and protecting both patients and service providers [2].

Telemedicine presents an opportunity to overcome many obstacles, including those of geography and logistics. According to a recent review, family physicians were the healthcare providers who made the most use of telemedicine services such as telephone visits. Telephone encounters can provide a means of following up with patients and monitoring disease, empowering patients, guiding patients, and providing quick and easy access to medical resources [3]. Remote care modalities in pediatric medicine, such as telephony, videoconferencing, and remote monitoring, have increased recently. Remote consultation over the telephone is a particularly popular modality for patient care among patients [4,5]. In a systematic review of telemedicine in pediatrics, Shah and Badawy (2021) demonstrate the distribution of various telemedicine approaches, such as videoconferencing consultations (45%), smartphone-based interventions (27%), telephone counseling (18%), and telemedicine-based screening visits (9%). The telephone modality is considered a common alternative form of care to face-to-face consultation in clinical settings [6].

Previous evidence showed outcomes involving symptom management, quality of life, satisfaction, medication adherence, visit completion rates, and disease progression among patients using telehealth technologies, were similar to, or better than, the outcomes of the control groups [5]. Many acute pediatric conditions can be managed safely and effectively through telemedicine, mainly when remote physical exam equipment is used [7].

While telephone consultations have many benefits, some concerns need to be addressed. A study conducted in Israel before the COVID-19 pandemic demonstrated several challenges for physicians, including diagnosing from a distance, treating unfamiliar patients, call urgency and loads, technical obstacles, and a "moral conflict" between the desire to meet parents' expectations and maintaining standards of care [8]. Nonetheless, the use of telemedicine during the pandemic and beyond has become prevalent, and additional challenges must be met to successfully expand telephone consultation as a modality of remote care [9].

According to a survey carried out in Israel that included 2536 respondents between October 2021 and March 2022, it was found that 19% reported that they contacted their family doctor during their last visit by telephone or video visit. It total, 44% of the respondents reported using telemedicine services (telephone visit, video visit, or chat) in the last year [10]. Data based on all visits to primary care in Clalit Health Services, the biggest HMO in Israel with more than 4 million patients, show that the share of visits provided remotely started at 5% before COVID-19, peaked at 40% during the first COVID-19 lockdown in April 2020, and stabilized to 20% post lockdown around June 2021 when the COVID-19 rate in Israel was very low [11]. Based on data that include all visits to pediatricians at Maccabi Health Services, the second largest HMO in Israel with approximately 2 million patients, telephone visits accounted for 0% of pediatrician visits before the pandemic, 17% of pediatrician visits during the first lockdown period, and 19% of pediatrician visits one month after the lockdown in May 2020 [5]. According to OECD data, the average number of annual doctor consultations among 12 European countries was 5.1 in-person consultations and 1.4 teleconsultations, meaning that about 22% of all consultations were teleconsultations [12]. In the US in 2021, according to the National Center for Health Statistics (NCHS), 37% of the adult population received remote health care in the last 12 months (with higher use by women and higher use for older ages) [13]. According to a national survey in the US conducted in 2021 and 2022, 22.5% reported the use of telehealth services (audio only or video) within the last 4 weeks [14]. Although the data presented reflect the use of telephone visits as part of the use of telemedicine services, it is possible to see a similar or higher use of telephone visits in Israel compared to other Western countries. It appears that telemedicine tools such as telephone visits have become an integral part of our lives and will continue to be used in the healthcare system. Previous studies investigated the use of telemedicine and telephone visits following COVID-19, in Israel and Western countries. Most studies focus on the frequency of use and patients' satisfaction with telemedicine but do not deal with doctor's satisfaction with the use of telephone visits and their perceptions of the quality and safety of its use. Consequently, it is essential to examine physicians' perceptions and concerns regarding telephone visits and engage physicians in development processes to improve and enhance the acceptance of telemedicine. The current multi-methods study aimed to assess physicians' satisfaction with telephone visits, evaluate the quality and safety of the telephone modality as perceived by pediatricians and family physicians, and generate recommendations to increase the efficiency and acceptability of this service. In mixed-method research, quantitative and qualitative methods are employed together to create a research outcome stronger than either method alone [15]. This method enables exploring more complex aspects of human and social interactions, therefore gaining a deeper understanding of the perceptions of physicians toward the use of telephone visits.

2. Materials and Methods

This study utilized qualitative and quantitative assessment methods, including a survey and in-depth interviews among pediatricians and family physicians working in Clalit Health Services (Clalit), Israel's largest health maintenance organization (HMO). The study was approved by the Ashkelon Academic College Ethics Committee (Approval #43-2022). Multi-methods research is a systemic approach to understanding the interaction of variables in a complex environment [16]. While quantitative assessment allows for exploring causal linkages among sets of data, qualitative assessment persuades through the rich description of perceptions and adds an understanding of the phenomenon that numbers alone cannot [15].

2.1. Population Sample

In total, 1000 pediatricians and 2500 family physicians working in Clalit were contacted by researchers, of which 342 responded to an online survey distributed via electronic mail (e-mail) (9.8% response rate) between January and April 2023. Two electronic e-mail reminders were sent one month and two months after the initial contact. The survey was closed in April 2023.

Interviewees were recruited using purposeful sampling. Purposeful sampling is a non-random sampling technique that uses specific criteria or purposes to select a sample [17]. The aim is to collect in-depth information from the right respondents. The inclusion criteria: pediatrician or family physician working in Clalit. We continued the interviews until theoretical saturation was reached. Signed informed consent was obtained for additional interviews, which were administered to 26 participants of the sample (7 pediatricians and 19 family physicians. See Appendix A) between March and April 2023. The interviews, lasting between forty minutes and an hour, were conducted by one of the authors (TS), who specializes in qualitative research methods in healthcare settings over the phone. Figure 1 describes the study participants in both quantitative and qualitative phases of data collection.

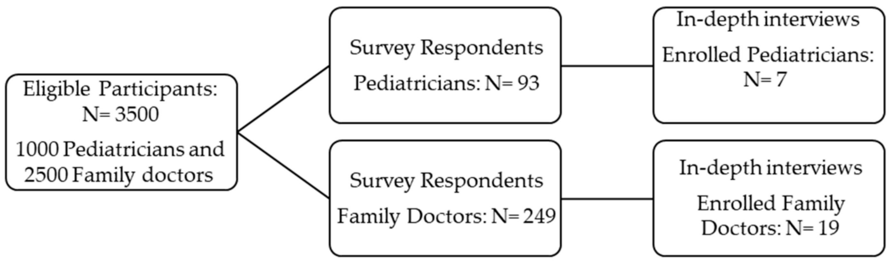

Figure 1. Flow diagram for study participants.

2.2. Research Tools

The survey developed by the researchers (see Supplementary File S1) was validated by two family physicians and one pediatrician using the content validation method. The content validation process included a readability test to determine whether the items or questions effectively represent the variables or constructs measured. Following their comments, ambiguous questions were clarified, and the questionnaire was evaluated in a piloted study. In the pilot, 12 participants including the study team and physicians responded to the survey. Respondents were asked for feedback related to the accuracy of the survey instructions and questions. The final questionnaire included 17 statements in three subsets: quality, safety, and satisfaction of telephone visits with patients. Four questions (3, 4, 5, and 6) were excluded from the classification as they represented perceptions of potential improvements and the usefulness of the telephone modality of telemedicine. Respondents were asked to rate their degree of agreement on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Questions 8 and 10–12 have a reverse evaluation scale; therefore, the responses were transposed for uniformity with further assessment. The questionnaire also included sociodemographic factors such as gender, age, number of years of experience in medicine, number of years of experience in telephone visits with patients, the geographic area of work in Israel, and the physicians' sector of the population (General, Arab, Ultra-Orthodox, which is a minority religious group characterized by strict adherence to the Jewish law of Halakha). In addition, participants were asked for their opinions regarding the situations in which telephone visits can be used safely. Table 1 presents the survey instrument validity assessment (Cronbach's alpha of the complete survey was $\alpha = 0.87$).

Table 1. The survey instrument validity assessment.

Subset	Number of Statements	Cronbach's α	ICC (95% CI) *	p-Value
Quality	4	0.759	0.714–0.799	<0.001
Safety	5	0.636	0.570–0.695	<0.001
Satisfaction	4	0.776	0.735–0.812	<0.001

* CI—confidence interval; ICC—intra-class correlation coefficient.

The interview guide was developed as a complementary tool to the survey (see Supplementary File S1). The topics that guided the question development were in line with the survey protocol as follows: (1) assessment of the quality of the telephone visit service, (2) challenges associated with the safety of the telephone visit service, and (3) physicians' satisfaction and concerns related to the telephone visit service. The interview guide was validated using the content validation method with one pediatrician and one family doctor to ensure a smooth interview flow and verify comprehension of the questions. The in-depth interviews were semi-structured. The wording and order of the questions changed according to the interview dynamics to maintain continuity and encourage openness of the interviewees. No prior relationship existed between the interviewer and the participants.

2.3. Statistical Analyses

Internal consistency was assessed by applying Cronbach's α coefficient to each subset and the overall instrument. In order to describe the distribution of the responses to the statements, Pearson's product–moment correlations of corresponding subsets and intra-class correlation coefficients (ICC) were calculated. Student t-tests were employed to establish the differences between subsets. A one-way ANOVA test included post-hook analysis using the Tukey method. Finally, multiple linear regression models with perceptions toward quality, safety, and satisfaction as outcomes were tested. A statistical significance level of $\alpha = 0.05$ was assumed throughout the study. All testing was performed using IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY, USA: IBM.

The interviews were analyzed using a thematic analysis method based on grounded theory [18]. The analysis included incorporating deductive themes from the research topic and based on an exhaustive literature review of telemedicine, together with inductive themes that emerged from the data [19]. As part of the analysis of the transcripts, all interviews were read several times to obtain a thorough understanding of the data. Following the study's objectives, researchers identified concepts, categories, and themes. Re-reading the transcripts prompted a reevaluation of the central themes by adding encoded quotes and examples. During the analysis, we conducted an ongoing internal quality audit, adapted from Mays and Pope [19]. The themes and quotes were translated and documented in English at the final stage. We used a standardized codebook to ensure the validity of the translations from Hebrew to English.

3. Results

3.1. Sample Characteristics and Perceptions towards Telephone Visits

Table 2 presents the survey participants' demographic data. The mean experience for family physicians and pediatricians was 23 years (SD ± 11.4) and 25 years (SD ± 10.5), respectively. The experience with the telephone modality was 5 years (SD ± 6.5) for family physicians and 5 years (SD ± 6.2) for pediatricians.

Table 2. Demographic characteristics of the survey sample.

Variable		Family (N = 249) N (%)	Pediatricians (N = 93) N (%)	All (N = 342) N (%)
Gender	Male	136 (54.8%)	40 (54.0%)	179 (52.3%)
	Female	112 (45.2%)	51 (56.0%)	163 (47.7%)
Population Sector	General	188 (75.5%)	70 (75.3%)	258 (75.4%)
	Arab	41 (16.4%)	15 (16.1%)	56 (16.4%)
	Ultra-Orthodox	20 (8%)	8 (8.6%)	28 (8.2%)
Geographic Area	North	64 (25.7%)	24 (25.8%)	88 (25.7%)
	Center	149 (59.8%)	51 (54.8%)	200 (58.5%)
	South	36 (14.5%)	18 (19.4)	54 (15.8%)
Age Group	≤40	26 (10.4%)	6 (6.5%)	32 (9.4%)
	41–50	32 (12.9%)	13 (14%)	45 (13.2%)
	51–60	89 (35.7%)	28 (30.1%)	117 (34.2%)
	61–70	91 (36.5%)	31 (33.3%)	122 (35.7%)
	70+	11 (4.4%)	15 (16.1%)	26 (7.6%)

Table 3 presents the means and standard deviations of the three research variables. No significant differences were observed between pediatricians and family physicians in perceptions of the quality, safety, and satisfaction of physicians regarding the use of telephone visits.

Table 3. Research variables mean and standard deviation.

Subset	Family Physicians (N = 249) Mean ± SD	Pediatricians (N = 93) Mean ± SD	All Samples (N = 342) Mean ± SD	*p*-Value between Groups *
Quality	2.26 ± 0.77	2.31 ± 0.74	2.27 ± 0.76	0.597
Safety	3.03 ± 0.76	3.02 ± 0.75	3.03 ± 0.76	0.841
Satisfaction	3.65 ± 0.82	3.69 ± 0.76	3.66 ± 0.80	0.689

* *t*-Test.

Table 4 presents the distribution of the responses. Anchor points 1 (strongly disagree) and 2 (somewhat disagree), and anchor points 4 (somewhat agree) and 5 (strongly agree) were combined to present the distribution. The survey population's responses showed that 48.4% of the respondents think that telephone visits cannot replace a face-to-face meeting, and 43% think that the quality of care in telephone visits is not the same as the quality of care provided in clinic visits. Similarly, about 80% think combining a face-to-face visit to the clinic with a telephone visit is recommended. Half of the respondents believe telephone visits are unsafe for patients and may involve risks. Fifty-four percent mentioned that telephone visits shorten the duration of a visit compared to a face-to-face visit in the clinic. Half of the respondents noted that the inability to examine a patient closely affects the doctor's decision making, making it difficult. Nevertheless, half of the respondents expressed satisfaction with telephone consultations. Fifty-two percent of the respondents agreed with the statement regarding whether transferring photos and documents would improve the quality of care, and 40.8% agreed with the statement regarding whether or not incorporating video recording during a telephone visit would improve the quality of service.

Table 4. Survey responses distribution.

Statement		Disagree	Neutral	Agree
In my opinion, the quality of care in telephone visits is the same as the quality of care provided in-clinic visits.	Family Pediatricians All	104 (41.8%) 43 (42.6%) 147 (43%)	87 (34.9%) 32 (34.4%) 119 (34.8%)	58 (23.3%) 18 (19.4%) 76 (22.2%)
In my opinion, a remote telephone visit can replace a face-to-face meeting in most meetings in my clinic.	Family Pediatricians All	118 (47.6%) 47 (50.5%) 165 (48.4%)	69 (27.8%) 29 (31.2%) 98 (28.7%)	61 (24.6%) 17 (18.3%) 78 (22.9%)
The possibility of transmitting photos and documents during a telephone visit will improve the quality of care provided during the visit.	Family Pediatricians All	62 (24.9%) 17 (18.3%) 79 (23.1%)	66 (26.5%) 19 (20.4%) 85 (24.9%)	121 (48.6%) 57 (61.3%) 178 (52%)
Incorporating video recording during a telephone visit will improve the quality of the care provided.	Family Pediatricians All	81 (32.7%) 29 (31.2%) 110 (32.3%)	69 (27.8%) 23 (24.7%) 92 (27%)	98 (39.5%) 41 (44.1%) 139 (40.8%)
In my opinion, a telephone visit shortens the duration of the visit compared to a face-to-face visit in the clinic.	Family Pediatricians All	56 (22.6%) 24 (26.1%) 80 (23.5%)	57 (23%) 18 (19.6%) 75 (22.1%)	135 (54.4%) 50 (54.3%) 185 (54.4%)
Regarding ongoing care, combining a face-to-face visit to the clinic with a telephone visit is recommended.	Family Pediatricians All	21 (8.6%) 8 (8.6%) 29 (8.6%)	31 (12.7%) 9 (9.7%) 40 (11.9%)	192 (78.7%) 76 (81.7%) 268 (79.5%)
I think telephone visits do not eliminate the need for face-to-face meetings and are complementary to them.	Family Pediatricians All	106 (43.1%) 38 (40.9%) 144 (42.5%)	56 (22.8%) 25 (26.9%) 81 (23.9%)	84 (34.1%) 30 (32.3%) 114 (33.6%)
In my opinion, a telephone visit increases the pressure for patients.	Family Pediatricians All	188 (76.1%) 74 (81.3%) 262 (77.5%)	43 (17.4%) 12 (13.2%) 55 (16.3%)	16 (6.5%) 5 (5.5%) 21 (6.2%)
In my opinion, a telephone visit is safe for the patient and does not involve increased risks.	Family Pediatricians All	125 (50.6%) 41 (45.1%) 166 (49.1%)	53 (21.5%) 26 (28.6%) 79 (23.4%)	69 (27.9%) 24 (26.4%) 93 (27.5%)
In my opinion, telephone visits harm patient compliance in carrying out the medical recommendations compared to a face-to-face visit at the clinic.	Family Pediatricians All	103 (42.6%) 46 (49.5%) 149 (44.5%)	59 (24.4%) 25 (26.9%) 84 (25.1%)	80 (33.1%) 22 (23.7%) 102 (30.4%)
The inability to closely examine patients makes the doctor's decision making more difficult.	Family Pediatricians All	56 (22.7%) 15 (16.1%) 71 (20.9%)	71 (28.7%) 24 (25.8%) 95 (27.9%)	120 (48.6%) 54 (58.1%) 174 (51.2%)
I sometimes feel uncertain about patients' medical conditions during a telephone visit.	Family Pediatricians All	68 (27.5%) 25 (27.2%) 93 (27.4%)	68 (27.5%) 22 (23.9%) 90 (26.5%)	111 (44.9%) 45 (48.9%) 156 (46%)
I feel confident in my professional abilities to perform a telephone visit correctly and optimally.	Family Pediatricians All	43 (17.6%) 18 (19.4%) 61 (18%)	65 (26.5%) 18 (19.4%) 83 (24.6%)	137 (55.9%) 57 (61.3%) 194 (57.4%)
I am satisfied with the use of telephone visits.	Family Pediatricians All	63 (25.6%) 24 (26.1%) 87 (25.7%)	59 (24%) 22 (23.9%) 81 (24%)	124 (50.4%) 46 (50%) 170 (50.3%)
Telephone visits are usually conducted efficiently and without technical problems.	Family Pediatricians All	46 (19%) 13 (14.3%) 59 (17.7%)	45 (18.6%) 24 (26.4%) 69 (20.7%)	151 (62.4%) 54 (59.3%) 205 (61.6%)
In most cases, patients are available during telephone visits and hold a conversation with the doctor attentively and in a quiet environment.	Family Pediatricians All	61 (25%) 24 (26.1%) 85 (25.3%)	72 (29.5%) 36 (39.1%) 108 (32.1%)	111 (45.5%) 32 (34.8%) 143 (42.6%)
In my opinion, it is safe to conduct a telephone visit only with existing patients whom the doctor has met face-to-face before	Family Pediatricians All	39 (16.2%) 16 (17.2%) 55 (16.5%)	52 (21.65) 18 (19.4%) 70 (21%)	150 (62.2%) 59 (63.4%) 209 (62.6%)

Table 5 presents the distribution of the responses to the question regarding the situations in which telephone visits can be used safely. In total, 222 of the participants responded to this question (64.9%). Most family physicians mentioned administrative care, routine actions, follow-up, and providing prescriptions as the situations in which telephone visits can be used safely. Pediatricians had similar opinions about the addition of not complicated cases.

Table 5. Recommended conditions in which telephone visits can be safely used.

Modes of Use	**Family Physicians (N = 155) N (%)**	**Pediatricians (N = 67) N (%)**	**All Respondents (N = 222) N (%)**
A physical examination is not required	23 (14.8%)	4 (6%)	27 (12.2%)
Admin care, routine actions	47 (30.3%)	15 (22.4%)	62 (27.9%)
General and urgent consultations	29 (18.7%)	8 (11.9%)	37 (16.7%)
Follow-up, prescriptions	31 (20%)	16 (23.9%)	47 (21.2%)
Not complicated cases	8 (5.2%)	16 (23.9%)	24 (10.8%)
Parental guidance	0	3 (4.5%)	3 (1.4%)
Referrals	10 (6.5%)	5 (7.5%)	15 (6.8%)
Contagious diseases	7 (4.5%)	0	7 (3.2%)

3.2. Differences in Perceptions towards Telephone Visits

A one-way ANOVA test and post hoc test using the Tukey method were performed to examine differences in perceptions towards telephone visits among sociodemographic groups of participants. Analysis showed significant differences by population sector regarding the perceptions of safety and satisfaction in the use of telephone visits (F = 3.16, $p < 0.05$ and F = 4.11, $p < 0.05$, respectively). Ultra-Orthodox physicians expressed lower perceptions of safety compared to Arabs and the general population (mean 2.78 (SD $\pm$ 0.7), 3.22 (SD $\pm$ 0.6), and 3.02 (SD $\pm$ 0.8), respectively). In addition, ultra-Orthodox physicians expressed lower satisfaction compared to Arabs and the general population (mean 3.31 (SD $\pm$ 0.8, 3.86 (SD $\pm$ 0.8), and 3.66 (SD $\pm$ 0.8, respectively). Furthermore, significant differences were found in the perceptions of safety according to geographical area of work (F = 3.09, $p < 0.05$). Physicians who work in the central part of the country expressed lower perceptions of safety compared to those who work in the north and the south of Israel (mean 2.96 (SD $\pm$ 0.8) vs. 3.20 (SD $\pm$ 0.6) and 3.00 (SD $\pm$ 0.8), respectively). No differences were found among age groups and years of experience in perceptions toward the quality of care, safety, and satisfaction with telephone consultations. To examine predictors of perceptions toward quality of care, safety, and satisfaction with telephone consultations, multiple linear regression models were tested. No variable showed a significant contribution to the prediction. (See results of regression analyses in Appendix B).

3.3. Associations between Perceptions

Pearson correlations were calculated to examine the associations between the study variables. Analysis revealed that physicians who held a positive perception towards the quality of using telephone visits were also likely to have a positive perception towards the safety of the service ($p < 0.001$, r = 0.73) and expressed satisfaction with using telephone visits ($p < 0.001$, r = 0.62). Similarly, physicians who positively perceived the service's safety were also likely to express satisfaction with using it ($p < 0.001$, r = 0.68).

3.4. In-Depth Interviews

The interviews highlighted three themes equivalent to the main survey variables: (1) the quality of the telephone visit service, (2) the safety of the service, and (3) physicians' satisfaction.

3.4.1. The Quality of the Telephone Visit Service

Most interviewees gave a high rating to the quality of care provided using a telephone visit in cases where there is no need for a physical examination (84.6%). As with the survey responses, family physicians tended to rate the quality of care higher than pediatricians, who expressed more concerns regarding the quality of care provided in telephone consultations. Family physicians mentioned that quality medical care using telephone visits could be provided in cases of older patients, patients with pain management, and chronic diseases. As Interviewee 2, a family doctor, explained: "The telephone visit is suitable for follow-up calls, reporting on treatment, side effects from a drug, conversations about the results of tests, various administrative issues such as forms, chronic problems such as balancing diabetes, medication changes. On the other hand, anything with a physical change requiring an examination is unsuitable for a telephone visit, like a new problem or an existing problem that requires special follow-up". Most interviewees noted that very few telephone visits end with the patient being invited for an examination at the clinic, and even fewer end with a visit to the emergency department, with the assessment of about 10% of the patients required to arrive at the clinic after a telephone visit.

3.4.2. The Safety of the Telephone Visit Service

Regarding safety, most interviewees noted that patient safety is maintained in telephone visits, as in visits to the clinic (69.2%). However, 46% of the physicians expressed concerns about patient safety, mainly due to the inability to closely examine patients. In addition, physicians noted they feel that communicating with patients during telephone visits is complicated as they cannot see the patient's reactions or ensure understanding of the information by the patients, which may affect the physicians' decision making. As Interviewee 4, a family doctor, explained: "I'm afraid of an inaccurate diagnosis and other risks to a patient's safety, also because I can't see them. If I could see what the patient looks like, for example listening to the lungs, and more, it would be much better, and I would miss less. Also, regarding explanations about the treatment, it is easier to ensure understanding when they are here. It's easier to miss information on the phone". In total, 77% of the interviewees noted that telephone visits are safe only with former patients they have already seen in the clinic. Knowing the patient affects the quality and safety of care provided in a telephone visit. Some interviewees mentioned that in cases where they do not know the patients and there are personal or psychological issues, they prefer that the patient come at least once to a face-to-face visit in the clinic. As Interviewee 9, a family physician explained: "The experience of the doctor is important, but what is of particular significance is gaining a thorough understanding of the patient before beginning the telephone visit. Whether the doctor is experienced or new, does not matter. What matters is a former relationship with the patient".

3.4.3. Physicians' Satisfaction

Most interviewees expressed high satisfaction with telephone visits and noted that they are convenient and effective in terms of healthcare delivery when used correctly (77%). Some physicians mentioned the usefulness of using telephone visits and the positive effect on workload. As Interviewee 12, a family doctor, explained: "I perceive the service to be very efficient and easy to use. I am very satisfied. Receiving patients only face-to-face is very exhausting at the end of the day. It is psychologically difficult to receive so many patients in the clinic. It is a positive change in my routine and relieves the burden. In addition, I am also satisfied because my patients are satisfied, especially the young ones". However, 15% of the physicians expressed dissatisfaction with telephone visits and significant concerns regarding using telephone visits in broad circumstances. "Doing things over the phone is lower quality than the frontal visit. I don't see the patient. I strongly believe in the importance of the physical relationship between physicians and patients. Physicians are less able to do what is needed on the phone and cannot reach psychosocial issues. In the clinic, I do get to it. The telephone visit reduces my enjoyment of the medical practice". (Interviewee 7, a family doctor).

4. Discussion

The current multi-methods study examined satisfaction, quality, and safety of telephone visits, as perceived by pediatricians and family physicians in Clalit Health Services. Our findings shed light on some of the barriers involving telephone visits and possible solutions. The study demonstrates disagreement among primary physicians as to the quality and safety levels of the telephone consultation modality, although the reported satisfaction was slightly higher.

The telephone modality is convenient and efficient when patients use it in appropriate cases, such as consultations requiring advice about medicine or treatment, follow-up calls, and laboratory test results. Most interviewees noted that very few telephone visits end with the patient being invited for an examination at the clinic, and even fewer end with a visit to the emergency department, with the assessment of about 10% of the patients required to arrive at the clinic after a telephone visit. However, the physicians noted that some cases require a physical examination or a conversation about psychosocial issues in which there is no substitute for a face-to-face meeting with the patients.

The results showed that physicians did not think the quality of care in telephone visits was similar to the quality of care provided in clinic visits. Interviewees mentioned that the quality of the telephone visit could be maintained primarily in cases where a physical examination is not required. In addition, about half of the respondents did not think the telephone visit was entirely safe for patients. Past studies have also identified concerns among physicians about the quality and safety of phone consultations for telemedicine. A systematic review of telephone triage safety in out-of-hours care found that telephone triage was safe for 97% of patients. However, the review showed that ten studies using high-risk simulated patients showed that only 46% were safe [20]. A recent systematic review that explored the barriers and challenges of telemedicine use found that while physicians recognized the potential benefits of telemedicine, they also had concerns about the inability to conduct physical examinations and possible misdiagnoses [21]. The negative impact of telemedicine on the patient–physician relationship and empathic communication was mentioned previously [22,23], as was the difference in the quality of telephone visits, which varies according to the biopsychosocial complexity of the personal visit with the patient [24].

Furthermore, the availability of culturally and linguistically appropriate telehealth services, as well as confidence in electronic health-related communication or care, were factors associated with the adoption of telemedicine [25]. Our findings showed that physicians from the ultra-Orthodox sector expressed lower satisfaction with the telephone modality compared to physicians from the general sector and the Arab sector. A possible reason for this is that the ultra-Orthodox population in Israel shows lower technological skills than the general population and uses telemedicine services less frequently. Differences in perceptions may, in part, emerge from the population that these physicians serve which affects their perceptions. Our findings also showed that physicians who work in the central part of the country expressed lower safety perceptions compared to those in the north and the south of Israel (the periphery). According to the physician interviews, knowing the patient affects the safety of care provided in the telephone visit. A recent study conducted in Israel found that the primary source of treatment preferred by patients is their primary physicians. It was also found that the residents of the periphery gave up medical services significantly more than others [26]. It can be assumed that most of them turn to their primary physician as their first address which creates a better familiarity between the physician and the patient. Health equity considerations for telemedicine must take into account demographic factors and their intersections [25].

Aside from the barriers mentioned, our findings showed that 50% of family physicians and 50% of pediatricians mentioned that they were satisfied with the use of telephone consultations. Recent studies have shown high satisfaction with telemedicine by patients and healthcare providers [27–29]. A systematic review of telephone consultations in primary care found that telephone consultations were associated with high levels of patient satisfaction, reduced costs, and improved patient care access [30]. Moreover, recent studies showed that patients and healthcare providers were willing to continue to use remote healthcare as part of their follow-up visits even after the COVID-19 pandemic [31–34].

Previous studies of physicians' satisfaction with telemedicine found high satisfaction with telemedicine use among physicians across different specialties, geographic locations, practice locations, and care situations, both for patient care and for consultations with other physicians [35–37]. A recent study surveyed primary care physicians' satisfaction with phone consultations for minor illnesses and injuries. It found that physicians were generally satisfied with the phone consultation modality, which was perceived as a valuable tool for improving patient access to care [36]. Physicians tend to be satisfied with telemedicine if they have input into its development, and administrative support, the technology is reliable and easy to use, and there is adequate reimbursement for its use [38].

Policy Recommendations for Improving the Telephone Consultation Service

Our findings uncover the barriers to the acceptance of this modality and may help to improve and set guidelines that may positively affect the future quality and safety of the telephone visit service and increase the acceptability of this service. These recommendations include:

1 The gap between reported rates of satisfaction and reported rates of quality and safety of telephone visits requires adopting guidelines for a proper and balanced selection of patients and clinical issues, including performing telephone visits mainly with patients that were previously seen in the clinic and when there is no need for a physical examination. This may enable getting the most out of a telephone visit while minimizing potential quality and safety issues.
2 Implementing technological upgrades to the modality (such as transferring photos and documents and incorporating video recording during the telephone visit) is also supported by a recent study that examined how different forms of remote care may affect the clinical behavior of the physician in remote primary care [39] to improve the quality of the service.
3 Implementing patient education practices—explaining to patients about the telephone visit service, the suitable medical conditions for using the service, and how to communicate with the doctor during the telephone visit while emphasizing the patient's role in telephone communication.

Our findings regarding the obstacles and recommendations described by the participants provide additional insight into the barriers identified by a previous systematic review of empirical studies on online health consultation. Researchers identified several obstacles categorized as internal and external influences on Home Online Health Consultations (HOHC). Internal factors refer to the users' behaviors and motivations while using and interacting with the system. These factors include patients' resistance, poor body language and communication, and negative perceptions of HOHC privacy and security. External factors refer to the system usage and surrounding environment that influence users' acceptance and use of HOHC services, such as slow internet speed, poor network signal, difficulty with system use, lack of organizational support, and home obstructions [40]. The various factors influencing the adoption of telephone visits as a modality for providing healthcare need a further in-depth examination to uncover obstacles and design targeted strategies to address them.

This study has several limitations. There is a possibility that recall bias may have influenced the findings, and the data should be compared with in-person visits in a more controlled manner. Another limitation is that the researchers wrote a questionnaire not previously tested in other research frameworks. Nevertheless, the questionnaire is valid, and high reliability of the questionnaire items was found. Finally, the response rate to the questionnaire was relatively low, and non-randomized data were analyzed. However, an examination of the study data set showed that respondent and non-respondent groups were similar in demographic variables such as gender, population sector, and geographical area of work. Yet, 43.7% of family doctors and 50.4% of pediatricians in Israel are above the age of 55, while our study sample included 76.6% of family doctors and 79% of pediatricians above the age of 51. The low response rate to surveys among physicians is a well-known challenge, especially with online surveys. Similar recent evaluations of Telemedicine yielded similar low response rates ranging from 4.3% [41] to 20% [42]. Nevertheless, although non-randomized with bias in the age variable, our study data set analysis provides valuable insight into the perceptions toward telephone visits among family and pediatrician doctors.

5. Conclusions

Our findings highlight the perceptions of family physicians and pediatricians regarding how to use telephone visits while addressing the risk assessment of the modality of care and its benefits in the possible improvement of health services. Although physicians reported satisfaction, the reported rates of quality (2.27 ± 0.76) and safety (3.02 ± 0.75) of telephone visits among physicians should be further examined. Involving primary physicians in the continuous assessment and improvement of the telephone visit modality will increase quality and safety, as well as raise acceptance of the use of telephone visits among primary care physicians.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare12020212/s1, File S1: Study questionnaire and interview guide.

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Appendix A Interviewees' Characteristics

Table A1. Interviewees' Characteristics and coding.

Interview Number	Male/ Female	Specialization	Seniority (Years)
1	F	Family physician	30
2	F	Family physician	15
3	M	Family physician	20
4	F	Family physician	18

Table A1. *Cont.*

Interview Number	Male/ Female	Specialization	Seniority (Years)
5	M	Family physician	20
6	F	Pediatrician	11
7	M	Family physician	15
8	M	Pediatrician	11
9	M	Family physician	5
10	F	Family physician	36
11	F	Family physician	20
12	F	Family physician	17
13	F	Family physician	30
14	F	Family physician	1
15	F	Family physician	25
16	M	Family physician	32
17	M	Family physician	25
18	F	Pediatrician	20
19	M	Family physician	28
20	M	Family physician	35
21	M	Pediatrician	33
22	M	Family physician	25
23	M	Pediatrician	27
24	F	Pediatrician	20
25	F	Pediatrician	20
26	F	Family physician	20

Appendix B Regression Analyses

Table A2. Regression model for study variables as predictors of perceptions toward quality.

Dimension/Variable	$B(SE_B)$	β	*p* Value
Gender	−0.13(0.11)	−0.00	0.90
Age	0.54(0.05)	0.59	0.30
Type of Doctor	0.02 (0.12)	0.01	0.85
R^2	0.07		
F	0.46		

Table A3. Multiple regression model for study variables as predictors of perceptions toward safety.

Dimension/Variable	$B(SE_B)$	β	*p* Value
Gender	−0.02(0.08)	−0.01	0.73
Age	0.04(0.04)	0.65	0.25
Type of Doctor	−0.05(0.09)	−0.03	0.79
R^2	0.05		
F	0.49		

Table A4. Multiple regression model for study variables as predictors of perceptions of satisfaction.

Dimension/Variable	$B(SE_B)$	β	p Value
Gender	−0.01(0.09)	−0.01	0.90
Age	−0.01(0.04)	−0.01	0.30
Type of Doctor	0.03(0.10)	0.01	0.85
R^2	0.00		
F	0.07		

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Review

Mobile Apps for COVID-19: A Systematic Review of Reviews

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Abstract: Background: One measure national governments took to react to the acute respiratory syndrome coronavirus type 2 (SARS-CoV-2) pandemic was mobile applications (apps). This study aims to provide a high-level overview of published reviews of mobile apps used in association with coronavirus disease 19 (COVID-19), examine factors that contributed to the success of these apps, and provide data for further research into this topic. Methods: We conducted a systematic review of reviews (also referred to as an umbrella review) and searched two databases, Medline and Embase, for peer-reviewed reviews of COVID-19 mobile apps that were written in English and published between January 1st 2020 and April 25th 2022. Results: Out of the initial 17,611 studies, 24 studies were eligible for the analysis. Publication dates ranged from May 2020 to January 2022. In total, 54% (n = 13) of the studies were published in 2021, and 33% (n = 8) were published in 2020. Most reviews included in our review of reviews analyzed apps from the USA, the UK, and India. Apps from most of the African and Middle and South American countries were not analyzed in the reviews included in our study. Categorization resulted in four clusters (app overview, privacy and security, MARS rating, and miscellaneous). Conclusions: Our study provides a high-level overview of 24 reviews of apps for COVID-19, identifies factors that contributed to the success of these apps, and identifies a gap in the current literature. The study provides data for further analyses and further research.

Keywords: SARS-CoV-2; mobile applications; mHealth; telemedicine; systematic review

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1. Introduction

The first reports about a novel coronavirus in Wuhan, China, were published in February 2020 [1,2]. The pathogen, which is now called severe acute respiratory syndrome coronavirus type 2 (SARS-CoV-2), caused severe respiratory symptoms, including fever, dizziness, and cough. The World Health Organization (WHO) declared SARS-CoV-2 a global pandemic on the 11th of March 2020 after the virus spread internationally and the number of cases outside of China increased 13-fold within two weeks [3]. Almost three years later, a dashboard presented by Dong et al. [4] registers over 676,000,000 infections and 6,881,955 deaths globally as of March 10th 2023 [5]. As growing parts of the population were ill with coronavirus disease 19 (COVID-19), clinical capacities were endangered, requiring national governments to act. Especially before vaccines were widely available, government-imposed measures ranged from basic hygiene recommendations, such as the mandatory wearing of medical masks, to lockdowns that interrupted life for up to several weeks [6,7].

The use of mobile applications in health, also known as mHealth, has gained significant attention in recent years. mHealth has been shown to have a positive impact on chronic disease management, including cardiovascular diseases and diabetes mellitus [8]. It offers advantages such as convenience, potential cost-effectiveness, and scalability, making it an attractive option for patient communication, monitoring, and education [9]. Additionally, mHealth tools have been observed to impact patients who are less inclined to engage with traditional health services, thus improving access to healthcare [9]. However, the use of mHealth in improving health outcomes faces barriers, particularly in developing countries, including technical, financial, political, social, ethical, and cultural challenges [10]. Despite these barriers, mHealth has shown potential in infectious disease control. They are seen as a valuable tool for the early detection and monitoring of infectious diseases [11–13]. Therefore, mHealth presents a promising avenue for enhancing healthcare delivery, particularly in the context of chronic disease management and infectious disease control.

Apps have already proven themselves effective in tracking and containing the viral spread in previous endemic situations, such as with Ebola [14], malaria, and tuberculosis [11]. Governments started to develop mobile applications (apps) for COVID-19 to support their efforts in containing the pandemic, such as information sharing, symptom monitoring, and contact tracing [15–17]. In parallel, researchers analyzed these apps to assess them either in general or regarding their suitability for the purpose they were developed for. Consequently, a lot of reviews have been performed to synthesize the results of these studies [18–22]. However, these reviews usually focus on a narrow aspect of apps for COVID-19 and to our knowledge, no work has yet synthesized the findings of all the reviews in the form of a systematic review of reviews, also referred to as an umbrella review [23].

Objective

The primary objective is to identify reviews on the subject of mobile apps for COVID-19 to provide a high-level overview of what has been published on the topic since the beginning of the pandemic. The aim is to provide an overview of the different public review articles about apps for COVID-19 for the academic community. We seek to identify gaps in the evidence on a metalevel, investigate factors that contributed to the success of the apps, and provide recommendations for possible future epidemic situations. The data collected through this review can serve as a basis for future studies to further investigate the gaps and success factors and address new research questions.

2. Materials and Methods

2.1. Systematic Literature Search

We conducted a systematic review of reviews structured according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement from 2020 [24]. To organize the review process and reduce possible bias, we created a review protocol according to the PRISMA-P extension for review protocols [25,26], which is presented in the Supplementary Materials Table S1.

The population, intervention, control, outcome (PICO) [27] framework was used to define inclusion and exclusion criteria. As shown in Table 1, we searched for reviews of COVID-19-related apps designed for people who had possibly been exposed to SARS-CoV-2 and/or people diagnosed with COVID-19. We included any kind of review articles, which included both reviews of the academic literature and apps. Reviews provide a comprehensive and critical evaluation of existing research, aiming to summarize, analyze, and synthesize the current state of knowledge on a specific topic. Studies that were not reviews, such as any kind of primary research, e.g., surveys, were excluded. The identified reviews were then qualitatively analyzed using their metadata, subject, used methods, and results. Reviews were included with or without any comparator.

To further qualify for inclusion, publications needed to be reviews, without specifying any kind of review, available in the English language, peer-reviewed, and published between January 1st 2020 and April 25th 2022, the start date to attribute to the onset of the pandemic. We searched the two databases, Medline and Embase, using fixed search strings that were created using features identified through PICO (see Table 2). The search strings were developed by one researcher (M.A.) and validated by another researcher (F.H.). We consulted a librarian from Neu-Ulm University of Applied Sciences (T.G.) during the development of the search string. The strings were also externally validated by two other researchers (M.F. and J.K.) who have previously published systematic reviews. Medline was accessed through the PubMed interface [28]. We did not conduct any complementary searches. We searched two general literature databases after consulting an information specialist and optimized the yield and minimized the effort of searching for evidence for this umbrella review according to the recommendations by Golder and Wright [29].

Table 1. Key eligibility features are identified using the PICO framework.

Dimension	Description
Population	People at risk of being exposed to SARS-CoV-2 or who were diagnosed with COVID-19
Intervention	Reviews of COVID-19-related apps
Control	With or without a comparator
Outcome	Metadata Review's subject Methods used Results

Table 2. Search strings for the respective databases.

Database	Search String
Medline	*("SARS-CoV-2"[Mesh] OR SARS-CoV-2[tw] OR COVID-19[tw] OR CORONA) AND ("Mobile Applications"[Mesh] OR Mobile Applications[tw] OR Smartphone[tw] OR Telemedicine [tw])*
Embase	*('mobile application'/exp OR 'mobile application' OR 'smartphone'/exp OR smartphone OR 'mobile phone'/exp OR 'mobile phone' OR 'telemedicine'/exp OR 'telemedicine') AND ('coronavirus disease 2019' OR '19')*

Our search strategy followed five steps: 1. database search; 2. title/abstract screening; 3. retrieval of eligible publications; 4. full-text screening; and 5. analysis. For step 1, no filters or limitations were used. During steps 2 and 4, the two reviewers (F.H. and M.A.) were unaware of each other's decisions, and conflicts were then discussed until consensus was achieved. If consensus had not been reached through the discussion, a third reviewer (J.S.) would have reviewed the paper and made a final decision. In step 4, the reason for exclusion was documented. The reasons for exclusion were as follows: wrong intervention (n = 22), wrong type of paper (n = 20), wrong language (n = 2), and wording outcomes and wrong setting (each n = 1). A list of reports excluded during full-text screening, along with reasons for exclusion, is available in the Supplementary Materials Table S3.

2.2. Data Extraction

Our search results were exported in text or .ris file formats. *EndNote20* was used for literature management. Entries were imported into the systematic review software *Covidence* [30] for screening and data extraction.

The data extraction and quality assessment templates were created in *Covidence* [30]. The template includes a study's metadata, subject, methods, and results. As an initial means of categorization, we recorded whether studies included literature reviews, app reviews, or both. Our template for quality assessment consists of items from the A Measurement Tool to Assess Systematic Reviews (AMSTAR) [31]. We used version 2 of AMSTAR, which was created for the assessment of randomized clinical studies [31] and includes sixteen items in total. As this review does not contain clinical studies, the items of AMSTAR were removed because they did not fit the context. Both extraction and quality assessment templates are available in Supplementary Materials Tables S4 and S5.

2.3. Quality Assessment

The quality of included reviews was assessed using the AMSTAR 2 tool, a validated instrument for appraising the quality of systematic reviews [31]. AMSTAR2 covers 16 domains, of which 7 are considered critical. Of the remaining 9 items, 3 are considered critical.

Critical domains are considered especially influential for review validity. The remaining critical domains are as follows: (1) protocol pre-registration (item 2), (2) literature search strategy (item 4), and (3) list and justification for excluded studies (item 7). Each included review was rated for adequacy on each domain as either "Yes", "No", or "Partial Yes" (available only for domains 2, 4, 7, and 8).

The fulfillment of each dimension across the different reviews was assessed using a table. Based on these domains, we also assigned a summary quality rating as "critically low" (≥2 "no" ratings on the critical domain), "low" (≤1 "no" ratings on critical domains), "moderate" (≥2 "no" ratings on non-critical domains), or "high" (≤1 "no" on a non-critical domains) to each review.

2.4. Data Synthesis and Analysis

One researcher (M.A.) manually extracted the data and another researcher (F.H.) validated the extractions. Conflicts were discussed until consensus was achieved. After data extraction, studies were assigned keywords that described their topic and methodology. We then grouped studies based on the similarity of these keywords.

Some reviews applied the Mobile Application Rating Scale (MARS) by Stoyanov et al. [32], which is a widely used questionnaire-based tool that assesses app quality [33,34]. Overall app quality is further divided into four dimensions "Engagement", "Functionality", "Information quality" and "Aesthetics". To compare the results of studies using MARS, we analyzed the MARS total scores of all included apps and mean scores per dimension.

3. Results

3.1. Systematic Literature Search

A total of 23,959 records were found via database searches. Figure 1 shows the number of records resulting from each search step. Medline was searched on April 23th 2022 and Embase on April 25th 2022. After the automated removal of duplicates via *Covidence* [30], 17,611 records were manually screened according to title and abstract, resulting in 70 remaining reports. After full-text screening and the exclusion of another 46 reports, the 24 studies from Table 3 were included in the analysis.

Table 3. The 24 included reviews sorted by category with the AMSTAR rating.

Study ID	Title	Objective	Category	AMSTAR Rating
Bassi 2020 [35]	An overview of mobile applications (apps) to support the coronavirus disease 2019 response in India	To identify COVID-19-related mobile apps and highlight gaps to inform the development of future mHealth initiatives.	Overview	Low
Islam 2020 [20]	A Review on the Mobile Applications Developed for COVID-19: An Exploratory Analysis	To explore the existing mobile applications developed for the COVID-19 pandemic.	Overview	Low
Collado-Borrell 2020 [36]	Features and Functionalities of Smartphone Apps Related to COVID-19: Systematic Search in App Stores and Content Analysis	To identify smartphone apps designed to address the COVID-19 pandemic and analyze their characteristics.	Overview	Low
Ming 2020 [37]	Mobile Health Apps on COVID-19 Launched in the Early Days of the Pandemic: Content Analysis and Review	To analyze and evaluate the contents and features of COVID-19 mobile apps.	Overview	Critically low
Alanzi 2021 [18]	A Review of Mobile Applications Available in the App and Google Play Stores Used During the COVID-19 Outbreak	To review the functionalities and effectiveness of mHealth apps during the COVID-19 outbreak.	Overview	Critically low

Table 3. *Cont.*

Study ID	Title	Objective	Category	AMSTAR Rating
Almalki 2021 [21]	Health Apps for Combating COVID-19: Descriptive Review and Taxonomy	To categorize health apps related to COVID-19, explore their key technical features, and classify their purposes.	Overview	Low
Zhang 2021 [38]	An Overview of Commercially Available Apps in the Initial Months of the COVID-19 Pandemic	To identify the commercial applications that are currently available for COVID-19 and explore their functionalities.	Overview	Critically low
Lee 2021 [39]	Mobile Apps Leveraged in the COVID-19 Pandemic in East and South-East Asia: Review and Content Analysis	To examine free apps from East and Southeast Asian countries, highlight their key characteristics, and interpret the relation of apps' release dates and commencement dates of other COVID-19 public health policies.	Overview	Low
Erfannia 2022 [40]	Reviewing and Content Analysis of Persian Language Mobile Health Apps for COVID-19 Management.	To carry out a content analysis of free Persian mobile health apps in the management of COVID-19 and determine the relationship between the popularity and quality of these apps.	Overview	Low
JohnLeonSingh 2020 [19]	Mobile Health Apps That Help With COVID-19 Management: Scoping Review	To scope the evidence base on apps that were developed in response to COVID-19.	Privacy and Security	Low
Hatamian 2021 [41]	A privacy and security analysis of early-deployed COVID-19 contact tracing Android apps.	To analyze the privacy and security performance of Android contact-tracing applications, including code privileges, promises, privacy policies, and static and dynamic performance.	Privacy and Security	Critically low
Nazayer 2021 [42]	Contact-tracing applications: A review of technologies	To examine design decisions related to COVID-19 contact-tracing applications and the implications of these decisions.	Privacy and Security	Critically low
Kouliaridis 2021 [43]	Dissecting contact tracing apps in the Android platform.	To analyze all the official Android contact-tracing apps deployed by European countries regarding privacy and security via static and dynamic code analysis.	Privacy and Security	Critically low
Kolasa 2021 [44]	State of the Art in Adoption of Contact Tracing Apps and Recommendations Regarding Privacy Protection and Public Health: Systematic Review	To analyze available COVID-19 contact-tracing apps and verify to what extent public health interests and data privacy standards can be fulfilled simultaneously in the process of the adoption of digital health technologies.	Privacy and Security	Low
Alshawi 2022 [45]	Data privacy during pandemics: a systematic literature review of COVID-19 smartphone applications.	To provide a better study of privacy concerns in the context of COVID-19 apps, examine and analyze existing studies on COVID-19 apps and privacy concerns and their findings, and provide summaries.	Privacy an Security	Critically low

Table 3. *Cont.*

Study ID	Title	Objective	Category	AMSTAR Rating
Davalbhakta 2020 [46]	A Systematic Review of Smartphone Applications Available for Corona Virus Disease 2019 (COVID19) and the Assessment of their Quality Using the Mobile Application Rating Scale (MARS)	To assess mobile applications for COVID-19 using the Mobile Application Rating Scale.	MARS	Moderate
Salehinejad 2021 [47]	A review and content analysis of national apps for COVID-19 management using Mobile Application Rating Scale (MARS)	To develop a reliable measure and rate the quality of COVID-19 mobile health apps.	MARS	Low
Wang 2021 [48]	Investigating Popular Mental Health Mobile Application Downloads and Activity During the COVID-19 Pandemic.	To analyze downloads and the user activity of select popular mental health apps during COVID-19	MARS	Low
Kahnbach 2021 [49]	Quality and Adoption of COVID-19 Tracing Apps and Recommendations for Development: Systematic Interdisciplinary Review of European Apps	To investigate the quality characteristics of national European COVID-19 contact-tracing apps, investigate associations between app quality and adoption, and identify app features contributing to higher app quality.	MARS	Low
Fan 2022 [50]	The function and quality of individual epidemic prevention and control apps during the COVID-19 pandemic: A systematic review of Chinese apps.	To investigate the functional characteristics of individual epidemic prevention and control apps in China and evaluate their quality.	MARS	Moderate
Kondylakis 2020 [22]	COVID-19 Mobile Apps: A Systematic Review of the Literature	To review studies that have used and evaluated mobile apps for COVID-19.	Miscellaneous	Low
Akinbi 2021 [51]	Contact tracing apps for the COVID-19 pandemic: a systematic literature review of challenges and future directions for neo-liberal societies	To encompass current challenges facing contact-tracing applications and recommendations that address such challenges in the fight against the COVID-19 pandemic in neo-liberal societies.	Miscellaneous	Critically low
Blacklow 2021 [52]	Usability, inclusivity, and content evaluation of COVID-19 contact tracing apps in the United States.	To evaluate COVID-19 contact-tracing apps via an evaluation framework with objective measures of usability that are presented in this work.	Miscellaneous	Low
Jenniskens 2021 [53]	Effectiveness of contact tracing apps for SARS-CoV-2: A rapid systematic review	To systematically review evidence on the effectiveness of contact-tracing apps (CTAs) for SARSCoV-2 on epidemiological and clinical outcomes.	Miscellaneous	Low

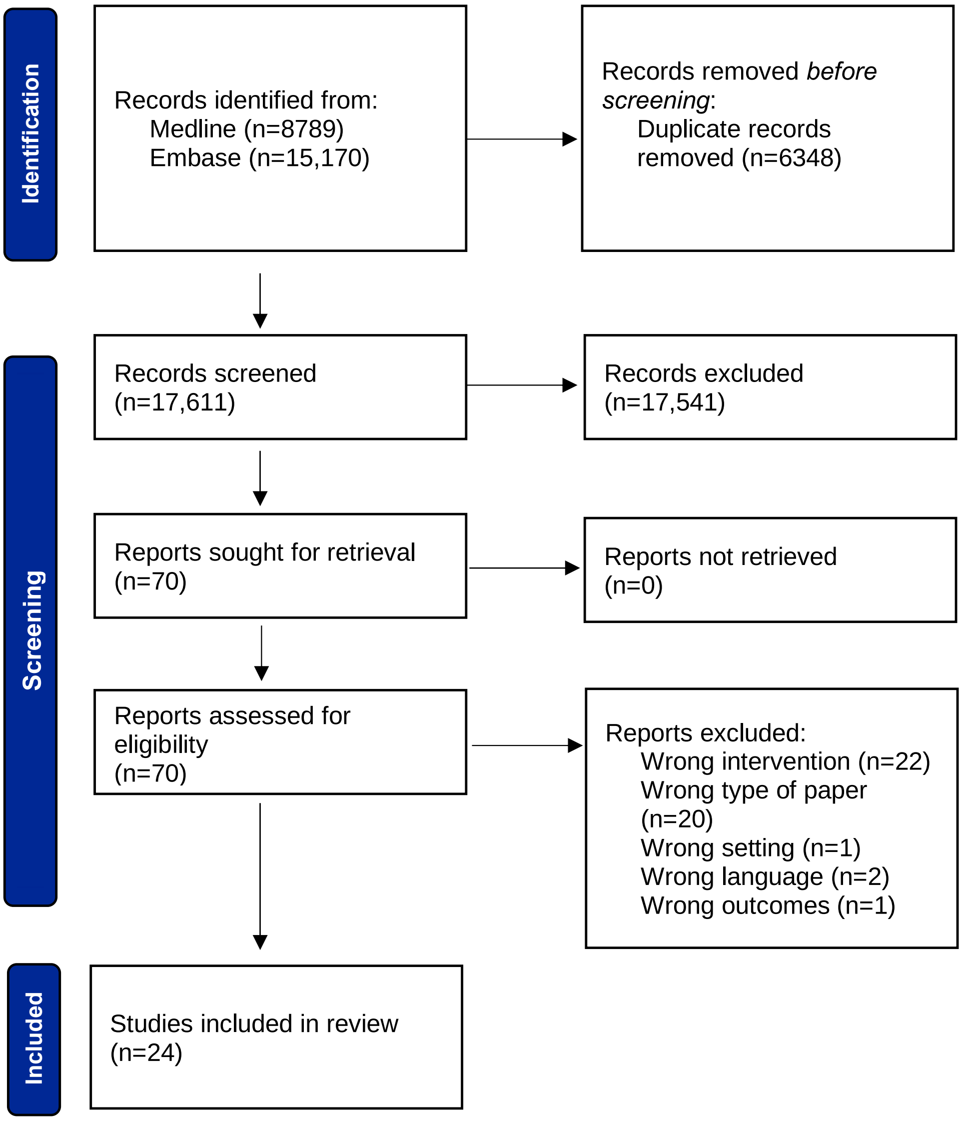

Figure 1. The PRISMA flowchart illustrates step by step how we identified the 24 studies to include in our analysis.

3.2. Spatiotemporal Analysis

Figure 2 illustrates a timeline of the 24 articles included in our review by publication date. The publication dates range from May 2020 to January 2022. In total, 54.2% (n = 13) of the studies were published in 2021; 33.3% (n = 8) of the studies were published in 2020. The other three studies were published in 2022 (n = 3, 12.5%). The timeline demonstrates how most reviews were published between May 2020 and July 2021, with visibly fewer publications after July 2021.

Figure 3 visualizes a geographical analysis of the number of reviews in which apps from the respective countries were examined.

The map shows that most reviews were on apps from the United States (n = 9), the United Kingdom (n = 8), and India (n = 7). Among other origin countries of the analyzed apps are Australia (n = 5), Singapore (n = 4), and Vietnam (n = 4), as well as Canada, Brazil, China, Malaysia, Russia, and the United Arab Emirates (n = 3 each). There were also many European countries (including the United Kingdom, Italy (n = 6), Spain (n = 6), and Germany and France (n = 5 each)). Few reviews analyzed apps from African countries or Central America. Several reviews analyzed apps from more than one country.

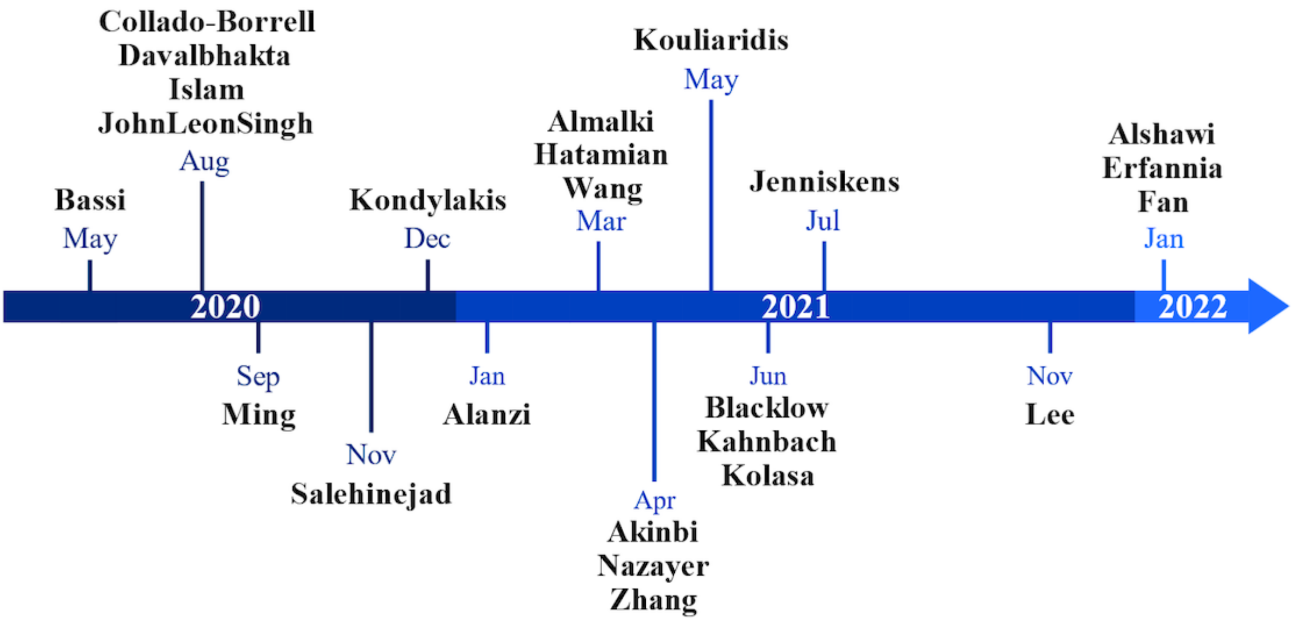

Figure 2. The timeline of published reviews on apps for COVID-19 included in our review.

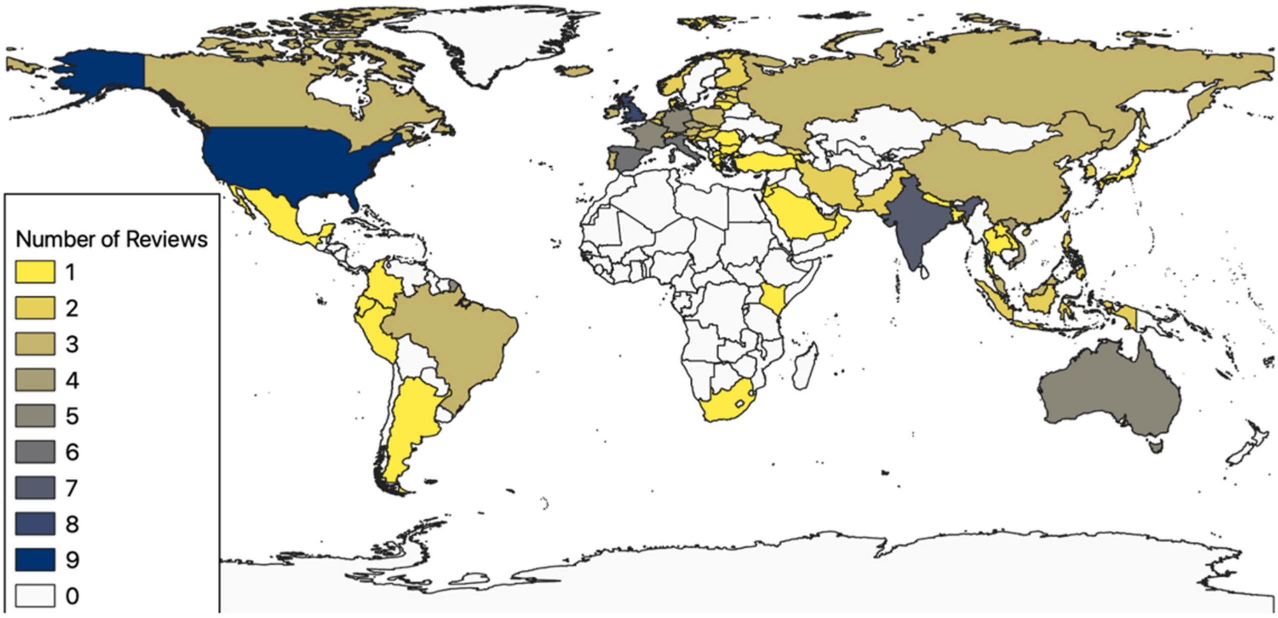

Figure 3. Visualization of the number of reviews in which apps from the respective countries were examined.

3.3. Categorization

Figure 4a shows how most publications (n = 17; 71%) were reviews of apps followed by literature reviews (n = 5; 21%) and hybrid reviews (n = 2; 8%). We defined hybrid reviews as reviews that include both the literature and apps. We grouped the included reviews into four categories (visualized in Figure 4b). These categories include reviews that provide an overview of published apps (n = 9; 37.5%), focus on privacy and security (n = 6; 25%), and use MARS for rating apps (n = 5; 21%) and those that did not fit into any of the previous categories (n = 4; 16.5%).

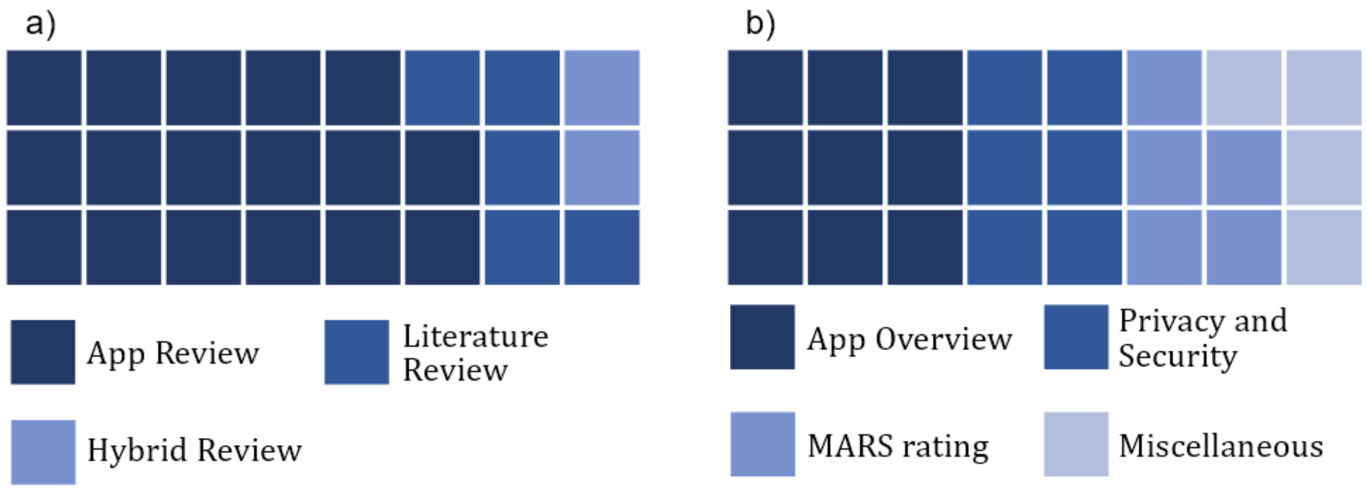

Figure 4. (**a**) Publications were either reviews of apps, literature reviews, or both: (**b**) categorization resulted in four categories.

In the following sections, which are structured according to our categorization, we narratively describe the key outcomes of the included studies. We provide a table with all the extracted data in the Supplementary Materials.

3.3.1. App Overview

The largest category was "app overview" ($n = 9$). Included reviews [18,20,21,35–40] share the primary purpose of identifying available apps for COVID-19 and summarizing their features. In total, 55% ($n = 5$) of these reviews [18,21,36,39,40] followed the PRISMA guidelines. The publication by Bassi et al. [35] from May 2020 reviewed 50 Indian apps and functions mapped against the guidelines provided by the WHO. Aarogya Setu was found to be the most popular Indian COVID-19 app. The review by Islam et al. [20] included 25 apps from multiple countries, and they visually mapped 26 identified features onto nine objectives. The review by Collado-Borrell et al. [36] enumerated the characteristics of 114 identified apps that were available in August 2020. They discussed how, contrary to other reviews of health-related apps, many of the reviewed COVID-19 apps have been designed by governments. Ming et al. [37] analyzed 58 apps for self-monitoring and education. In total, 58.3% ($n = 28$) of the apps scored at least four points on a seven-point scale proposed by Nouri et al. [54]. In feature assessments, apps from Apple and Android scored a mean of three and two points, respectively, on a five-point scale by Izahar et al. [55]. Finally, they provided recommendations for apps for COVID-19. Alanzi [18] provided an overview of 12 COVID-19 apps from Saudi Arabia, Italy, Singapore, the UK, and the USA. In total, 75% ($n = 9$) of the apps were contact-tracing apps (CTAs). He discussed the potential benefits of an integrated application that contained multiple features as features were at the time spread across multiple apps. By using the open-coding technique, Almalki and Giancicci [21] identified 29 key technical features in 115 apps, out of which they created a taxonomy that included five COVID-19 app purposes. The two most frequent technical features were basic health information (36.52%; $n = 42$) and contact tracing (27.83%; $n = 32$). Zhang et al. [38] identified 103 commercial COVID-19 apps and showed a steady increase in app publications from February to April 2020. The review by Lee et al. [39] identified 46 free COVID-19 apps by governments from 11 countries within East and Southeast Asia alongside key characteristics and functions. Most apps (70%; $n = 32$) were intended for the general public, the most used technology was GPS (61%; $n = 28$), and usage was mandatory for 52% of the applications ($n = 24$). Erfannia et al. [40] evaluated four Persian apps with a self-made checklist consisting of 37 yes or no questions. All apps performed well regarding ease of use and privacy while needing improvement in education, monitoring, and data sharing.

3.3.2. Privacy and Security

Six reviews [19,41–45] were grouped as they all assessed apps for COVID-19 concerning either privacy or security. Singh et al. [19] presented a review of 29 apps and how apps from 19 countries differed in their degree of privacy invasion. They showed how CTAs supported real-time location tracking, including data from public surveillance systems, government information systems, or credit card transactions, while other countries used GPS-based geofencing technology to enforce the quarantine of individuals. Hatamian et al. [41] analyzed 28 Android-based CTAs regarding their privileges, privacy policies, run-time permission access, and vulnerabilities. CTAs generally required more permissions than needed and only partly justified their request. In total, 64.3% (n = 18) of apps did not fulfill half of the 12 policy principles proposed by Hatamian et al. [56]. No policy enforced noticing users upon a privacy breach as required by the European General Data Protection Regulation (GDPR). In total, 61% (n = 17) of the apps requested at least one form of location interface. Apps from the EU generally requested fewer and less privacy-invasive permissions, had higher-quality policies, and were more secure. Nazayer et al. [42] discussed how centralized app architectures provide more data to track secondary infections and perform research, while decentralized architectures provide a higher level of privacy. They further argue how a collection of more data can increase functionality at the cost of user privacy and how the integration of multiple technologies in one COVID-19 CTA could increase overall benefits. Within the review by Kouliaridis et al. [43], static code analysis exposed apps that were potentially susceptible to common weakness enumerations (CWE; 62%), as well as issues with apps' manifest files (88%), shared libraries (46%), outdated software components (25%), or data leakage (33%). Kolasa et al. [44] developed two checklists based on a report by the Ada Lovelace Institute [57], the privacy code of conduct for mobile health apps from the European Commission [58], and the guidelines on the use of location and contract-tracing tools in the context COVID-19 from the European Data Protection Board [59], through which they found differing balances between data privacy and public health interests, which they attributed to socio-geographical differences. The systematic literature review of 40 studies by Alshawi et al. [45] found that while Asian countries often trade in privacy in the name realm of public health via mandatory app uptake, other countries' app adoption rates struggle with civic acceptance. They then demonstrate how governments around the world vary greatly in privacy protection and point out the need for policies that ensure such protection.

3.3.3. App Reviews Using the Mobile Application Rating Scale

Five reviews [32,47–50,60] rated COVID-19 apps using MARS. Across all five reviews, the overall mean MARS scores of all analyzed apps were above the possible mean (3.7 [60], 4.2 [47], 4.07 [48], 3.97 [49], 3.81, and 3.56 [50]). Except for Salehinejad et al. [47], all reviews rated the "Functionality" dimension as the best and "Engagement" as the worst on average, as Figure 5 demonstrates.

Davalbhakta et al. [60] provided examples of good design choices concerning each MARS dimension. They generalized that apps from India usually scored higher in functionality, while apps from the UK and the USA scored higher in information dissemination. While assessing national and international apps for COVID-19, Salehinejad et al. [47] pointed out the focus of developers on functionality, identifying the engagement and aesthetics dimensions as potential target areas for improvements. In their rating of the 16 most popular mental health apps according to Carlo et al. [61], Wang et al. [48] found an increase in interest in mental health apps, which they attributed in part to an increase in mental health issues during the pandemic. The review of Kahnbach et al. [49] investigated the quality characteristics of 21 national European COVID-19 CTAs using the German modification of MARS (MARS-G) by Messner et al. [62]. They found a positive correlation between app quality and app adoption rate. Acknowledging that the Chinese government has spread pandemic apps across several marketplaces, Fan et al. included 20 apps that were either independent apps or WeChat applets. They noted a diversity of regional apps, which reduced their usability as users traveled. They also discussed the impact of the mandatory use of certain COVID-19 apps and QR codes issued by the Chinese government.

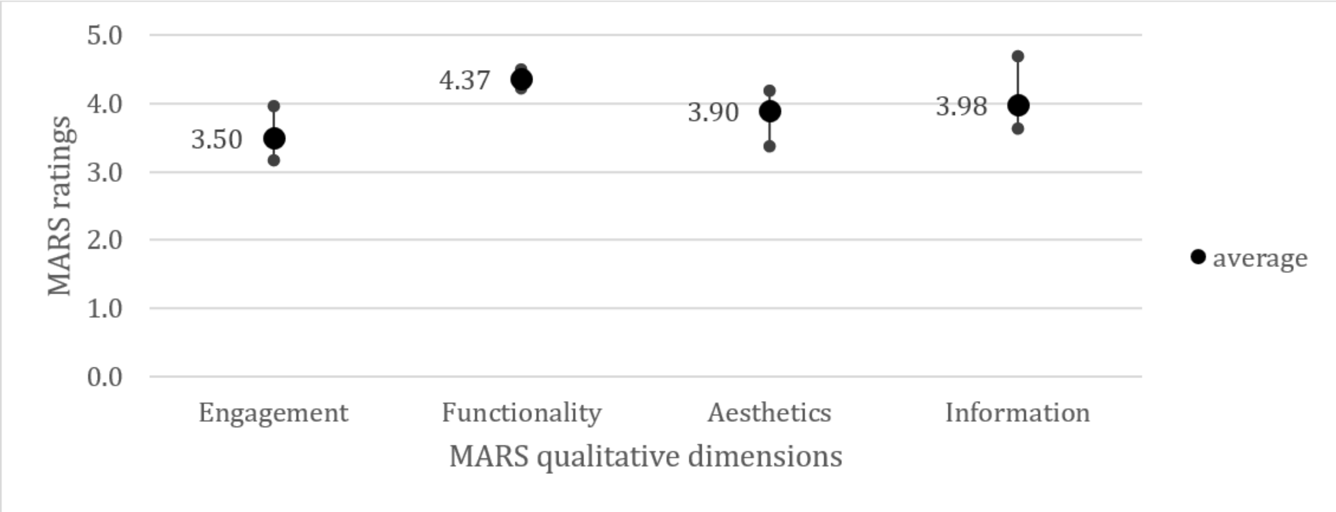

Figure 5. An overview of the average (with minimum and maximum) ratings of MARS dimensions across all five reviews.

3.3.4. Miscellaneous

Four reviews [22,51–53] were grouped as "Miscellaneous". In their assessment using the tool by the Effective Public Health Practice Project (EPHPP) [63], Kondylakis et al. [22] found moderate quality for two (17%) and weak methodological quality for ten (83%) studies. They suspected that the authors desired to publish quickly at the beginning of the pandemic and lastly summarized implications for clinical practice. Akinbi et al. [51] inspected challenges and future directions for CTAs in neo-liberal societies via a systematic literature review; privacy concerns were the most popular subject (46%). They discussed the importance of adopting privacy-preserving technologies and maintaining a high level of transparency, a human-centered development of CTAs, and ethical considerations that prevent the disadvantage of parts of the population. Blacklow et al. [52] presented a 14-item evaluation framework through which they analyzed 26 apps from the USA with a focus on accessibility and inclusivity. In total, 69% of the apps exceeded 9th-grade readability in the context of a referenced average reading level of 7th–8th grade in the U.S. [64]. Moreover, 65% of the apps were available only in English, and 69% of the apps did not include videos or illustrations to explain how they function. Reviewing the literature on the effectiveness of CTAs on epidemiological outcomes, Jenniskens et al. [53] judged two observational–comparative studies to be of low methodological quality. The other 15 model-based studies indicated the benefits of CTAs on the reproduction rate (R), as well as the rates of infection and mortality.

3.4. Quality Assessment

The AMSTAR ratings of each of the included reviews are shown in Table 3. The detailed rating by item can be found in the Supplementary Materials S6. The quality rating was low, with most studies having a rating of "low" (n = 14), followed by "critically low" (n = 8) and "moderate" (n = 2).

4. Discussion

4.1. Principal Results

We present a high-level overview of 24 reviews on mobile apps for COVID-19 that were published between January 1st 2020 and April 25th 2022. Most reviews were published before July 2021. Out of the 24 reviews, the majority were reviews of apps (71%), followed by reviews of the published literature (21%) and hybrid reviews that looked at both apps and the literature (8%). The overall quality of the included reviews is low with respect to the majority of articles. Most articles either achieved a "critically low" (*n* = 8) or "low" (*n* = 14) AMSTAR rating. Only two articles received a "moderate" rating. Little research has been performed on apps from Africa and Central and South America. Overview reviews identified that many apps that have been published globally were mostly developed under supervision from national or local governments and used common technologies, such as Bluetooth and GPS, to perform their purposes. Reviews with a focus on privacy and security reported differing degrees of privacy invasion across countries and security vulnerabilities within apps. Generally, Asian countries collected more user data than in Europe or North America, and usage was more often mandatory. Reviews that rated apps by MARS consistently found high-quality apps and identified the most potential regarding further improvement in making apps more engaging. Other reviews identified privacy concerns to be the main factor keeping people in neo-liberal societies from using CTAs, reported bad accessibility and inclusivity in apps, and found a lack of methodologically sound studies that evaluated mobile apps for COVID-19.

Considering that the WHO declared SARS-CoV-2 a pandemic in March 2020 [3], most reviews from 2020 were published rather quickly (Figure 2). The fast publication time could be attributable to a global focus on the COVID-19 pandemic and scholars' desire to share results as quickly as possible. The visible gap after July 2021 may reflect a lower sense of urgency around COVID-19, driven by less lethal virus variants such as the omicron strand [65], steadily increasing vaccination rates [66], and more accurate information about how to manage the risks of COVID-19. There was a large geographical bias in the research on COVID-19 mobile apps. Many articles focused on apps from the USA, Europe, and India, for which, aside from their strong academic sectors, one could assume a correlation in case numbers to be the reason. African and Central and South American countries have mostly been ignored so far, emphasizing the need for research on apps developed by them.

COVID-19 mobile apps have served purposes from simple ones such as information dissemination and symptom monitoring to complex ones like contact tracing. With more development over time, apps have been extended to support additional features that reflect the introduction of COVID-19 vaccinations and changing legal contexts. The share of apps with a governmental background is untypically high for health apps [36]. This is likely due to restrictions that Google [67] and Apple [68] have put in place for COVID-19 apps to ensure the credibility of apps and the information shared. Governments in many Asian countries are able to implement more privacy-invasive features, as there are fewer legal restrictions compared to European or North American countries, and mandatory app uptake ensured that a sufficient number of people used the apps [19,35,39,41,42,44,45]. In particular, in European countries, the efficiency of certain features was limited by the strict data privacy regulation through the GDPR and voluntary app uptake. As Akinbi et al. concluded, people in neo-liberal societies, especially within Europe, were naturally skeptical towards their governments and tended to question privacy invasion [51]. Alshawi, via an example of France, demonstrated how people may refuse to use CTAs due to this skepticism, which logically would decrease their effectiveness [45,69]. The reported security vulnerabilities in popular CTAs [41,43] are especially critical as health data are one of the most vulnerable types of data and also because public acceptance is built on trust that as little data as possible are collected and that these data are safe from abuse and theft. The overall very high total ratings across MARS reviews [47–50,60] likely reflect the global focus and the governmental support in developing them. Although some authors referred to "above-average" ratings (Refs. [49,60]), as we are unaware of a published average MARS score, such a benchmark still needs to be developed. In the context of MARS, making apps more engaging seemed to have the greatest potential in increasing app quality [48–50,60], with better app quality contributing to increased app adoption [49]. The gap in accessibility and inclusivity regarding required reading levels, available languages, and the extent to which app functions were described by appropriate illustrations that were pointed out by Blacklow et al. [52] reveals another dimension for improvement. In particular, in the context of medical knowledge that may seem complex and even intimidating to people without a medical background, together with a continuously globalized world, having several supported languages that are appropriate to the geographical context and easily understandable is critical for public acceptance and, consequently, app uptake. While reviews of evaluation studies indicated a positive influence of CTAs on pandemic progression, they also pointed out a lack of evidence due to methodological weaknesses [22,53]. In this context, as retrospective studies struggle with many confounders, methodologically rigorous study designs need to be developed now to prepare for possible future epidemic situations.

Wangler and Jansky [70] discuss concerns concerning the clarity of the content, transparency, and privacy in mHealth applications. In a study, a significant amount of reviewed mHealth applications had poor quality and did not follow best practices in data security [71]. Patients often do not use the mHealth application that they have installed because of security concerns, loss of interest, costs, or badly designed user interfaces [72].

4.2. Limitations

As the review protocol did not meet the inclusion criteria of the protocol publishing platform PROSPERO, it could not be published before the review. This reduces transparency and makes the review susceptible to bias because we cannot prove that we did not deviate from the original protocol.

Although screening was carried out by two reviewers operating independently, all qualitative reviews may be influenced by reviewers' subjectivity. It is therefore possible that other scholars could obtain different results when using the same dataset.

This review is limited by the timeframe of the database search and our narrow search strategy. Records published or updated after our search or research that did not meet our inclusion criteria were not considered [73]. It is possible that we thus unintentionally failed to include some relevant research. We only searched two databases; the search of additional databases would have led to more results. The fact that we only included reviews of COVID-19-related apps is a limitation, as other research that, for example, studied factors contributing to the success and failure of contact-tracing systems [74] were not included in this review of reviews and could have provided additional insights.

4.3. Comparison with Prior Work

To our knowledge, this is the first systematic review of reviews (umbrella review) on the topic of mobile apps for COVID-19. A number of reviews have been published that were included in our work, but a review of reviews that summarizes the findings of these reviews has not been published so far. In addition to providing this high-level overview of the state of the literature about apps for COVID-19, the results of our review can serve as a unique data source for future research via secondary data analysis to address more specific research objectives about this topic.

5. Conclusions

We present a high-level overview of 24 reviews on mobile apps for COVID-19 during the first two and a half years of the pandemic. There appeared to be a lower sense of urgency to publish research on mobile apps for COVID-19 after July 2021. The quality of the included reviews is quite low. Further, we observe a need for research on COVID-19 mobile apps from African and Central and South American countries, as apps from these countries are currently ignored in the literature. Apps were mostly developed with governmental backgrounds, which was reflected by consistent reports of high app quality according to MARS. Although reviews that evaluated studies on COVID-19 mobile apps regarding their effectiveness indicated positive influences of these apps on pandemic progression, there is yet no evidence due to methodological deficits. Future research is needed on means to maximize voluntary app uptake in possible future epidemics, including data minimization, transparency, and user engagement. The development of rigorous and methodological study designs can prepare the generation of evidence regarding the use of future mobile apps for epidemics.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/healthcare12020139/s1. Table S1: Review protocol; Table S2: All included studies; Table S3: Records excluded during full-text-screening together with reasons for exclusion; Table S4: Data extraction template; Table S5: AMSTAR template; Table S6: Quality rating using the modified AMSTAR.

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Perspective

Telehealth Competencies: Training Physicians for a New Reality?

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Abstract: In North America, telehealth increased by 40% between 2019 and 2020 and stabilized at 40% in 2021. As telehealth becomes more common, it is essential to ensure that healthcare providers have the required skills to overcome the challenges and barriers of this new modality of care. While the COVID-19 pandemic has accelerated the design and implementation of telehealth curricula in healthcare education programs, its general adoption is still a major gap and an important barrier to ensuring scaling up and sustainability of the telesshealth practice. Lack of experienced faculty and limited curricular time are two of the most common barriers to expanding telehealth education. Overcoming the barriers of telehealth curricula implementation may require moving away from the classic expert model of learning in which novices learn from experts. As the adoption of telehealth curricula is still in its early stages, institutions may need to plan for faculty development and trainee education at the same time. Questions regarding the timing and content of telehealth education, the interprofessional development of curricula, and the identification of optimal pedagogical methods remain open and crucial. This article reflects on these questions and presents telesimulation as an ideal instructional method for the training of telehealth competencies. Telesimulation can provide opportunities for practical training across a range of telehealth competencies, fostering not only technical proficiency but also communication skills and interprofessional collaboration.

Keywords: telehealth; telehealth competencies; telesimulation

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1. Introduction

Telehealth, a New Normal without a Roadmap for Teaching and Learning?

Telehealth is a rapidly growing emerging area in medicine [1]. In the United States, telehealth visits increased from 1.4 million visits (1.1%) between 2018 and 2019 to 35 million visits (35.3%) in 2020 [2]. Similarly, in Canada, virtual care increased by 40% between 2019 and 2020 and stabilized at 40% in 2021 [3]. A report from the Canadian Medical Association, in conjunction with other medical regulatory bodies released in February 2022, shows that 94% of physicians use virtual care and that 64% of them will maintain or increase their current level of use [3]. It is, therefore, safe to say that telehealth is here to stay and that its implementation will most likely continue to increase.

Telehealth, also known as virtual care or telemedicine, refers to "any interaction between patients and/or members of their circle of care, occurring remotely, using any forms of communication or information technologies with the aim of facilitating or maximizing the quality and effectiveness of patient care" ([3] p. 3).

The rapid evolution of communication technologies has propelled telehealth, and consequently, a broad array of opportunities of distant care are now possible ranging from asynchronous e-consults, outpatient specialty teleconsultations (synchronous video), telementoring, virtual check-in, remote patient monitoring, and acute virtual care visit. Telehealth is rapidly becoming an essential model of care [4]. Yet, telehealth is considered to be a disruptive and rapid transition without a roadmap [5].

Telehealth has been identified as a priority action plan in the development of global and accessible healthcare systems, even before the pandemic [6,7]; however, its deployment and scaling-up depend on several factors. Some of these factors include technology, sources of funding, and regulatory frameworks that ensure patient safety [3,8–11]. Research investigating the post-assessment of telemedicine during the pandemic, has shed light on the need to further produce guidelines and protocols for addressing patient management through telemedicine [12]. However, and most importantly, if telehealth is to be the next revolution of the healthcare system, it becomes necessary to consider how to train a skilled workforce able to integrate telehealth into routine care [8]. This article focuses on the training needs of medical students and physicians in practice for whom telemedicine is a new reality.

Implementation of telehealth curricula might seem an like an evolution (a response to adapting to a change) for those schools that already had a telehealth curriculum and a revolution (a sudden and a violent change) for those who are just beginning to understand how to use it. A study reporting the state of the art of telehealth in education in the U.S. indicates that established medical schools accredited before 2002, are more likely to have integrated telehealth curricula than newer schools [13].

While there is an emergent body of literature aiming to determine telehealth competencies for physicians [3,5,14–17], the methods of implementing telehealth teaching and learning are still lacking in the academic medicine field [5,18]. The goal of the current perspective is to draw attention to the changes that telehealth brings in practicing medicine, and mainly to reflect on the opportunities and the challenges of integrating telehealth curricula into medical training, which will inevitably be part of the mandate for medical schools to prepare the next generation of physicians for this new reality [18]. We start by presenting the emerging telehealth competency frameworks proposed by the main medical regulatory bodies in the United States and in Canada and discuss how these frameworks can be operationalized in the implementation of a telehealth curriculum from an early integration in the preclinical stages. We also present instructional models for integrating teaching and training of telehealth competencies. We further bring attention to the need to provide telehealth training for both students and medical educators, for whom telehealth is also a new reality. We therefore advocate for a new model away from the classic expert model, in which students and educators have the need to simultaneously learn and develop telehealth competencies. We finally shed light on the use of telesimulation as a future direction for providing telehealth training and assessment. Telesimulation is an ideal instructional tool for reproducing a variety of telehealth situations in a controlled and standardized manner.

2. Methodology

This present perspective paper aligns with the established norms for producing commentary [19]. Commentary and perspective articles are intended to draw attention to current theory and practice [20]. The framework presented in this paper emerged from the best available evidence from the last three years on the topic of telehealth curriculum and telehealth competencies as well as the authors' (ICP and PD) experience implementing a telesimulation curriculum for large cohorts [21]. While telemedicine emerged mainly during the COVID pandemic, telemedicine curricula are still a gap in the literature. Therefore, the arguments about the applicability of telehealth curricula also emerged from the combined expertise of the authors (more than 10,000 h) in curriculum development and telesimulation (ICP and PD), instructional simulation, and research (IT and PD).

3. Discussion

3.1. Telehealth Competencies: An Evolution or a Revolution of the Physicians' Competencies Landscape?

As telehealth becomes more common, it is essential to ensure that healthcare providers have the required skills to overcome the challenges and barriers of this new modality of care. Telehealth requires different skills than traditional in-person care [16,17,22–24]. "Remote encounters require unique communication and technical skills and present interpersonal challenges distinct from traditional in-person visits" [24]. For instance, physicians may need to demonstrate their ability to deescalate difficult patient situations over a remote connection while being professional and using interpersonal and communication skills to provide the best care possible [16]. Digital knowledge and virtual clinical attitudes are some of the emergent competencies that providers need to master to deliver virtual interactions in a safe, relevant, and ethical manner [25].

Telehealth brings to the front a paradigm flip in which the doctor comes to the patient and not the other way around. In this sense, telemedicine is an equivalent of a doctor's home visit, in which the physician has a unique window of opportunity to characterize the patient's individual context and tailor diagnostic and treatment strategies [26]. This new paradigm puts into evidence that telehealth challenges patient care competencies in all its dimensions (e.g., physical examination, history taking, clinical reasoning, patient management, etc.). Physicians may also be prompted to integrate health data collected via mobile health (mHealth) applications that measure individuals' health data in everyday life [27]. Data-informed medicine will require physicians to capture, record, and retain health data that facilitates its aggregation, analysis, and inform medical decisions [14]. As a lack of knowledge and digital skills are some of the barriers identified in the physicians' adoption of and satisfaction towards telehealth [3], it is critical to provide physicians with opportunities for learning and practicing virtual care and data-informed medicine.

Since the COVID-19 pandemic, different academic and professional regulatory organizations have included emergent telehealth competencies in their standards. The Accreditation Council for Graduate Medical Education (ACGME) [28] updated the physicians' milestones in 2021 and included digital health as one of the six sub-competencies of patient care milestones. The ACGME describes digital health into an increasing continuum of five acquisition levels, 1 being the lowest level of acquisition and 5 the highest level of acquisition (see Table 1).

Table 1. Patient care: digital health milestones as adapted from the ACGME milestones for accredited residency programs [28].

Level 1	Level 2	Level 3	Level 4	Level 5
Uses electronic health record (EHR) for routine patient care activities.	Expands use of the EHR to include and reconcile secondary data sources in patient care activities.	Effectively uses EHR capabilities in managing acute and chronic care of patients.	Uses the EHR to facilitate achievement of quality targets for patient panels.	Leads improvements to the EHR.
Identifies the required components for a telehealth visit.	Performs assigned telehealth visits using approved technology.	Identifies clinical situations that can be managed through a telehealth visit.	Integrates telehealth effectively into clinical practice for the management of acute and chronic illness.	Develops and innovates new ways to use emerging technologies to augment telehealth visits.

A similar update to medical competencies was conducted by the Association of American Medical Colleges (AAMC) [1], who set telehealth standards to guide schools and teaching hospitals in the design and implementation of curricular and professional development activities. This framework describes six emerging competencies along the continuum of learning starting at the entry to residency to the post-residency stage (see Table 2).

Table 2. Telehealth competences as adapted from the AAMC telehealth framework.

Telehealth Competency Domain	Brief Description	Example of Skills for a Recent Medical School Graduate	Example of Skills for an Experienced Faculty Physician
Patient safety and appropriate use of telehealth	Clinicians will understand when and why to use telehealth and how to assess patient readiness, patient safety, practice readiness, and end-user readiness.	Explains to patients and caregivers the uses, limitations, and benefits of telehealth—that is the use of electronic communications technology to provide care at a distance.	Role model and taches how to practice telehealth, mitigate risks of providing care at a distance, and assess methods for improvement
Access and equity in telehealth	Clinicians will understand telehealth delivery that addresses and mitigate cultural biases as well as physician bias for or against telehealth and that accounts for physical and mental disabilities and non-health-related individual and community needs and limitations.	Describes one's own implicit and explicit biases and their implications when considering telehealth.	Role models and taches how to recognize and mitigate biases during telehealth encounters.
Communication via telehealth	Clinicians will effectively communicate with patients, families, caregivers, and healthcare team members using telehealth modalities. They will also integrate both the transmission and receipt of information with the goal of effective knowledge transfer, professionalism, and understanding within a therapeutic relationship	Develops an effective rapport with patients via real or simulated video visits, attending to eye contact, tone, body language, and nonverbal cues.	Role models and teaches effective rapport-building with patients via video visits, attending to eye contact, tone, body language, and nonverbal cues.
Data collection and assessment via telehealth	Clinicians will obtain and manage clinical information via telehealth to ensure appropriate high-quality care.	Obtains history (from patient, family, and/or caregiver) during a real or simulated telehealth encounter.	Role models and teaches the skills required to obtain a history (from patient, family, and/ or caregiver) during a telehealth encounter and incorporates the information into the management plan.
Technology for telehealth	Clinicians will have basic knowledge of technology needed for the delivery of high-quality telehealth services.	Explains equipment required for conducting care via telehealth at both originating and distant sites.	Able to use, and teach others while using, equipment for the intended service at both originating and distant sites.
Ethical practices and legal requirements for telehealth	Clinicians will understand the federal, state, and local facility practice requirements to meet the minimal standards to deliver healthcare via telehealth. Clinicians will maintain patient privacy while minimizing risk to the clinician and patient during telehealth encounters, putting the patient's interest first, and preserving or enhancing the doctor-patient relationship.	Describes locally relevant legal and privacy regulations for telehealth.	Role models and complies with legal and privacy regulations for telehealth at the local, state, and federal levels.

A forthcoming update to the physician competency framework proposed by the Canadian Royal College of Medicine, CanMEDS, is scheduled for released in 2025. It is anticipated that a substantial modification of all the physician roles will occur to better align with the needs of virtual care [15]. Virtual care (VC) is the preferred term to denominate "provision of individual patient care using technology" [14,15]. This revision involves modifying competencies that already present in the CanMEDS 2015 and introducing new competencies related to the use and integration of technologies in the provision of care. As illustrated in Table 3, the majority of new competencies focus on data-informed medicine skills, encompassing the collection, exchange, aggregation, and analysis data [14].

Table 3. Anticipated changes to the CanMEDS physician competency framework regarding virtual care.

CanMEDS Competency Category	Description in the CanMEDS Framework	Anticipated Modification or Inclusion of Competencies for the CanMEDS 2025
Medical Expert role	As Medical Experts, physicians integrate all of the CanMEDS Roles, applying medical knowledge, clinical skills, and professional values in their provision of high-quality and safe patient-centered care. Medical Expert is the central physician Role in the CanMEDS Framework and defines the physician's clinical scope of practice.	Developing expertise using virtual tools to provide safe, comprehensive patient care.
Communicator role	As Communicators, physicians form relationships with patients and their families that facilitate the gathering and sharing of essential information for effective healthcare.	Recognizes that communication skills are different in a virtual setting and emphasize that physicians need to be excellent communicators regardless of the use of technology.
Collaborator role	as Collaborators, physicians work effectively with other healthcare professionals to provide safe, high-quality, patient-centered care.	modified to include in-person and virtual collaboration in multidisciplinary teams.
Leader role	As Leaders, physicians engage with others to contribute to a vision of a high-quality healthcare system and take responsibility for the delivery of excellent patient care through their activities as clinicians, administrators, scholars, or teachers.	Highlights how the healthcare system is impacted by virtual care, and how new models of care (including virtual care) can improve upon current approaches to healthcare delivery.
Health Advocate role	As Health Advocates, physicians contribute their expertise and influence as they work with communities or patient populations to improve health. They work with those they serve to determine and understand needs, speak on behalf of others when required, and support the mobilization of resources to effect change.	The Health Advocate role focuses on equitable access to virtual care, how digital health can be leveraged to identify community needs, and touches on media advocacy in the digital age.
Scholar role	As Scholars, physicians demonstrate a lifelong commitment to excellence in practice through continuous learning and by teaching others, evaluating evidence, and contributing to scholarship.	The Scholar role focuses on staying up to date with and using technology and recognizes that due to the internet, healthcare literature is evolving past the traditional journal article.
Professional role	As Professionals, physicians are committed to the health and well-being of individual patients and society through ethical practice, high personal standards of behavior, accountability to the profession and society, physician-led regulation, and maintenance of personal health.	The Professional role includes the skills and safeguarding mechanisms that have only now become necessary, given the increase in the use of virtual care.

Despite the existence of various emerging telehealth standards, common content areas among them encompass technology skills (e.g., software, troubleshooting difficulties), professionalism (e.g., informed consent and patient privacy), communication skills, physical examination skills in telehealth environments, and the affordance and limitation of telehealth visits [29].

Telehealth competencies contribute to establishing common foundational concepts and standards that ensure consistency and a sustainable clinician workforce necessary to deploy high-quality virtual care [13,30]. Rather than constituting a new and independent set of skills, telehealth competencies are proposed as a supplement to existing ones (e.g., entrustable professional activities and milestones) [1,5,16].

3.2. Telehealth Education: Is There a Teaching and a Training Model Guiding the Design and Implementation Telehealth Curricula?

Like any other set of new skills, telehealth skills and principles need to be taught and trained. Opportunities to acquire and practice telehealth skills are crucial factors associated with physicians' adoption and satisfaction of telehealth [3]. However, physicians and trainees often receive little or no training to effectively implement telehealth encounters [13,31]. While the COVID-19 pandemic has accelerated the design and implementation of telehealth curricula in healthcare education programs [29], its widespread adoption remains a significant gap and a crucial barrier to ensuring scaling and sustainability of telehealth practice [18,32]. Lack of experienced faculty and limited curricular time are two of the most common barriers to expanding telehealth education [13].

There is still a lack of evidence about the teaching and training models guiding telehealth curricula [13,18], and several important questions remain relevant. For instance, at what point in training should telehealth education be integrated? What topics should be addressed and prioritized in telehealth training? What are the best pedagogical methods to teach, train, and assess telehealth competencies [33]? Should telehealth curricula be developed at an interprofessional level? These questions are addressed in the following sections of the present article.

3.3. At What Point in Training Should Telehealth Curricula Be Integrated?

The emerging body of literature on teaching and training of telehealth competencies has mainly focused on medical residency and continuing medical education [1,34,35]. However, early integration of telehealth curricula, at the preclinical stage, can positively impact the use and generalization of telehealth practice [13,17,29,35,36]. "Rather than struggling to fit telemedicine into an already overflowing curriculum, medical schools are most successfully able to include telemedicine competencies when they build them into existing components of the curriculum" [35]. For instance, telehealth training can overlap activities already integrated in the curriculum related to rural care, interprofessional training [35], communication, data collection and assessment, professional behavior and patient safety [17].

The design of a comprehensive telehealth curriculum requires consideration of various aspects to ensure that healthcare professionals are well-equipped to provide effective VC. Telehealth curricula may be designed to cover a variety of topics; however, it is fundamental that learners acquire fundamental knowledge about the differences between the delivery of traditional and telemedicine care [34]. The telehealth competency frameworks mentioned previously (see Tables 1–3) can help to guide the development of learning goals and objectives; however, as with any other curriculum, learning goals must be aligned with a clear understanding of the learners' needs, the content sequences, resources, and assessment methods [37].

A stepwise and longitudinal exposure to telehealth practice can start by conducting patient interviews over live video-streamed [38] and progress to elective telehealth clerkships [39] and interprofessional remote simulations [40]. It is important that telehealth curricula focus not only on practical aspects, such as communication and professionalism, but also that they include opportunities to learn and practice the technical knowledge of telehealth [33], such as how to use telehealth software [41]. Table 4 presents a list of some possible topics to integrate into a telehealth curriculum.

Table 4. Possible topics to integrate into a telehealth curriculum.

Preserving patient privacy [13,17]
Encounter with patient with sensitive issues or limited ability to engage in virtual visits (e.g., patients with hearing-impaired, low health literacy, limited proficiency in the language being treated) [17]
Consideration of patient willingness and readiness for receiving care via telehealth [29]
Incorporation of patient social supports [17]
Limitations of telehealth [13]
Potential changes to the doctor-patient relationship [13]
Remote communication skills [13]
Different telehealth modalities and technologies [13]
Methods of conducting a remote patient history and physical examination [13]
Potential risk to patient [13]
Good website manners [13]/virtual presence [33]
Issues of equitable access [13]
Telemedicine as a tool for reducing health inequities [42]
Federal, state, and local facility and practice requirements [13]
Preparedness of practices [13]
Common problems/troubleshooting [13]
Video-conference-directed resuscitations [43]
Treatment procedure through telemedicine [44]
Features of telemedicine [44]
Medical liability in telemedicine [44]

3.4. What Are the Instructional Methods for Teaching, Training, and Assessing Telehealth Competencies?

There is still limited evidence about the instructional methods used in the delivery of telehealth curricula and its efficacy [33]; however, teaching and training telehealth competencies can adapt and integrate a variety of instructional strategies, including classical lectures, video/podcasts, peer teaching, and simulation [13] (see Table 5).

Table 5. Methods used to teach telehealth, adapted from Khullar et al. [13].

Clinical experience—ambulatory
Lecture
Case-based Learning
Clinical experience—inpatient
Discussion, small group
Simulation
Standardized/Simulated Patient
Preceptorship
Discussion, large group
Team-based learning
Virtual patient
Problem-based learning
Role play
Self-directed learning
Workshop
Video/podcast
Peer teaching
Other

Note: The list of methods used to teach telehealth is organized in descendent order from the most popular ones to the least popular in medical schools in U.S. before the pandemic according to Khullar et al. [13].

The didactics required to teach telehealth can vary greatly depending on the telehealth modality being targeted and the learning objectives. For instance, if we follow Yaghobian et al.'s [34] stepwise approach for implementing telemedicine training in medical school, we may include telemedicine objectives and terminology in the first year, which can be better aligned with methods such as lectures, videos, and podcasts; then, telemedicine practice behaviors and clinical applications can be introduced in the final 3 years by implementing experiential learning strategies such as simulation, standardized/simulated patient, and roleplay. Finally, telemedicine practice training can be applied in residency rotations, achieved through preceptorship, observation, and gradual participation in virtual patient encounters.

3.5. Implications for Educating a New Task Force of Medical Educators

Overcoming the barriers of telehealth curricula implementation may require moving away from the classic expert model of learning, in which novices learn from experts. As the adoption of telehealth curricula is still in its early stages, medical education institutions may need to plan for faculty development and trainee education at the same time [17,45]. There are already some formal programs for training faculty members in different domains, including mental health and cardiology—more specifically, stroke teleassistance. Table 6 describes some examples of continuous professional programs addressing telehealth competencies.

Table 6. Examples of continuous professional programs addressing telehealth competencies.

Institution	Type of Training	Target Public	Topics Covered
Thomas Jefferson University—National Center for Telehealth Education and research (NCTER) [46]	Telehealth facilitator certificate [47]	Healthcare professions	- Applications of telehealth. - Limitations of telehealth. - Differences between telehealth and standard healthcare delivery. - Applications of outpatient an inpatient telehealth - Telehealth platforms. - Troubleshooting of common telehealth technology issues. - Standards and ethical principles of virtual healthcare. - Interprofessional telehealth. - Telehealth etiquette and telehealth coordination.
University of Delaware [48]	Advanced Telehealth Coordinator Certificate—online course	Clinicians, administrators, managers, healthcare IT, and health-related professions.	- Principles of telehealth. - eICU Telehealth resources. - Telehealth funding and Reimbursement - Telehealth policies. - Telemental Health and Ethics. - Quality. - Telehealth in the Home and Remote Patient Monitoring. - Chronic Diseases Telehealth Clinic applications. - Telehealth operational Considerations. - Telehealth Program Planning. - Telehealth management. - Advanced telehealth coordination.

Table 6. *Cont.*

Institution	Type of Training	Target Public	Topics Covered
Telehealth certificate institute [49]	Telemental Health Training Certificate (THTC)	Behavioral health professionals	- History, research and settings of telemental health. - Legal practice of telemental health—licensing laws and federal regulations. - Boundaries of competence when using digital or communication technology. - Clinical, legal and ethical considerations when selecting telemental technology. - Benefits and risks of telemental health. - Development of emergency management plans during a telemental health session. - Patients' criteria for telemental health services. - Effective video or phone session. - Prepare the client for a video or phone session and technological challenges. - Telemental ethical professional practice. - Technology, assessment, and treatment services to fit specific cultural needs.
Telehealth certificate institute [50]	TeleStroke facilitator/ presenter/ Technician Certificate Training Program	Nurses, medical assistants, or medical techs.	- Formulation of accurate algorithms for the diagnosis of a patient with cerebral ischemic stroke. - Patient maneuvering techniques to enhance TeleStroke encounters. - Uses of stroke scoring scale to minimize morbidity and mortality.
American board of telehealth (ABT) powered by the American heart association (AHA) [51]	Courses: - CORE concepts in telehealth certificate program [52] - Telebehavioral health certificate program [53] - TelePrimary care certificate program [54]	Medical professionals	- Introduction to telehealth. - Technology. - Telepresence skills and professionalism. - Legal, regulatory & quality. - Licensing, credentialing, and privileging. - Reimbursement. - Ethical considerations.

Telehealth education can also be extended to specific programs addressing rural and underserved communities or even disaster responses [55]. However, this topic is outside the scope of this article.

4. Future Directions

Training Physicians Telehealth Competencies Using Telesimulation

Telesimulation, a "direct descendent of telehealth" [10], is an ideal instructional method for teaching and learning telehealth competencies [41,56]. Telesimulation is useful for recreating a variety of telehealth components such as teleconsultation, teleadvice, teleassistance [57], tele-education, telemonitoring [58,59], telerehabilitation [60], telehomecare [61], etc. However, despite the growing literature on telesimulation, there is still a lack of consensus on the definition of the term and its overlapping meaning with other type of distance simulations, such as online, remote, and virtual simulation [10,62]. Common to all these terms is the sematic prefix "tele", which determines that an action is taken at a distance [63]. Following the definitions provided in the simulation dictionary, edited by the Society for Simulation in Healthcare [64], some differences can be established according the to the time in which simulation occurs (synchronous vs. asynchronous), the simulation tools used, the location of the instructor and the participants, and the type of feedback offered to participants. Table 7 summarizes the definition associated with distance simulation, including telesimulation.

Table 7. Differences of the distance simulation terms as they are defined in the *Healthcare Simulation Dictionary*, version 2.1.

		Distance Simulation	**Online Simulation**	**Remote-Controlled Simulation**	**Telesimulation**
Time. Is the simulation occurring in a synchronous or asynchronous manner?	Real-time (synchronous)	X	X	X	X
	Off-line (asynchronous)		X		
Simulation tools. What are the simulation tools or methods used?	Mannequin-based training	X		X	X
	Human patient simulation				X
	Virtual patient in a virtual world		X		
Simulation operated by	Participants	X	X	X	X
	Instructors			X	X
	Virtual instructor in a virtual world		X		
Instructor's (location) Where is the simulation instructor located?	On-site	X		X	
	Off-site	X		X	X
Participant's (location)	On-site			X	
	Off-site	X	X		X
Feedback given by	Instructor	X		X	X
	Virtual instructor on a virtual world		X		
	Human patient				X
	Mannequin			X	X
	Automated platform		X		
	Off-site	X	X		X

For the purpose of this article, we define telesimulation as follows [64]:

"Telesimulation consists of a communication technology to provide mannequin-based [and/or Distance-based high-fidelity human patient simulation training] simulation education between learners and instructors located remotely from one another. During these sessions, the instructor observes the learners in real time and provides immediate feedback during the debriefing. This platform obviates the need to have instructors, learners, and mannequins in the same place at the same time, potentially allowing simulation-based educational sessions to occur with greater frequency for institutions not located proximate to formal simulation centers" *Healthcare Simulation Dictionary* ([64] p. 52).

Although the previous definition, as stated in the *Healthcare Simulation Dictionary* [64], only considers mannequin-based telesimulation, telesimulation can also be adapted to distance-based simulated patient model to simulate a teleconsultations via videoconferencing tools [21]. In this type of encounter, the healthcare provider connects directly with a simulated patient via video conferencing software to conduct the equivalent of a visit.

When implementing telesimulation, it is useful to apply some distinctions made in telehealth between telecare and telecure [63,65]. "(1) Telecare—it occurs when someone advances a generic (health-related) request for assistance. A disease is not necessary to evoke such a request, and the other actor is not necessarily a health professional. (2) Telecure—it characterizes the action of taking charge of a specific problem (a disease). Since it implies a specific expertise (curing, treating, or managing a disease), the other actor must be a healthcare professional" ([65] p. 448).

Telesimulation allows participants to interact at a distance in a safe and standardized environment, beneficiating from timely feedback and individual or interprofessional virtual care scenarios [21]. Telesimulation can provide comprehensive and practical training for several telehealth competencies at the individual and at a team level. For instance, medical students can train communication skills when addressing sensitive issues, such as sexually transmitted infections and confidentiality [21]. Insights on how telesimulation can be effectively integrated into existing medical curricula can be found in another article of the same authors titled "A practical guide for translating in-person simulation curriculum to telesimulation" [21]. In addition, medical students and practitioners can also benefit from exposure to interprofessional work in a virtual environment [66,67], where they are able to consult with other professionals about a case, which—according to the previous definitions [65]—would be considered telecare because the agent of the interaction is not the patient but another healthcare professional.

An overarching learning objective of simulation-based learning is to optimize the degree of transfer ok knowledge, skills and attitudes to the real clinical environment [68]. One of the contributing aspects of simulation transfer is the level of realism or fidelity of the simulated environment, including the equipment, the setting, and the scenario [69]. However, telesimulation with stimulated patients reproduces the exact conditions of a telehealth consultation and therefore measurements of transfer of skills may not be necessary as the transfer condition is the telesimulation itself [68].

Research is still needed to provide insights about the indirect impacts of using telesimulation. For instance, we need research that accounts for learners' engagement and the positive and negative effects of cognitive load when using multiple communication channels during telesimulation [21].

5. Conclusions

The rise of telehealth as a transformative force in healthcare delivery is unmistakable, evident in its exponential growth in the United States and Canada. With telehealth firmly establishing itself as a new norm, it is imperative to address the considerable challenges and gaps in its implementation and integration into medical education. The rapid adoption during the pandemic has emphasized the importance of telehealth competencies for healthcare providers. This paradigm shift requires unique communication and technical skills, distinct from traditional in-person care, emphasizing the need for a skilled workforce capable of navigating this evolving modality.

While telehealth competencies are gaining recognition and have been incorporated into the standards of medical regulatory bodies, the implementation of telehealth curricula remains a complex task. Gaps persist in understanding the optimal timing for integration into medical training, prioritization of topics, and identification of effective pedagogical methods.

Notably, the emergent telehealth competencies contribute to the foundational concepts and standards needed for a consistent and sustainable clinician workforce in virtual care. The competency frameworks proposed by organizations such as ACGME and AAMC lay the groundwork for a systematic approach to telehealth education.

Despite the accelerated efforts in response to the COVID-19 pandemic, challenges in the adoption of telehealth education persist, marked by a scarcity of experienced faculty and limited curricular time. Questions regarding the timing and content of telehealth education, the interprofessional development of curricula, and the identification of optimal pedagogical methods remain open and crucial.

We present telesimulation as an ideal instructional method for telehealth competencies. Defined as a communication technology facilitating simulation education between learners and remote instructors, telesimulation offers a versatile platform for recreating diverse telehealth scenarios. This method, a direct descendant of telehealth, presents an opportunity for practical training across a range of telehealth competencies, fostering not only technical proficiency but also communication skills and interprofessional collaboration.

As we advocate for the incorporation of telesimulation into medical education, we recognize the need for further research to address gaps in understanding learner engagement and the effects of cognitive load during telesimulation. This holistic approach to telehealth integration, spanning early education stages through telesimulation in later training, aims to equip healthcare professionals with the multifaceted skills required in the dynamic landscape of virtual care.

6. Limitations

The present article must be interpreted in the context of several limitations. First, the data provided primarily focus on the telehealth education landscape in the United States and Canada. Telehealth implementation, challenges, and regulations can vary significantly in different countries and healthcare systems. Therefore, the generalizability of the arguments presented in a global context may be limited. Secondly, the present perspective addresses the integration of telehealth curricula in the context of medical education without addressing the variability between clinical settings and medical schools, which could add to the debate on how telehealth curricula might vary according to the context and resources available. Although this article acknowledges the barriers and difficulties associated with telehealth and the ethical aspects of it, there is not an in-depth exploration of these aspects, which could also influence the feasibility of implementing telehealth curricula.

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healthcare

Review

Content, Mechanism, and Outcome of Effective Telehealth Solutions for Management of Chronic Obstructive Pulmonary Diseases: A Narrative Review

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Abstract: Telehealth (TH) solutions for Chronic Obstructive Pulmonary Disease (COPD) are promising behavioral therapeutic interventions and can help individuals living with COPD to improve their health status. The linking content, mechanism, and outcome of TH interventions reported in the literature related to COPD care are unknown. This paper aims to summarize the existing literature about structured TH solutions in COPD care. We conducted an electronic search of the literature related to TH solutions for COPD management up to October 2023. Thirty papers presented TH solutions as an innovative treatment to manage COPD. TH and digital health solutions are used interchangeably in the literature, but both have the potential to improve care, accessibility, and quality of life. To date, current TH solutions in COPD care have a variety of content, mechanisms, and outcomes. TH solutions can enhance education as well as provide remote monitoring. The content of TH solutions can be summarized as symptom management, prompt physical activity, and psychological support. The mechanism of TH solutions is manipulated by factors such as content, mode of delivery, strategy, and intensity. The most common outcome measures with TH solutions were adherence to treatment, health status, and quality of life. Implementing effective TH with a COPD care bundle must consider important determinants such as patient's needs, familiarity with the technology, healthcare professional support, and data privacy. The development of effective TH solutions for COPD management also must consider patient engagement as a positive approach to optimizing implementation and effectiveness.

Keywords: digital health; telehealth; COPD; review

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1. Introduction

Chronic obstructive pulmonary disease (COPD) is a common, progressive respiratory disease that is growing in prevalence worldwide [1]. The Global Initiative for Chronic Obstructive Lung Disease (GOLD 2023) defines COPD "*as a heterogeneous lung condition characterized by chronic respiratory symptoms (dyspnea, cough, expectoration and/or exacerbations) due to abnormalities of the airways (bronchitis, bronchiolitis) and/or alveoli (emphysema) that cause persistent, often progressive, airflow obstruction*." [2]. GOLD is a well-known international organization, which is working to provide guidelines for COPD diagnosis, treatment, prevention, and management in order to assess the characteristics of COPD at a global scale, and to maximize available resources to support COPD care [1]. In COPD management, pharmacological and non-pharmacological treatments are mostly administrated together [3]. Pharmacological treatments such as bronchodilators, expectorants, antibiotics, and inhaled corticosteroids assist in controlling symptoms [3]. In parallel with non-pharmacological treatments, such as smoking cessation, pulmonary rehabilitation (PR), and vaccination, which play a role in self-management as well as maintaining and controlling the condition [4]. Technology can play an important role in facilitating the delivery of these treatments, promoting self-management. Even with the acute exacerbation of COPD (AECOPD), the "acute worsening of respiratory symptoms that results in additional therapy", patients may benefit from using technology to monitor the disease or detect the onset of deterioration.

Telehealth (TH) solutions for COPD care are promising therapeutic interventions and are valuable in helping individuals to manage symptoms, minimize hospitalization, and improve their health status [5,6]. Also, the current evidence supports self-management training via TH as a crucial component of the COPD care bundle to help individuals change their behaviors, thus controlling their symptoms and reducing hospital readmission due to AECOPD [7,8]. Since TH solutions for COPD care first appeared, researchers across the world have been able to better understand how to create, implement, and maintain TH solutions. Although, as of October 2023, more than 184 clinical trials documented the use of TH solutions with COPD, there are no data establishing an overview of the experience with TH solutions. In addition, there is a lack of knowledge in determining the connection between the content, mechanism, and outcome of these using interventions when dealing with COPD patients. To address this gap in the knowledge, a narrative review was conducted with the aim of summarizing the existing literature about the structured TH in COPD care as well as informing future developers about the current status.

2. Methods

The keywords related to telehealth and digital health solutions for COPD management were searched in two databases (PubMed and Medline) up to October 2023. The content, mechanism, and outcomes of clinical trials introducing and providing TH or digital health solutions were included. The review excluded articles that were not published in English or were not related to the scope of the review. To ensure that our review included appropriate and necessary keywords, we added Medical Subject Headings to the search as well as working with the health sciences librarian. Potential articles from the databases were exported to EndNote 20. After removing duplications, the main author reviewed all titles and abstracts and applied eligibility criteria. To collect data, a standard Excel spreadsheet was created. The final findings are summarized and criticized in narrative form. An example of the search strategy is provided in Supplementary Files S1 and S2.

3. Results

Research findings included 30 clinical trials that reported or provided TH or digital health solutions to manage COPD patients (Table 1). The oldest clinical trial was reported in 2008 and the latest was reported in 2023. Data were summarized and criticized, with a special focus on articles reporting details regarding interventions, including the content, mechanism, and outcomes.

3.1. Digital Solutions in Healthcare Services

The term TH became the most common terminology to describe this integration of information and communication technologies (ICTs) and healthcare services. It is currently the preferred term because it captures the broad applications of this technology in providing healthcare services [9]. The term digital health is a relatively new concept, defined as "the use of digital technologies for health" [10]. Both TH and digital health are broad concepts that might include planning, monitoring, assessment, diagnosis, education, and treatment [10]. In the literature, TH or digital health have been used successfully within different health care disciplines, including cardio-respiratory disease management, and in the provision of home care or self-management for patients with chronic diseases such as COPD [11,12]. In addition, technology can be used in COPD care to improve the timeframe of therapeutic contact, or as an alternative tool when access to care is not available [13] Figure 1.

3.2. Benefits of TH with COPD Management

Systematic reviews and meta-analysis showed that TH solutions that support self-management could contribute to improve user's skills in controlling COPD, especially those with transport or economic limitations, or geographical barriers [12,14]. Considering the high cost of health care services, the TH approach could lower costs while maintaining quality of treatment in primary care clinics, decrease the pressure on the specialty care clinics, deliver tailored care, and facilitate the coordination of care among healthcare professionals [15]. Also, TH could be an opportunity to facilitate education reinforcement for professionals, patients and/or caregivers [16]. Additionally, digital health allows for frequent reminders to be provided to users to practice behavior which strengthens an existing behavior, like self-monitoring and self-efficacy, or facilitates early interventions for COPD conditions by detecting their exacerbation at an early stage, and could therefore prevent unnecessary emergency visits and hospital readmissions [17,18], as shown in Figure 2.

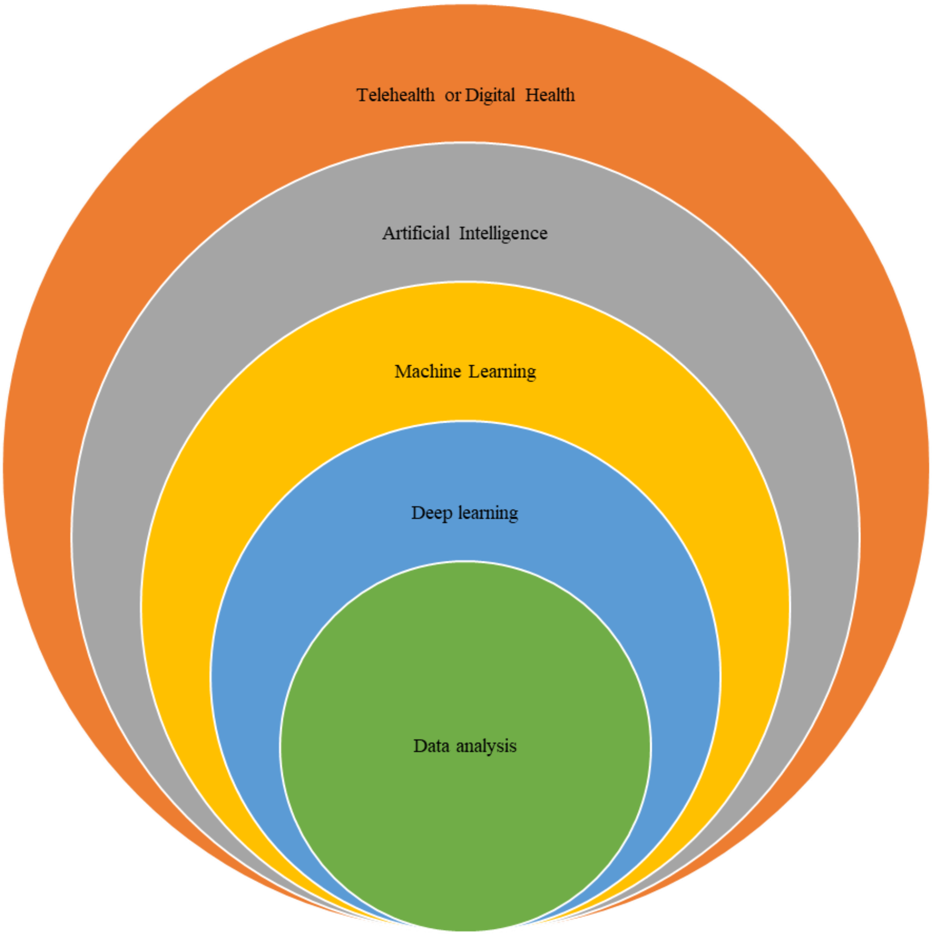

Figure 1. TH or Digital health concepts in COPD care.

3.3. Structures of TH Solutions

Development and innovation in digital health are steadily increasing [19]. Looking to digitalization alone as effective tool is not going to provide us with a better result in clinical practice. As clinicians, we could look at this technology as a key part of the package provided to the users. The package usually contains multiple components, which include complex mediums and interventions (i.e., telerehabilitation). However, it is difficult to evaluate the functionality of TH solutions that support disease management without considering three important components: (1) the context that was provided, (2) the mechanisms that package components went through, and (3) the outcomes that the solutions are targeting. The answers to these questions still need further clarification [20,21]. One way to resolve this conflict is understanding the functionality of digital health solutions in COPD management [22,23]. This functionality could be understood from a theoretical perspective by identifying the associations between the context, mechanisms, and outcomes of current

TH solutions that support disease management, in other words, the conceptual frameworks that enhance the connection between these elements and make technology a valuable tool in the delivery of care (Figure 3).

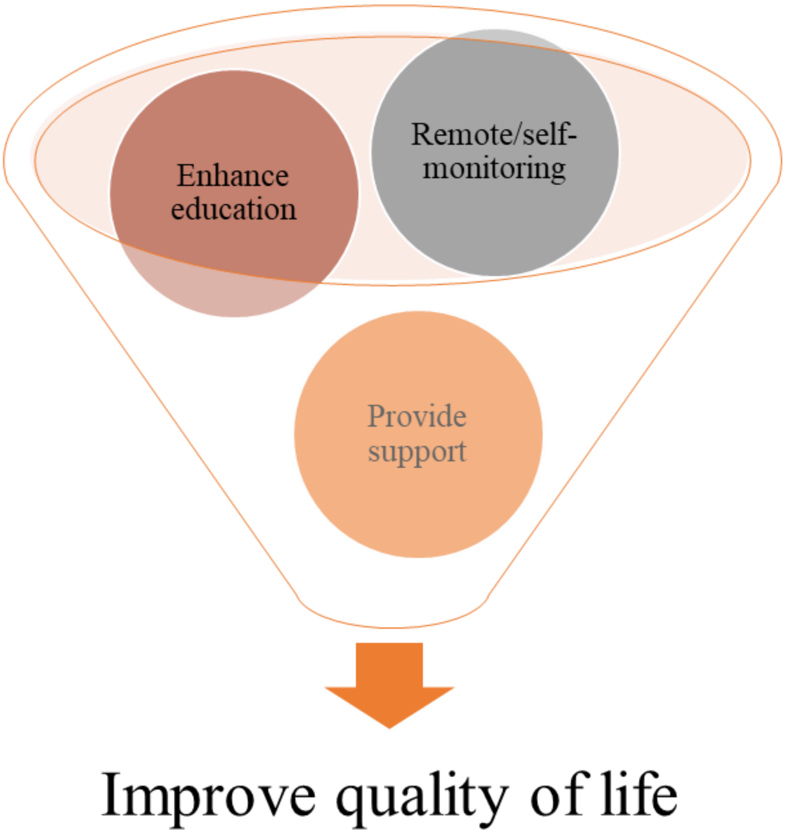

Figure 2. Benefits of TH with COPD management.

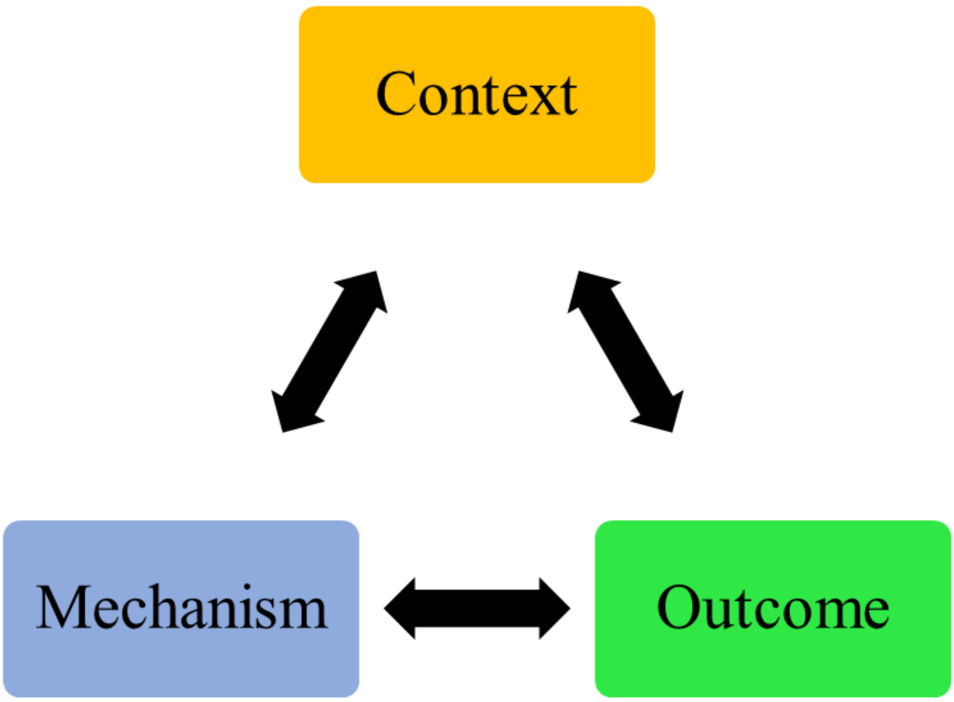

Figure 3. Structure of TH applications.

3.4. Context of Digital Health Solutions

The context of TH in COPD management includes three important factors: (1) the clinical setting, (2) digital health development, and (3) targeted populations. A summary of the literature is provided in Table 1.

Table 1. TH interventions' characteristics from 2008 to 2023.

Authors	Settings	Intervention with TH	Mode of Delivery	Intensity	Control Group Treatment	Summary of TH Outcomes Compared to Control Group
Trappenburg et al., 2008 [24]	Patient home (n = 165)	Software COPD self-management education	Telephone	1×/day for 6 months	Usual care	Reduction in AECOPD and hospitalization
Koff et al., 2009 [25]	Patient home (n = 40)	Online COPD self-management education	Web-based and telephone	1×/day for 3 months	Usual care	Improved quality of life
Halpin et al., 2011 [26]	Patient home (n = 79)	Automated text messages system	Text message	1×/day for 4 months	NR	Lower AECOPD but no change in quality of life
Lewis et al., 2011 [27]	Patient home (n = 40)	Home monitoring	Telephone	2×/day for 6 months	Usual care	No difference in hospitalization or length of stay
Stickland et al., 2011 [25]	Community center (n = 409)	Online COPD self-management education	Web-based and video calls	2×/week	In-person rehabilitation	Improvements in quality of life
Antoniades et al., 2012 [9]	Patient home (n = 44)	Online COPD self-management education	Web-based	1×/day for 12 months	Usual care	No reduction in hospitalization or improvement in quality of life
Chau et al., 2012 [28]	Patient home (n = 40)	Telecare services	Web-based and telephone	3×/day for 2 months	Community services	No difference in health-related quality of life
Dinesen et al., 2012 [29]	Patient home (n = 111)	Telerehabilitation	Video calls	1×/day for 4 months	Instructional book	Reduced hospitalization
Nield et al., 2012 [30]	Patient home (n = 22)	Online COPD self-management education	Video calls	1×/week for 1 month	Usual care and in-person education	Decreased dyspnea
De San Miguel et al., 2013 [31]	Patient home (n = 80)	Written COPD self-management education	Telephone	1×/day for 6 months	Usual care	Reduced hospitalization and length of stay
Pedone et al., 2013 [32]	Patient home (n = 99)	Telemonitoring	Web-based, telephone, and algorithm	1×/day for 9 months	Usual care	Reduced respiratory events and hospitalization
Pinnock et al., 2013 [33]	Patient home (n = 256)	Online COPD self-management education	Web-based, telephone, and algorithm	1×/day for 12 months	Usual care	Reduced admission to hospital but no change in quality of life
Schou et al., 2013 [34]	Patient home (n = 44)	NR	Video calls	1× /day for 3 months	Regular Hospitalization.	Improvements in lung volumes and oxygen saturation

Table 1. *Cont.*

Authors	Settings	Intervention with TH	Mode of Delivery	Intensity	Control Group Treatment	Summary of TH Outcomes Compared to Control Group
Calvo et al., 2014 [17]	Patient home Medical center (n = 60)	Home care with TH	Web-based and telephone	1×/day for 7 months	Usual care	Reduction in ER visits, hospitalization, and length of stay
Tabak et al., 2014 [35]	Patient home (n = 29)	Online COPD self-management education	Web-based and Video calls	1×/day for 9 months	Usual care	Increased patient adherence to exercise
Berkhof et al., 2015 [36]	Medical center & patient home (n = 101)	Phonecalls, education and follow ups	Telephone	Call/2 weeks for 6 months	Usual care	No improvements in health status
Jakobsen et al., 2015 [6]	Patient home (n = 57)	Virtual hospital	NR	1×/day for 6 months	Regular hospitalization	Reduced re-admission to hospital due to AECOPD
McDowell, 2015 [37]	Patient home (n = 110)	Home-based health care	Telephone	1×/day for 6 months	Usual care	Improved health related quality of life.
Ringbeak et al., 2015 [38]	Patient home (n = 281)	Online COPD self-management education and home exercise	Video calls	3×/week for 6 months	Usual care	No change in dropout or mortality
Tucker et al., 2016 [39]	Patient Home (n = 65)	Written home exercise with TH	Telephone	Call/2 weeks	Usual care	Improvement in physical activity
Ho et al., 2016 [40]	Patient home (n = 106)	Telemonitoring	Web-based and telephone	1×/day for 2 months	Usual care	Reduced number of hospitalizations due to AECOPD
Ringbeak et al., 2016 [41]	Patient home and outpatient (n = 116)	Online COPD self-management education and home exercise	Web-based, video calls	NR	In-person rehabilitation	Improved physical capacity but no improvement in CAT score.
Vianello et al., 2016 [42]	Hospital (n = 334)	Online COPD self-management education	Web-based and telephone	1×/day for 12 months	Usual care	Reduced readmission rate due to AECOPD
Farmer et al., 2017 [43]	Patient home (n = 116)	COPD self-management education with TH	Web-based	1×/day for 12 months	COPD self-Management education without TH	Improved health status and quality of life
Lilholt et al., 2017 [44]	Patient home and community center (n = 1225)	Telerehabilitation	Web-based, and telephone	NR	In-person rehabilitation	No difference in quality of life
Shany et al. ,2017 [45]	Patient home (n = 42)	Online COPD self-management education	Web-based and telephone	1×/day for 12 months	Home care	Reduction in hospitalization and length of stay

Table 1. *Cont.*

Authors	Settings	Intervention with TH	Mode of Delivery	Intensity	Control Group Treatment	Summary of TH Outcomes Compared to Control Group
Tsai et al., 2017 [46]	Patient home (n = 37)	Online COPD self-management education and home exercise	Video calls	3×/week	Usual PR	Improvements in physical capacity and quality of life
Soruano et al., 2018 [47]	Patient home (n = 237)	Telemonitoring	Internet modem	1×/day for 12 months	Usual care	TH did not reduce hospitalization due to AECOPD
Jolly et al., 2019 [48]	Patient home (n = 58)	Multimedia COPD self-management education and telephone coaching	Telephone	1×/day for 12 months	Usual care	Improvement in uptake in PR program
Jiang et al., 2020 [49]	Patient home (n = 106)	TelePR program	WeChat	3×/week for 6 months	Usual PR	No difference in symptoms score between TelePR and UC
Rassouli et al., 2021 [50]	Patients home (n = 168)	Online COPD self-management education	Web-based and telephone	5×/week for 6 months	Usual care	TH use improved CAT score and satisfaction with care.
Zanaboni et al., 2022 [51]	Patients home (n = 120)	TelePR	Video calls	3×/week for 2 years	Treadmill at home	TH redued hospitalization.
Polo et al., 2023 [52]	Hospital and participants' home (n = 209)	COPD TelePR program	Zoom and web-conferencing	2×/week for 2 months	Usual PR	TH improved COPD symptoms, fatigue, self-management, and lung volumes.

TH: telehealth, COPD: chronic obstructive pulmonary disease, PR: pulmonary rehabilitation, NR: not reported, TelePR: telepulmonary rehabilitation, AECOPD: acute exacerbation of COPD, ER: emergency room, CAT: COPD assessment tool, x: times, n: total number of participants in the study.

3.4.1. Clinical Settings

TH solutions have potential benefits in primary and secondary clinical settings [53]. For example, in the primary clinical settings, TH facilitates communication between the healthcare professionals and the patients to provide effective monitoring and assessment between clinical visits [54]. This application has been found to be helpful in clinical settings to provide prompt feedback and enhance exercise and treatment adherence [54]. In the secondary clinical settings, TH is used to facilitate coordination of care between primary and secondary health care centers, especially in small modern cities [55,56]. The coordination of care allows for healthcare providers like specialists to assess the COPD patients and provide advice on the action plan without traveling to the patient's location [56,57]. Mostly, this kind of TH solution refers to teleconsultations [58]. Clinical settings, for COPD, must consider setup and logistics as we are witnessing an increased interest in shifting routine care to an entirely digitalized setup. This phenomenon was accelerated by circumstances such as disease outbreaks [59,60] and some strategic plans to decrease the cost burden of these diseases [61], as shown in Table 2.

Table 2. Applications of TH solutions in clinical settings.

Clinical Settings	Objective and Summary of the Potential Benefits
Primary care settings	Evaluate the acceptability and feasibility of real-time interactive voice and video calls via Skype for teaching breathing exercises and decreasing dyspnea compared to usual care. People who received the teaching via Skype reported less dyspnea than those receiving usual care [30]. Evaluate the effects of exercise coaching via digital health versus self-training without coaching in COPD. Ref. [46] Professionals provided the coaching in the study as part of the telerehabilitation program. The study found that exercise coaching via digital health helped COPD patients to increase their adherence and exercise capacity compared to self-coaching without digital health [46].
Secondary care settings	Determine the effects of The Health Buddy (HB) telemonitoring device on health consumption and health-related quality of life (HRQoL) in patients with moderate to severe COPD. Using HB resulted in decreased hospital days and outpatient visits, but no significant changes were observed in HRQoL [24]. Determine the effect of supervised, home-based, real-time videoconferencing telerehabilitation on exercise capacity, self-efficacy, HRQoL and physical activity in patients with COPD compared with usual care without exercise training. The study showed that telerehabilitation improved endurance, exercise capacity, and self-efficacy in COPD when compared with usual care [46].

Primary care setting defined as one service provided in primary care settings. Secondary care settings defined as more than one service provided by tertiary hospitals or community centers.

3.4.2. Digital Health Solutions Development

According to the *Consolidated Standards of Reporting Trials of Electronic and Mobile Health Applications and onLine TeleHealth* (CONSORT-EHEALTH), TH interventions must be reported as one of three categories [62]. First, as an educational tool to provide education and improve patient knowledge, such as “living well with COPD or Asthma+Lung UK” [63,64]. Second, as an electronic tool for communication and to facilitate home-monitoring and/or remote monitoring for individuals with COPD. Third, as a comprehensive TH intervention to provide education, monitoring, assessment, and treatment to help manage the condition, such as telepulmonary rehabilitation programs and virtual hospitals [6,34]. The development of TH solutions in COPD also must consider patient engagement as positive approach toward optimizing implementation and improving usability [65]. The current TH interventions have introduced a variety of potential benefits that guided their development. None of the studies included in this review reported the theoretical framework that guided the development of the TH intervention.

3.5. Mechanism

TH solutions with COPD are multicomponent interventions (Table 3). Not all the TH solutions involved interventions [66]. There are studies of TH tools in the literature that only provided remote monitoring for COPD without any further interventions, even self-management or education [36,67], while others provided a virtual hospital at the patient’s home [6,34]. The mechanism of TH solutions is complicated, and depends on professional support as well as the standard care practice. To describe the mechanism of TH solutions that supported COPD management, we must consider four important factors: (1) content and format, (2) modes of delivery and level of technology, (3) strategy, and (4) the intensity of remote monitoring, which includes its frequency and duration, as shown in Figure 4.

Table 3. Summary of the mechanism factors of TH solutions.

Type of Support/Technology	Content (Covered One or a Combination of the Following Subjects)
■ Special modems [68] ■ Secure web-pages [69] ■ Automated call/text center [70] ■ Professional call center [71] ■ Alert system to detect deterioration [72] ■ Clinical decision software's [73] ■ Videoconference [46] ■ Patients portals [74] ■ Public internet platforms [75] ■ Smartphone applications [76] ■ Machine learning and artificial intelligence [77] ■ ChatGPT [78]	■ Symptoms management (i.e., breathlessness, medications, action plan) [36,45,79]. ■ Enhance physical activity (i.e., exercise training, maintaining a healthy lifestyle, energy-conserving technique) [38,46,80,81]. ■ Psychological and behavioral support (i.e., smoking cessation, adherence, compliance, problem-solving, self-efficacy, stress, and anxiety management) [24,25,30,33,75,82,83].
Mode of delivery	Strategy and intensity
■ Synchronized and asynchronized TH support [84]: ○ Patient's data stored in a secure modem. Then, COPD care provided by the healthcare professionals through digital health. ○ Digital systems recognize changes in data, then alert the healthcare center or healthcare team, but the system does not provide 24/7 communication (i.e., online chat or email) [84]. ○ Both modes considered as a means to store and forward digital health support [84]. ■ Immediate and live analytics, support and decision-making are available 24/7 for the users (i.e., predesigned algorithms and ML), and this mode is considered a real-time digital health support [84].	■ Strategy: ○ Individual or group [29,36,85,86]. ■ Intensity: ○ Duration and frequency of treatment/data transmission [17,28,30,32].

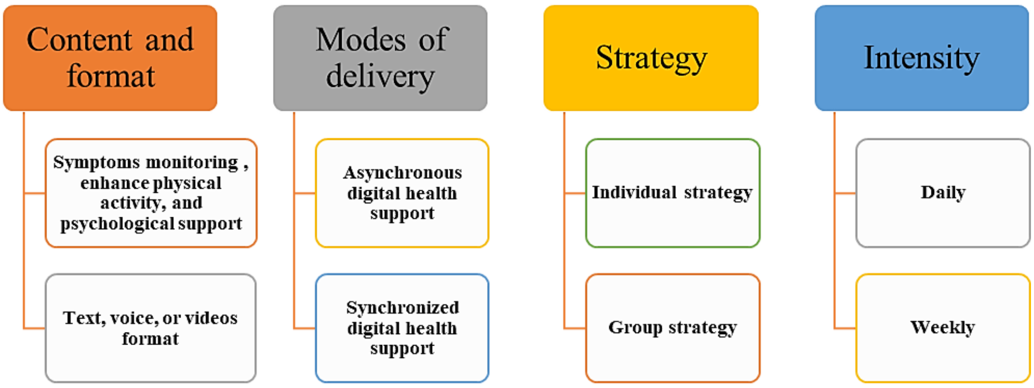

Figure 4. Factors describing the mechanism of TH solutions.

3.5.1. Content

The content of TH solutions is a broad topic. The evidence presented a wide range of variation in the content of COPD management [12,21]. That variation in the content comes from the different perspectives regarding the self-management support and/or different guidelines used to manage COPD. For instance, self-management with COPD has been defined as individuals' ability to master a broad range of tasks, including managing their symptoms, physical activity, coping with the mental consequences, and maintaining their lifestyle [87,88]. This support flows through a continuous opening channel via TH solutions and could include periodic home visits or calls to follow-up with the patients and provide feedback [89].

First, in symptoms' management using TH solutions, the content was described in the literature as giving the patients instructions, advice, and recommendations regarding what actions must be taken to control symptoms [36,45,79]. Patient–professional communication or professional–professional communication were used to visualize and monitor symptoms [36,45,79]. This supported disease maintenance and could help both patients and professionals to detect deterioration at an early stage [9,36,90].

The second type of content is physical activity via TH solutions. Physical activity has been described as giving the patient instruction, advice, and recommendations on how to perform exercise and training [38,46,80,81]. The exercise includes one or a combination of the following components: (1) structure physical exercise, (2) techniques for performing daily activity, (3) set exercise, (4) stretching and legs exercise, and (5) techniques for conserving energy. This content is mostly used with stable COPD patients without any recent exacerbations [38,46,80,81].

The third content is mental and well-being support. The mental and well-being support has been described as giving the users instructions, advice, and recommendations regarding psychological support [24,25,30,33,82,83]. The psychological support could include one or a combination of behavior change techniques [23]. These are mostly delivered to the patient in-person by the healthcare providers, especially when TH systems recognize alarms from the patient's side. The healthcare providers contact the patients and reassure them, provide information or feedback, and recommend relaxation techniques [23].

When these contents are delivered via TH solutions, a robust mechanism associated with these contents is required to explain how the solutions support feasibility and accessibility to improve health outcomes among COPDs [21,55]. Despite the variety in the content of TH solutions with COPD, all of them used either text or videos format. The text format could be delivered in many different modes, such as instruction books, written guidelines, and SMS messages [29,36,85], while the video format could be used to coach or teach the users a specific exercise, and/or provide recorded education and instructions [30,43,46].

3.5.2. Mode of Delivery

The modes of TH solutions in COPD care have been defined as the way that the content is delivered to the end-users [91]. Since the technology is a fast-growing field, there are three different styles of delivery, but in this paper we considered ICT as a crucial mode of delivery. From this perspective, TH support has been summarized as synchronous, asynchronous, and immediate or live analytics and decisions [84,92]. Advanced forms of synchronized digital health support via machine learning (ML) and artificial intelligence (AI) are growing and getting more attention. These involve using existing data to develop and train statistical models to support clinical judgment. The simple version of this method is described as reviewing the patterns in the data to reach an informed conclusion. It can be used to diagnose or treat people with COPD. Establishing these methods in COPD care requires a lot of data, and these methods are still under review by experts [92].

3.5.3. Strategy of Delivering Digital Health Support

- Individual strategy

The best example to describe this strategy is mobile health apps [9,43,63]. In terms of interaction, the users must access the mobile app to receive feedback from the healthcare provisional regarding their conditions, or feedback from a predesigned algorithm [93,94]. In terms of technology, this strategy requires advanced technological devices with internet access (i.e., a smart cellphone or tablet) to visualize, send, or receive information. This strategy involves partial interaction between the users and the healthcare providers, but full interaction between the users and the technological devices. For example, feedback could be delivered to the patient using well-known platforms such as "Living well with COPD" [95] and "myCOPD" [96] These platforms allow for the patient to access the education program and could be used at any time [63,95–97]. Another proposed approach to the individual strategy includes using a platform designed based on local guidelines.

This would require the patient to access the platform to conduct self-monitoring and receive education, support, and feedback from their healthcare provider [43]. Both approaches enhance the personalized care for individuals with COPD [98].

- Group strategy

The best example of this strategy is providing services in regular meetings, also known as community-based TH support [29,36,85,86]. In terms of interaction, this strategy involves interaction between users and healthcare professionals. This strategy does not require advanced ICT, but requires more effort from the patient and healthcare provider to complete the session or meet competencies [99]. The group strategy requires qualified healthcare professionals to deliver services or care. The patient, on the other hand, must attend the clinical or community center to receive support such as community-based telePR for COPD [99].

3.6. Intensity

Duration and Frequency

Treatment or management sessions for COPD via TH solutions have different intervals and durations. For example, some studies provide COPD management sessions for 10–20 min per day, mostly involving pulmonary rehabilitation and breathing exercises [26,27,46,100]. It seems that a specific aspect of self-management via TH (i.e., breathing exercises and pursed-lip breathing) takes less time than comprehensive disease management (i.e., exercise-coaching, energy conservation, medication follow-up and nutritional advice, and managing stress). Regarding the frequency of sessions, daily or weekly frequencies for a short duration seen more frequent in the literature [12,101].

3.7. Health Outcomes

TH solutions that support COPD management have variety of outcomes. This variety might come from the inconsistencies in using a theoretical model when the researchers design a TH solution [102]. For example, if a researcher designs a study to understand the rate of acceptance of digital health solutions among COPD patients, then the outcomes measured for that study must be related to the rate of technology acceptance, such as perceived ease of use and perceived usefulness [103]. TH studies in the literature targeted various outcomes, including clinical outcomes, treatment cost or adherence, and changes in patient behavior [104–106]. Also, clinical outcomes such as time to AECOPD, emergency department visits, hospitalization [107], need for non-invasive mechanical ventilation [108], length of stay [109], physical activity [110], health status, and HRQoL [111] were mostly measured as primary or secondary outcomes [106].

3.8. Determinants of TH Solutions

Before implementing TH solutions, stakeholders and policymakers must think about the factors that influence adaption and adherence. Providing individuals with easy access to basic and advanced communication technologies, as well as digital health platforms, is an important determinant. Another factor is the presence of well-trained healthcare experts to manage and administer the platform, as well as a technical support team available 24 h a day, 7 days a week to resolve any technological issues. Third, data transformations on the envisaged digital health platforms must be safe. Fourth, platform users' needs must be taken into account, such as hearing and vision limitations in the elderly [14].

3.9. Other Promising Applications for TH in COPD Care

Digital health can be used to provide medical education and training (tele-education), especially when there has been a disruption in direct management, training sessions, seminars, and medical education. Even in units like ICUs, tele-education and/or remote training via ZOOM, Skype, or Microsoft Teams has supplanted traditional techniques in teaching and training programmes [112]. In the COPD care literature, this experience has a positive influence and leads to better treatment adherence outcomes [52].

The use of virtual ICUs in management has rapidly increased to address the dearth of health care workers and to ease family visits to critically sick patients. The use of virtual ICU had positive results in terms of reducing physiological stress and anxiety, and enhancing staff morale, according to cross-sectional data [60]. In addition, virtual ICU is an excellent opportunity for family members to share their joy and relief [60]. Virtual reality (VR) has also played a significant role in the treatment of COPD patients. One of the most important applications of VR is in pain management for COPD patients with back pain. Experts have proved that using virtual reality to provide care to those people is a workable and powerful tool in healthcare delivery. In addition, VR can be a fun tool to stimulate physical activity among persons in PR programmes [14]. VR is extremely beneficial since it allows for these patients to continue their treatment at home, avoiding the need to visit community centres and hospitals.

AI is also considered an innovative new form of technology that has helped in COPD diagnosis [77]. Kaplen et al. evaluated the ability of AI to detect COPD diagnosis, and the results showed that AI can distinguish between COPD and asthma [77]. AI, therefore, can provide rapid information to make a medical decision.

There are certain limitations to this review. Firstly, we may not have included all prospective TH trials in this narrative review, because we only looked through two key databases: PubMed and Medline. Nonetheless, given that PubMed and Medline are considered the largest medical databases, we are certain that we have not overlooked any significant research in the literature. Although our research was restricted to publications released during the last 15 years, this evaluation encompasses a wide range of the literature.

4. Discussion and Conclusions

This review contributed to the literature by providing an overview of the existing structured TH solutions in COPD care and the way they work. Over the last 15 years, several studies dealing with this topic have been published. The current review concentrates on describing the connection between content, mechanism, and outcomes in clinical trials that provided TH solutions to individuals with COPD. This narrative review is the first to focus exclusively on this specific aspect of innovative care for COPD patients. Researchers have made significant effort to prove that TH approaches can increase the availability and accessibility of effective care for the COPD population. Despite this, many lessons have been learned from this review.

First, TH or digital health solutions in COPD management can be heterogeneous in their content, mechanism, and outcome, all of which have contributed to their efficiency and effectiveness. Second, current evidence suggests that using digital health solutions in COPD management could provide benefits such as managing symptoms and enhancing physical activity, and improving mental health. Third, some factors, including strategy, intensity, delivery medium, and content, can affect TH solutions' function. Additionally, the three most commonly used outcome indicators for TH solutions were quality of life, health status, and treatment adherence. Therefore, the COPD care bundle's successful implementation of TH must consider key factors such as patient demands, familiarity with the technology, support from medical professionals, and data privacy. Finally, to achieve optimal implementation and efficacy, theoretical frameworks and patient engagement must be considered in the development of TH solutions for COPD care.

Researchers should focus on developing smarter, interactive digital health solutions for people with COPD in the future. The integration of TH solutions into the model of care should consider simplification, as the technology could be a challenge for certain patients. It is recommended that future work report the degree to which the use of TH solutions has contributed to reducing healthcare costs. The principle of delivering high-quality healthcare services through various modes must be reinforced. This makes it possible for healthcare systems to use innovative approaches depending on the needs and preferences of patients.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare11243164/s1, Supplementary File S1: Example of search strategy from PubMed. Supplementary File S2: Number of publications per year from 2008 to 2023.

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Article

The Impact of a Multicomponent Platform Intervention on the Daily Lives of Older Adults

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Abstract: Gerontechnology is an interdisciplinary field of research involving gerontology and technology in order to help older adults identify and slow down the effects of age-related physical and cognitive decline. It has enormous potential to allow individuals to remain in their own homes and improve their quality of life. This study aims to assess the impact of a multicomponent platform, consisting of an ambient sensor, wearable devices, and a cloud application, as an intervention in terms of usability and acceptance as primary outcomes and well-being, quality of life, and self-efficacy as secondary outcomes in a sample of 25 older adults aged over 65 after 21 days of non-supervised usage at home. This research involved the use of a mixed-methods approach, in which both qualitative and quantitative data were collected in three different measurements. Overall, the participants shared good engagement with the integrated platform. The system achieved positive results in terms of both usability and acceptance, especially the smartwatch. The state of complete well-being slightly improved over the period, whereas self-efficacy remained stable. This study demonstrates the ability of target users to use technology independently in their home environment: it strengthens the idea that this technology is ready for mainstream use and offers food for thought for developers who create products for the aging population.

Keywords: gerontechnology; active and healthy aging; older adults; technology-based intervention; independent living; usability; acceptance

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1. Introduction

Gerontechnology is an interdisciplinary field of research and application involving gerontology, the scientific study of aging which examines the biological, psychological, and sociological factors associated with the aging process [1] and technology that can help older adults identify, prevent, and slow down the effects of age-related physical and cognitive declines [2]. Its areas of competence are technology for independent people (e.g., work and self-fulfillment), assistive technology (e.g., housing and health), and technology for communication and leisure. Therefore, gerontechnology has enormous potential to ensure better care and an improved sense of security and quality of life for older adults [3], but it also clashes with three different types of barriers, such as decreased cognitive functions, accessibility, and a lack of knowledge about technology [4,5]. In fact, although gerontechnology is really supportive of daily living, over the last few decades, several studies have investigated the numerous reasons why older individuals are less inclined to use technology [6].

Chung et al. [7] observed that for aging-in-place technology to be truly adopted by older adults, devices should address seniors' values, self-perceptions, and ethical issues at the intersection of aging, technology, and home environment [8]. Older adults highlight that the main deciding factors on whether to use or accept technologies are that these technologies should allow them to remain in their own homes and age in place, improve their quality of life, and be perceived as useful [9], especially in the tracking of health [10].

On one hand, older adults tend to associate the adoption of new technologies with a lack of confidence in their ability to understand or access them, resulting in a sense of frustration and inadequacy [11]. The concept of usability is therefore linked to the ease of use of the devices and the possibility of taking advantage of short training, perhaps with the help of caregivers. Since lower self-efficacy and higher computer anxiety predict lower use of technology, the learning perspective in the development and deployment of new technologies should play a significant role so as to facilitate access by older users [12].

On the other hand, privacy is a critical factor affecting older adults' acceptance of smart home technology [9]. Seniors want to feel that they have the power to control their lives and surroundings for as long as possible, and not to be controlled. They want to decide whether and how to use the technology, when it is turned on or off, where it is placed, and with whom to share the collected data. Stakeholders often underline the value of empowerment and self-management to promote well-being [13]. Autonomy for smart home technology means "the assistive technology developed for elderly care must not interfere with the will of the person it is designed to care for" [14]. Older adults want to be perceived as strong, capable, and independent individuals, and this desire stems from their wish to not be perceived as a burden to family, friends, or society, in general [8]. Any device that projects negative aging stereotypes is likely to be rejected by older adults, even if the device is helpful [15]. A recent mapping review on studies of successful aging via assistive information and communication technologies [6] mapped a heterogeneous scenario of research gaps where mixed methods research and the cooperation among clinical, technical, societal, and research areas might help in reaching the effectiveness of solutions to improve the quality of life of older adults [6].

In our view, it could be stimulating for designers and stakeholders starting from the description of individual cases: in fact, when home monitoring technology for aging in place is used appropriately, it can improve independence and quality of life, maintain the health and well-being of older adults, facilitate their engagement in everyday tasks, and support caregivers and healthcare professionals [16,17]. In this work, a combined approach integrating ambient sensors and wearable monitoring devices is associated with a network platform that gives access to caregivers, researchers, and third-party services to address the needs of older adults. For all of these reasons, this manuscript aims to assess two research questions: (1) to what extent usability and acceptance can impact a multicomponent platform intervention and (2) to what extent a multicomponent platform intervention improves well-being, quality of life, and self-efficacy in a sample of 25 older adults aged over 65 with a Mini-Mental State Evaluation (MMSE) [18] score between 21 and 27 after 21 days of non-supervised usage at home.

Therefore, this paper first describes the study design and the participants' interaction with the SAVE platform, then discusses the results obtained in terms of usability, acceptance, well-being, and self-efficacy, and finally offers food for thought for developers that aim to create products that meet the end users' needs [19], and could also be a source of inspiration for larger studies [6].

2. Materials and Methods

2.1. Study Design

This study involves the use of the SAVE platform for a total of 21 consecutive days. We recommended that the participants use the system every day and we checked the time of interactions through the SAVE cloud application. The research was managed by qualified personnel, who ensured both the supervision of the tests by specialists and the detailed measurement of the first interaction between the users and the prototype system. This personal guarantee also facilitated the training on the use of the technology. The study involved the use of a mixed-methods approach, in which both qualitative (open questions) and quantitative (standardized tests) data were collected in three different measurements: (1) at time 0 before the start of the experimentation (T0); (2) at time 1, after 10 days, i.e., at the midterm of the trial (T1); and (3) at time 2, after 21 days, i.e., at the end of the trial (T2). The log data of the usage of the SAVE system were continuously stored over the 21-day test period.

The study was approved by the Ethical Committee of Istituto di Ricerca e Cura a Carattere Scientifico, Istituto Nazionale Ricovero e Cura Anziani (IRCCS INRCA) and then registered on the platform ClinicalTrials.gov with the registration number NCT05626556.

2.2. Participants

The study involved 25 primary users who met the inclusion and exclusion criteria described in Table 1.

Table 1. Eligibility criteria for primary users.

End User Type	Inclusion Criteria	Exclusion Criteria
	- Age $\geq$ 65 years - Mini-Mental State Evaluation (MMSE) score between 21 and 27 - Healthy or mild-to-moderate chronic illness or musculoskeletal disease - Feel physically fit to participate in the study (assessment with FAC and Barthel index): sufficiently capable of moving, able to maintain and change their position, manipulate and move objects, move in their place of residence, experience the surrounding environment, and move by means of transport - Live alone or with a spouse - Interest in the project - Able to perform the tasks suggested by the caregiver - Able to use a smartphone and smartwatch - The presence of a caregiver	- Age < 65 years - MMSE < 21, subjects diagnosed with dementia or MMSE $\geq$ 28 or $\leq$20 - Participants suffering from severe chronic disease (e.g., symptomatic cardiovascular or respiratory disease, myocardial infarction, or stroke in the last 6 months or the presence of significant visual and/or auditory impairment, severe metabolic dysfunction, and oncological pathologies) or severe disability - Participants who are carriers of cardiac pacemakers or implantable defibrillators - The presence of conditions that make it difficult to use a smart device (e.g., moderate/severe dementia, aphasia, etc.) - A person placed under guardianship - Nickel allergy

The participants had an average age of 81.2 years and were represented by women at 64% and men at 36%. The majority of them (48%) were widowed, 44% were married, and 8% were single. A total of 44% of the seniors had a primary education level, 28% had a secondary education level, and 28% had a tertiary education level (university or further education). Approximately 44% of users live in the city, 40% live in a village, and 16% live in a county town. Approximately 92% of the participants are retired, whilst 8% are still working. Among the latter, more than half of users (52%) work full-time or are self-employed. Approximately 12% of participants report having family duties/obligations, e.g., taking care of grandchildren. The majority of the sample (52%) carries out leisure activities (e.g., dance, reading, or chess), and only 32% of users regularly exercise (e.g., walking or swimming).

The average MMSE score (25.6 ± 1.9) was between 21 and 27, a range that was predefined in the inclusion criteria. The average FAC score (4.8 ± 0.5) shows that the users have the ability to achieve autonomy in walking and the average BI score (19.1 ± 2.8) highlights that they have a fairly independent functional status, that is, the ability to perform normal daily activities required to meet basic needs and fulfill usual roles. Table 2 shows the users' characteristics.

Table 2. Users' characteristics.

	All Users (N = 25)
Age, mean ± sd	81.2 ± 6.8
Gender, n (%)	
Male	9 (36.0%)
Female	16 (64.0%)
Marital status, n (%)	
Married	11 (44.0%)
Single	2 (8.0%)
Widowed	12 (48.0%)
Education, n (%)	
Primary	11 (44.0%)
Secondary	7 (28.0%)
Tertiary	7 (28.0%)
Settlement, n (%)	
County town	4 (16.0%)
City	11 (44.0%)
Village	10 (40.0%)
Retired, n (%)	23 (92%)
Job, n (%)	
Full-time/Self-employed	13 (52.0%)
None	11 (44.0%)
NA	1 (4.0%)
Family duties, n (%)	3 (12.0%)
Leisure activities, n (%)	13 (52.0%)
Physical exercise, n (%)	8 (32.0%)
MMSE, mean ± sd	25.6 ± 1.9
FAC, mean ± sd	4.8 ± 0.5
BI, mean ± sd	19.1 ± 2.8

2.3. The Intervention

The concept of the SAVE system is that of a multi-component platform intervention based on multiple smart-home and wearable sensors streamed directly to a cloud-based platform, where algorithms detect any behavioral and physiological information about older adults' well-being and security in their habitat. This platform was developed under the framework of a European-funded project (EU Grant Agreement AAL-CP-2018-5-149), named SAfety of elderly people and Vicinity Ensuring—SAVE—by following a user-driven approach [20].

As shown in Figure 1, the SAVE solution consists of:

- A kit of sensors (Aqara Home) composed of 1 control unit, 1 smoke sensor (kitchen), 2 flood sensors (kitchen and bathroom), 1 contact sensor (entrance door), and 2 presence sensors;
- A smartwatch (Samsung Galaxy Watch3) with the SAVE software pre-installed (Version 1.0; Website: SAVE Web App (saveaal.eu). The smartwatch included a wide range of sensors, which could be used to measure physical activity (the number of steps and their frequency and the speed of movement), obtain some basic biological signals (e.g., pulse beat), provide an SOS service (call to the caregiver), and detect possible falls. This information was then used to assess the well-being of users;
- A SAVE Sensors Adapter.

All tools were connected to the SAVE cloud application.

The SAVE system was installed in end users' homes, by positioning all of the kits in the appropriate rooms and by offering relevant training to the end-users for using all of the different devices. The sensors were located in places where they do not affect the daily activity of the users, with them being easy to move according to preferences and small enough to blend into the background. Thus, at the end of the installation, the users had the Aqara Home System in their homes, a Samsung smartwatch, and a SAVE Sensors Adapter, all of which were connected to a router with unlimited Internet access.

After installing the system, a brief instruction training session on the use and purpose of these devices was performed. This ensured that the end users were encouraged to use them, and we performed some tests with them:

- Heart rate testing in association with the frequency indicated on the smartwatch;
- Testing the emergency system by pressing the power button 3 times;
- Testing of the flood and door sensors by visualizing the values received by the SAVE cloud app through the SAVE web app;
- Calling a friend/relative from their smartwatch.

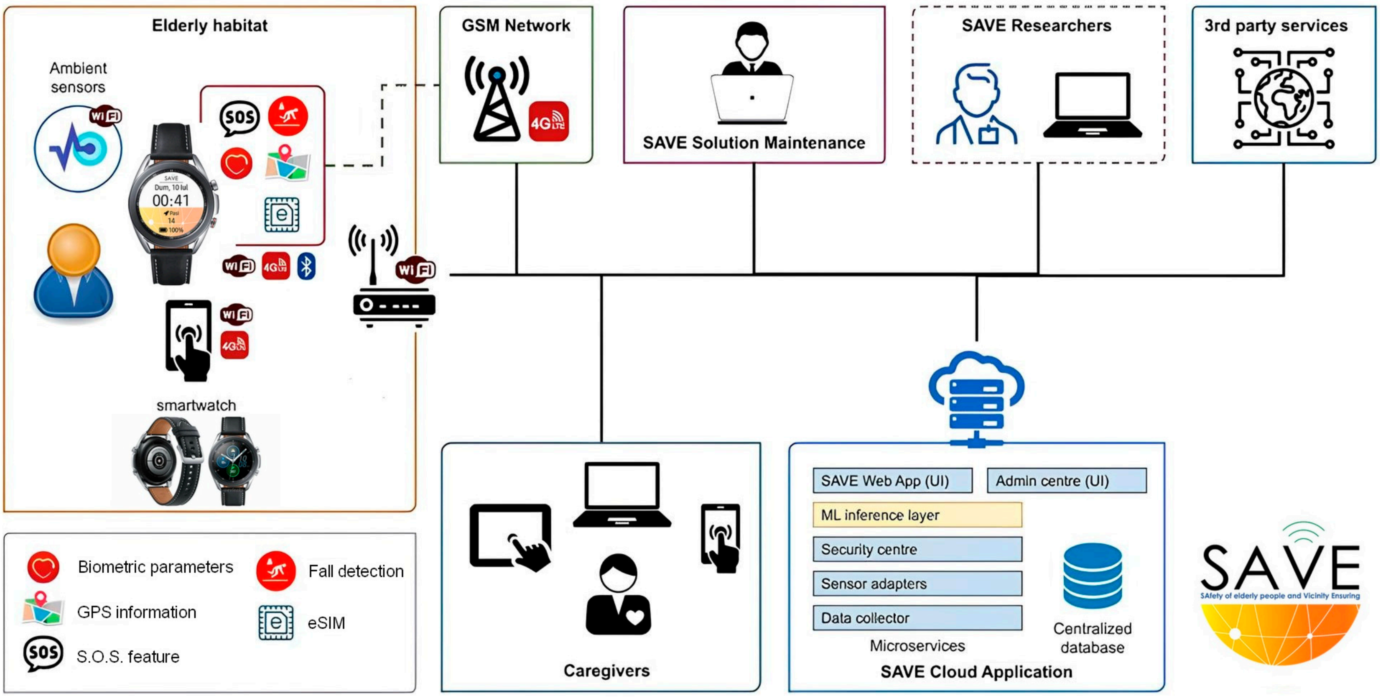


Figure 1. The SAVE multicomponent platform.

2.4. The Outcomes

The primary outcomes were:

Usability is understood as "the extent to which a product can be used by certain users to achieve certain goals with effectiveness, efficiency and satisfaction in a given context of use". This result was measured through the SUS scale [21] and the UEQ-S questionnaire [22].

Acceptance is the degree to which users come to accept and use a form of technology. This result was measured through the QUEST 2.0 scale [23].

The secondary outcomes were:

Well-being is understood as "a state of complete physical, mental and social well-being, and not simply as the absence of disease". This result was measured through the WHO-5 Index [24] and the EQ-5D-5L questionnaire [25].

Self-efficacy is understood as the set of beliefs we have about our ability to complete a certain task. This result was measured through the short version of the GSE self-efficacy scale [26].

2.5. Study Setting

The Istituto di Ricerca e Cura a Carattere Scientifico and Istituto Nazionale Ricovero e Cura Anziani (the IRCCS INRCA is located in the city of Ancona in Italy and the Laboratorio delle Idee is located in the town of Fabriano) managed the enrollment of users and data collection.

2.6. Data Collection

Data collection was started in August 2022 and finished in June 2023. Three different data collection tools were developed. Their details are reported in Table 3.

Table 3. Dimensions, scales, and timing of data collection.

Type of End Users	Dimensions	Scales	Time		
			T0	T1	T2
Primary users	Health and Wellness Condition	Mini-Mental State Examination (MMSE) [6]	X		
		Functional Ambulation Category (FAC) [27]	X		
		Barthel Index (BI) [28]	X		
		SF-12v2™ Health Survey [29]	X	X	X
		Five Well-Being (WHO-5) Index [24]	X	X	X
		EuroQol–5 Dimension–5 Level (EQ-5D-5L) [25]	X	X	X
	Self-efficacy	General Self-Efficacy Scale (GSE) [26]	X	X	X
	Usability and Acceptance	System Usability Scale (SUS) [21]		X	X
		User Experience Questionnaire (UEQ-S) [22]		X	X
		Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST 2.0) [23]		X	X
	Privacy and Stigma	Open questions	X	X	X

2.7. Data Analysis

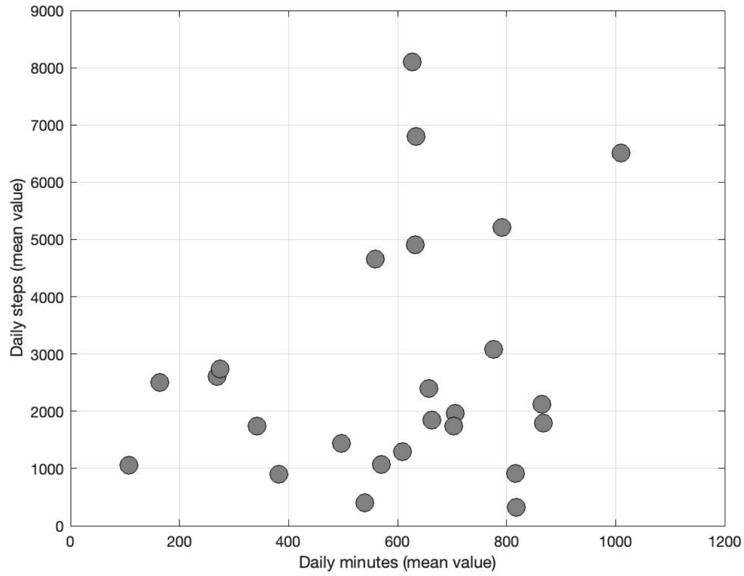
The users' characteristics were described by reporting the mean and standard deviation for continuous variables and the absolute number and percentage for categorical variables. The distribution of SF-12 domains, Who-5, GSE, and EQ-5D at baseline (T0) and at the end of the trial (T2) and the distribution of SUS and QUEST scores at the midterm of the trial (T1) and T2 are displayed together with the median and 95% confidence interval (95%CI). The User Experience Questionnaire (UEQ-S) was analyzed by using the Compare Scale Means for UEQ-S tool by Schrepp [30]. All other analyses were performed by using GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, CA, USA).

3. Results

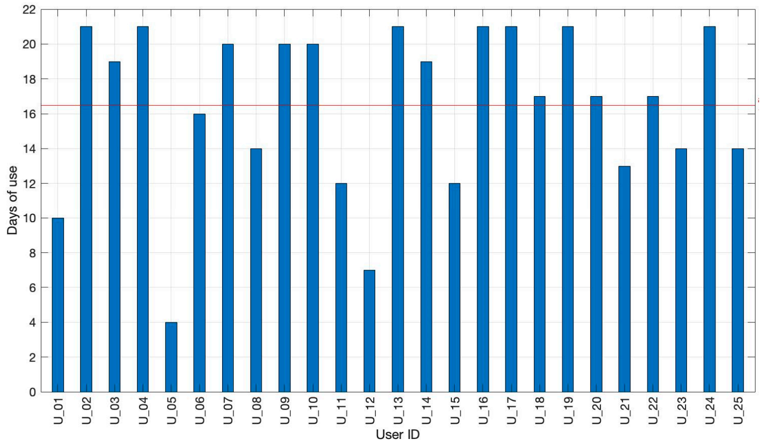
All data reported in the following subparagraphs are shown in Supplementary Table S1.

3.1. Smartwatch Usage

Figure 2a illustrates the relationship between the daily minutes of smartwatch usage and the average number of steps taken each day by Italian users. The majority of users do not exceed an average of 4000 steps per day, regardless of the duration of smartwatch usage. The average total daily steps taken by users is 2724 steps. The mean daily usage of the smartwatch corresponds to 595 min (9.9 h). Considering that the smartwatch requires daily charging (recommended for at least two hours, ideally overnight), the acceptability is high, with an average daily usage of 9.9 h. Figure 2b displays the total number of days of smartwatch usage for each user. The red line represents the average days of usage by all users, which is 16.5 days.



(**a**) Relationship between the daily minutes of smartwatch usage and the average number of steps taken each day by users. Circles represent the daily minutes of smartwatch usage and the average number of steps taken each day



(**b**) Average days of usage.

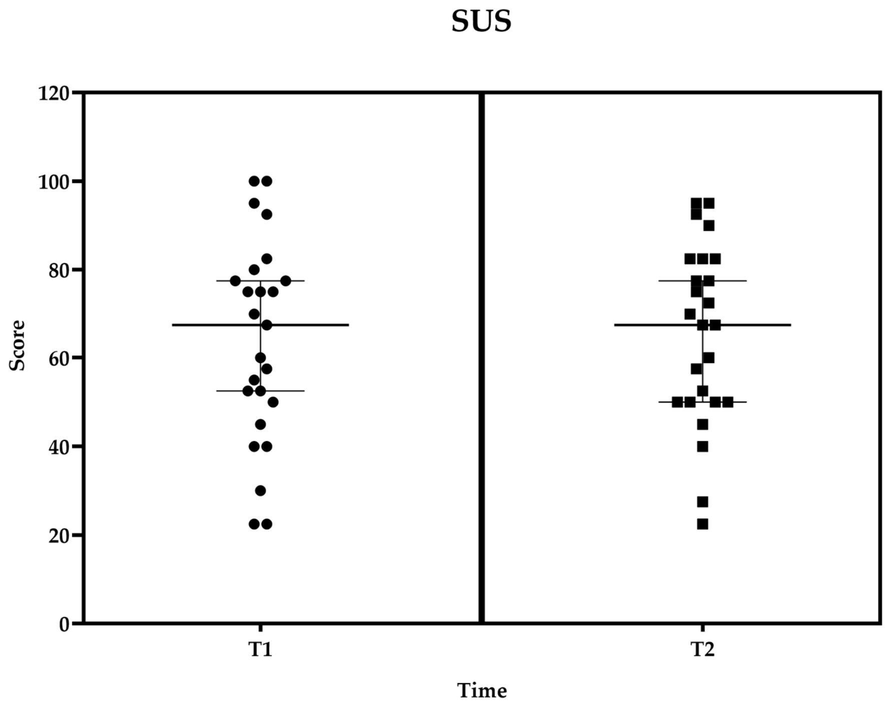
Figure 2. Correlation between the mean daily minutes of smartwatch usage and the mean daily number of steps taken by each Italian user (**a**) and the number of days of smartwatch usage for each user (**b**). The red line represents the average days of usage.

3.2. Usability and Acceptance

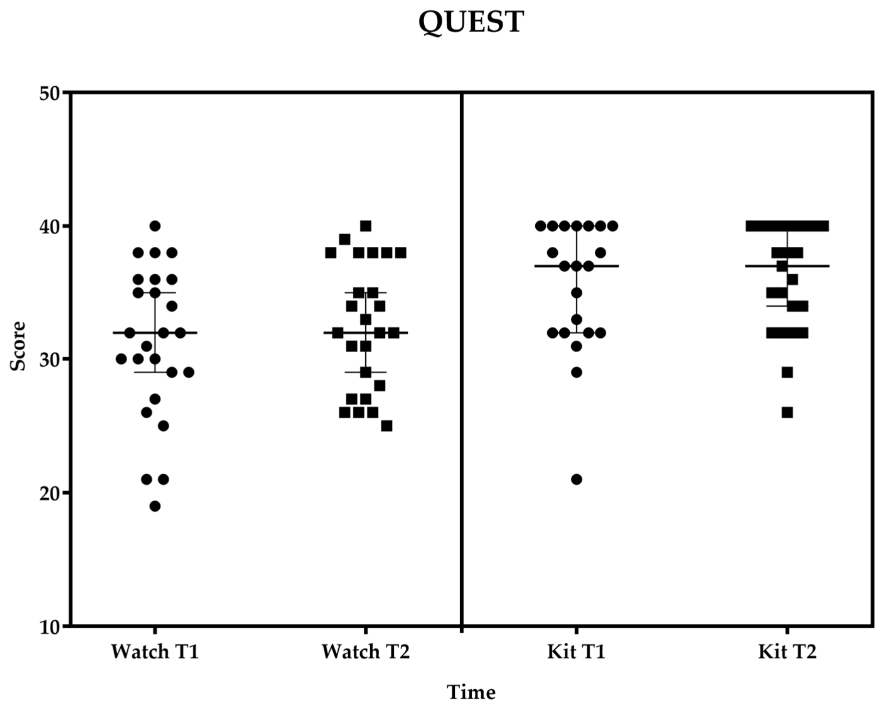
All participants successfully completed the SUS. The SUS is scored out of 100, with a higher score indicating greater perceived usability. As shown in Figure 3a, the system received a mean score of 63.8 ± 22.8 at T1 and 65.3 ± 20.4 at T2. These scores were compared and interpreted considering the acceptable average value of 68 (SD 12.5), which was determined for a variety of products and tools, including websites and technologies, provided by Sauro and Lewis [31], after the analysis of more than 5000 user scores encompassing almost 500 studies.

As shown in Figure 3b, the mean QUEST score for the smartwatch varied from 31.2 ± 5.7 at T1 to 32.5 ± 4.8 at T2, and, for the kit of sensors, from 35.4 ± 4.9 at T1 to 36.0 ± 4.1 at T2, indicating a level of 'quite satisfied' overall with the system.

As regards user experience, in Figure 4, different results were reported. The perspicuity (i.e., the ease of becoming familiar with the product), as well as the efficiency (i.e., the ability to solve tasks without unnecessary effort), increased over time. On the contrary, the dependability (the feeling of being in control of the interaction) and the stimulation (i.e., the motivation to use the product) remained stable, whereas the attractiveness (i.e., the overall impression of the product) and the novelty, that is, the power of the system to catch the interest of the users, decreased in the last period of usage.



(**a**) Distribution of the SUS score.



(**b**) Distribution of the QUEST score.

Figure 3. Distribution of SUS (**a**) and QUEST (**b**) scores for the smartwatch and kit of sensors at the midterm of the trial (T1) and T2 displayed together with the median and 95% confidence interval (95%CI). Boxes represent values at T2; Circles represent values at T0 or T1 as appropriated.

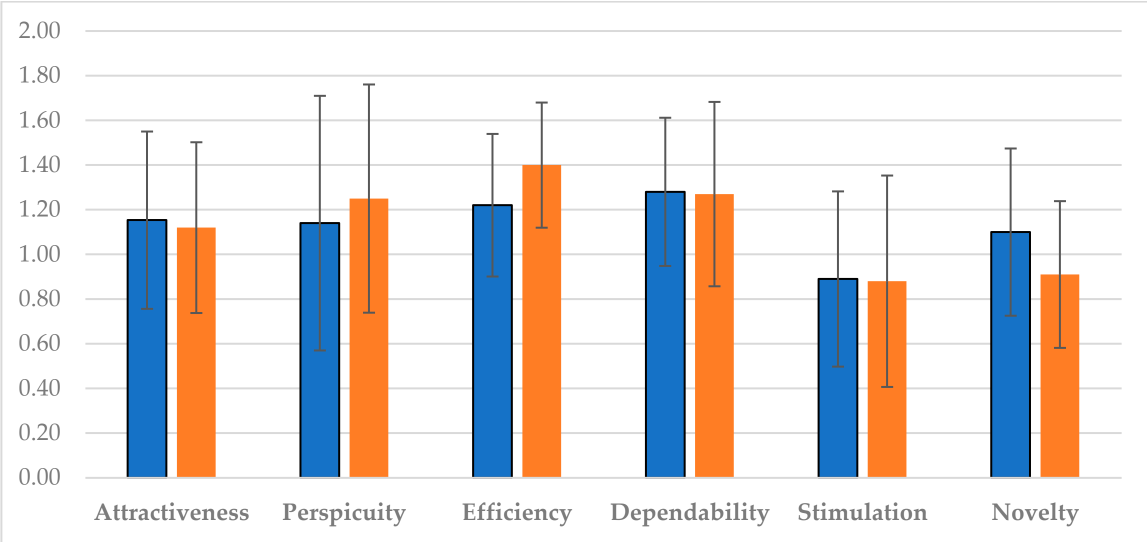
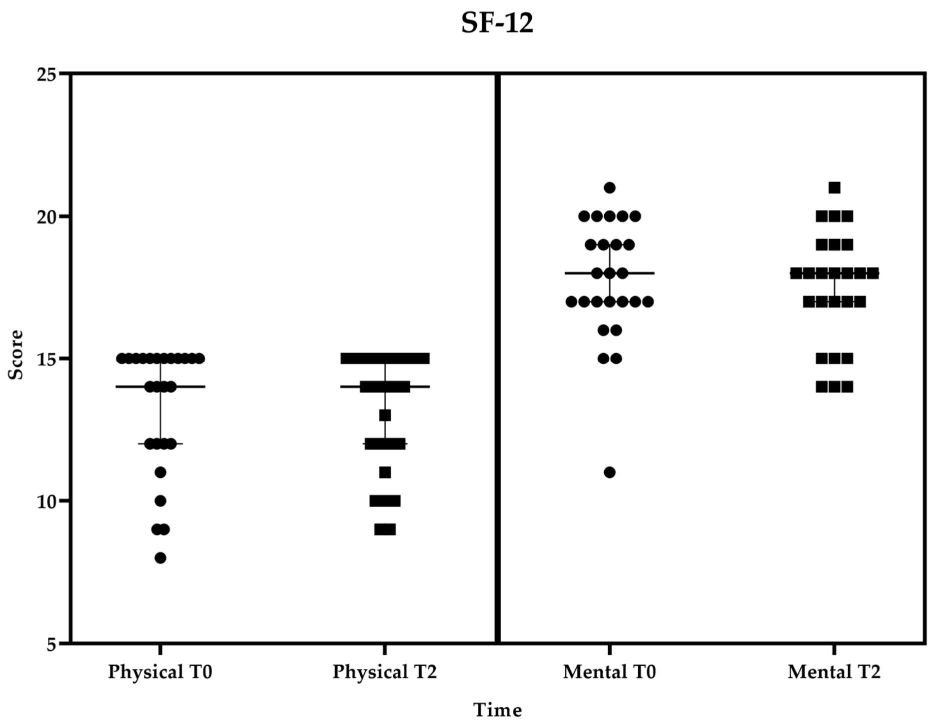


Figure 4. The user experience scale means and the corresponding 5% confidence intervals at T1 (blue color) and T2 (orange color).

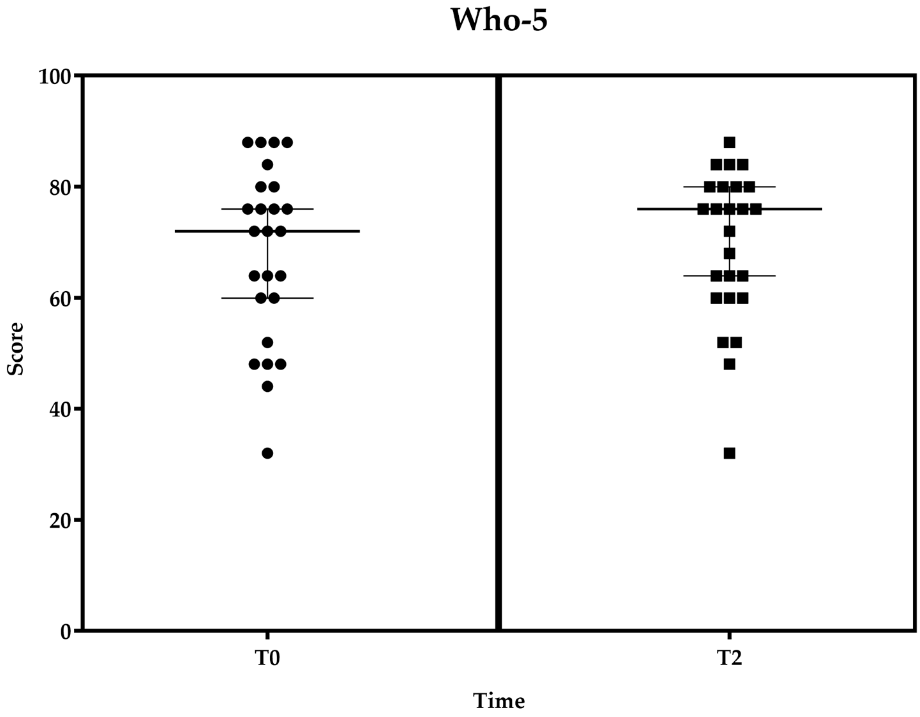
3.3. Well-Being and Self-Efficacy

As reported in Figure 5a, without any change in the perceived health status monitored through the SF-12, the state of complete physical, mental, and social well-being, as measured through the WHO-5 Index and the EQ-5D-5L questionnaires, slightly improved over the period, with it ranging from 68.0 ± 15.7 to 69.4 ± 13.7 in the case of WHO-5 (Figure 5b) and from 71.2 ± 13.5 to 74.0 ± 12.7 in the case of EQ-5D-5L (Figure 5c). Self-efficacy as the set of beliefs about the ability to complete a certain task was measured through the short version of the GSE self-efficacy scale, and it remained stable (Figure 5d).

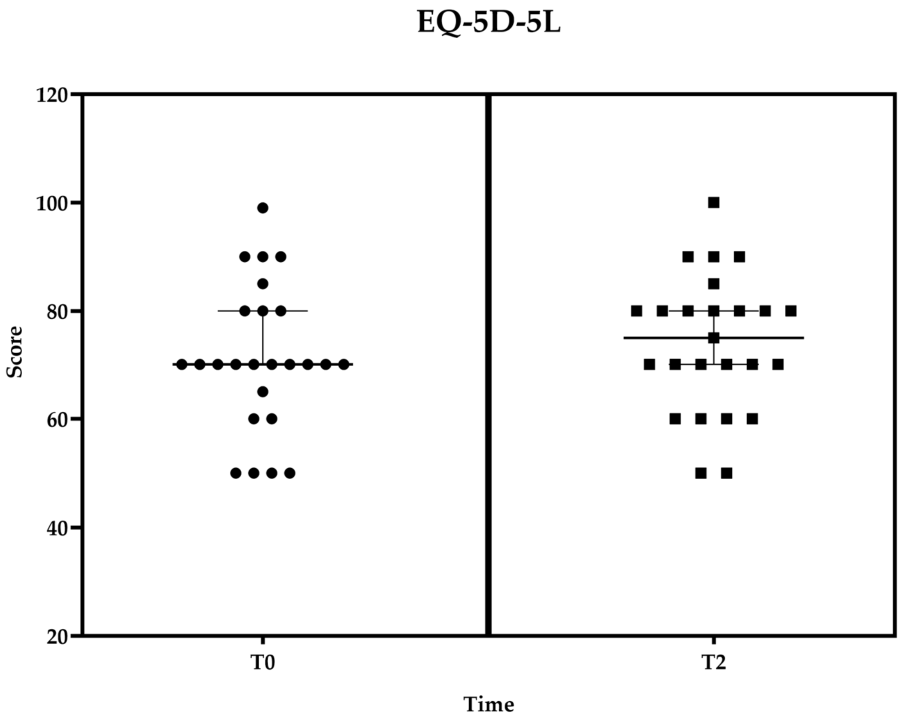


(**a**) Distribution of the SF-12 scores.

Figure 5. *Cont.*

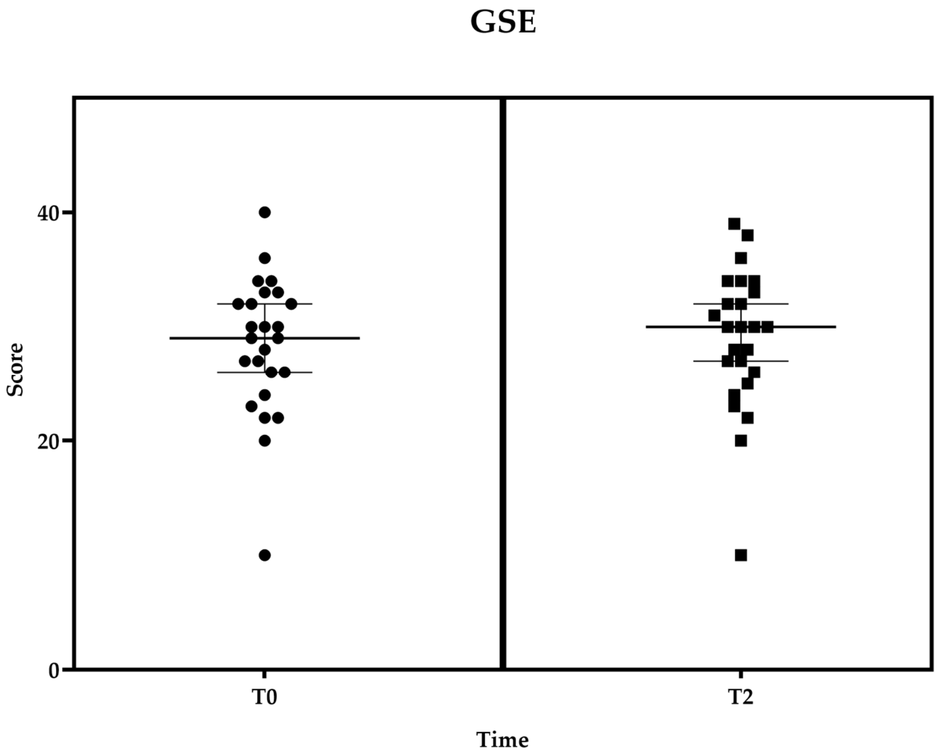


(**b**) Distribution of the WHO-5 scores.



(**c**) Distribution of the EQ-5D-5L scores.

Figure 5. *Cont.*



(**d**) Distribution of the GSE scores.

Figure 5. Distribution of SF-12 (**a**), WHO-5 (**b**), EQ-5D-5L (**c**), and GSE (**d**) at T1 and T2 displayed together with the median and 95% confidence interval (95%CI). Boxes represent values at T2; Circles represent values at T0 or T1 as appropriated.

4. Discussion

The purpose of this study was to assess the impact of a multicomponent platform intervention in terms of usability and acceptance as the primary outcomes and well-being, quality of life, and self-efficacy as the secondary outcomes in a sample of 25 older adults aged over 65 with a Mini-Mental State Evaluation (MMSE) [18] score between 21 and 27 after 21 days of non-supervised usage at home. Even if this study recruited users in the early stages of cognitive decline, they all used devices independently and were still able to manage routine changes, such as introducing novel technological tools into their daily lives [32]. Indeed, the participants involved in this study demonstrated a positive approach, they all provided useful feedback to facilitate the understanding of the data gathered, and only one participant withdrew from the trial. It is well known that for people living with cognitive decline, all novelties can produce distress. In this study, users benefited from general training on the correct use of the different system components (i.e., the smartwatch and kit of sensors) and were given two dedicated phone numbers to call for technical assistance or clarity of doubts related to the proper use of the system. As reported in the results, becoming familiar with such technology seems to be a good property to assure good usability, user experience, and acceptance outcomes. This finding is in line with other studies in which older adults appeared to be compliant with the use of innovative solutions [33]. In a recent scoping review [34], the key to matching the n needs and requirements of older adult users to ensure accessibility and usability is considered a priority in the design phase of any device. An in-depth understanding of users, their needs, and the contexts in which the systems are used are significant information to consider [2]. Effectively, in the reported study, this activity was carried out from the beginning in order to ensure the user-centered design [20].

The aging population is interested and competent in using these health technologies, especially wearables and portables [35], with the use of such technologies reaching an average of 829.85 min/day [36]. In our study, users reached an average of 595 min/day. Compliance may depend on the ease of use and the perceived benefits obtained by the use of technologies. This is true also with technology that is not at a high technology readiness level (TRL) as in the case of the SAVE platform, and this can demonstrate that the technology is ready for mainstream use as reported in other studies [15]. In particular, those technologies that keep track of and measure physiological parameters can be widely used and spread in the silver market. Unfortunately, as reported in the state-of-the-art literature, a difficult barrier to overcome is the poor experience of the majority of older adults in using this technology [2,34] which can be overcome by supporting users with dedicated assistance in case of need.

Literature research indicates that technology-based interventions that are appropriately designed can bring many benefits to older people, such as increasing independence, maximizing physical and mental health, and improving their quality of life [37], and the data collected through this study partially confirms this idea. This is probably due to a minimum time of exposition, 21 days, which did not engage the older adults for a long time to appreciate such benefits. Indeed, the methodological approach such as the design of the study presents challenges [6].

Limitations of the Study and Future Directions

The first limitation of this study concerns the readiness level of the technology used which may have impacted the results. Even if the TRL was low, it was in line with a recent systematic review [9] that lists a huge number of studies in the field that are still in the development and testing phase (TRL5) or in the demonstration phase, pilot phase, and prototypical system validation (TRL6). Another limitation is related to the small sample size enrollment, gender disparities, and the specific Italian national context and culture which could be seen as a bias that does not allow for the generalization of the results. Also, the limited time of usage of the system is a limitation; in the specific case of this study, this was due to the time and cost boundaries of a funded research project. By the way, longer trials are needed to measure changes in user experience and familiarity with the system. Furthermore, sharing the strengths and weaknesses of research is fundamental for building common knowledge from previous studies. New technologies are reaching great utility in helping to maintain health and self-care more and more, independence, and autonomy to maintain or increase individuals' quality of life [2]. Technology-based interventions seem to focus on a single domain of intervention (physical, cognitive, mental, emotional, etc.) rather than approach the multinational promotion of health [34]. Focus on such a multidimensional approach could increase the necessary availability of evidence to move the actual debate one step forward. This study holds significant implications, especially for those individuals invested in the development of technologies designed to provide support and monitoring for seniors facing cognitive decline. It markedly emphasizes the prospect of progressing towards an approach that encompasses the integration of sensors and multi-component strategies, all while adhering to stringent criteria regarding acceptability and usability. This suggests that future initiatives in the field could benefit from the approach outlined in the study, which focuses on harmonizing advanced technical functionalities with attention to practicality and acceptance among elderly users.

5. Conclusions

This study aimed to evaluate the usability and acceptance of a multi-component platform intervention by 25 users living with cognitive decline. It demonstrated the ability of target users to use technology independently in their home environment. Overall, the participants shared good engagement with the integrated system. Despite limitations, this study strengthens the idea that gerotechnology is ready for mainstream use and it would offer food for thought for developers who design products for the aging population or could be used as a source of inspiration for larger studies. These kinds of devices have enormous potential to ensure better care and an improved sense of security and quality of life for older adults [3]. Indeed, in the last decade, digital healthcare technologies have rapidly grown in diagnostics, therapy, assistance, epidemiology, and other sectors [38], but, as demonstrated by this study, when such tools match the older population market, different barriers must be considered. In this study, we focused on usability and acceptance, and we also mentioned the lack of knowledge on how to use and benefit from technology [4,5]. Even if the demographic trends will solve the e-health literacy issue and maybe legal and safety concerns will also be solved [39], the largest studies and strongest cooperation among sectors (i.e., technology, health and care, research, policy, and social sectors) still remain vital to proof the real impact of technology in the healthcare field.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare11243102/s1. Table S1: Baseline characteristics and test scores before the start of the experimentation (T0), at the midterm of the trial (T1), and at the end of the trial (T2) of the users.

Author Contributions: Conceptualization, V.S. and M.R.; methodology, V.S. and A.A.M.; software, D.M.K.; data curation, M.d.R.; writing—original draft preparation, V.S. and M.R.; writing—review and editing, E.F., G.C., L.P., S.P., A.R., S.-A.M., A.A.M., D.M.K., A.M., M.A., L.A., and M.d.R. supervision, V.S. and M.R.; project administration, S.-A.M. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was carried out in accordance with the EU Regulation No. 679 of the European Parliament and of the Council of 27 April 2016 and the Helsinki Declaration (2013). The research protocol was approved in Italy by the Ethic Committee of IRCCS INRCA on 31st March 2022 with approval number 0015579. The clinical trial was registered on the platform ClinicalTrials.gov with the registration number NCT05626556.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available in the article itself.

Conflicts of Interest: The authors declare no conflict of interest.

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Beyond Hypoglossal Hype: Social Media Perspectives on the Inspire Upper Airway Stimulation System

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Abstract: In the landscape of sleep surgery, the Inspire® Upper Airway Stimulation (UAS) device has gained prominence as an increasingly popular treatment option for obstructive sleep apnea, prompting significant discourse across social media platforms. This study explores the social media narrative of the UAS device, particularly the nature of multimedia content, author demographics, and audience engagement on Instagram, Facebook, and TikTok. Our analysis encompassed 423 public posts, revealing images (67.4%) and videos (28.1%) as the dominant content types, with over a third of posts authored by physicians. A notable 40% of posts were advertisements, whereas patient experiences comprised 34.5%. TikTok, although presenting a smaller sample size, showed a substantially higher engagement rate, with posts averaging 152.9 likes, compared with Instagram and Facebook at 32.7 and 41.2 likes, respectively. The findings underscore the need for otolaryngologists and healthcare professionals to provide clear, evidence-based information on digital platforms. Given social media's expanding role in healthcare, medical professionals must foster digital literacy and safeguard the accuracy of health information online. In this study, we concluded that maintaining an evidence-based, transparent digital dialogue for medical innovations such as the UAS device necessitates collaborative efforts among physicians, health institutions, and technology companies.

Keywords: sleep apnea; obstructive; electric stimulation therapy; social media; health communication; patient education as topic; telemedicine; implantable neurostimulators; hypoglossal nerve

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1. Introduction

Upper airway stimulation (UAS) has been a breakthrough technique in the domain of sleep surgery for the treatment of obstructive sleep apnea (OSA) [1–5]. Once a novel approach, it has rapidly ascended in popularity, transforming from an innovative technique to a mainstay in sleep surgery clinical practice. UAS, also known as hypoglossal nerve stimulation, represents a novel therapeutic approach to obstructive sleep apnea, particularly in patients who struggle with continuous positive airway pressure (CPAP) therapy. This treatment involves the surgical implantation of a device that stimulates the hypoglossal nerve, which controls tongue movements. By targeting this nerve, UAS prevents the tongue from collapsing backward during sleep, thereby maintaining an open airway. The device's activation is timed with the patient's breathing cycle, ensuring that airway obstruction is minimized during sleep. This approach offers a less invasive alternative to traditional OSA treatments, focusing on improving sleep quality and reducing apnea events.

The rapid rise of this procedure and its recognition by both the medical community and the lay public can be seen in the influence of social media on disseminating healthcare information. With the contemporary patient being more connected than ever, healthcare information exchange, particularly via social media, has reached unprecedented levels [6–9]. However, this increasing reliance on social media as a primary source of health-related information brings forth a surfeit of concerns [10]. Despite its growing acceptance in the medical community, the procedure remains in its nascent stages, with long-term outcomes still under investigation [1,4,11]. As the boundary between authentic medical advice and influencer-led endorsements becomes increasingly blurred on social platforms, the responsibility of physicians to convey accurate, evidence-based information intensifies [10,12,13].

Social media's integration into the fabric of modern healthcare communication presents both opportunities and challenges [7,14]. While social media platforms offer a vast, accessible arena for healthcare discourse, they also create avenues for misinformation, partial information, and biased narratives. This phenomenon is especially pronounced in the case of new medical technologies like UAS, where public understanding is still evolving. Consequently, there is a critical gap in understanding the nature and impact of social media narratives on UAS. Our research aims to fill this gap by systematically analyzing the portrayal of UAS on key social media platforms. By doing so, we seek to provide insights into the current digital discourse surrounding UAS, identify prevalent themes and narratives, and assess their potential impact on patient perceptions and decision-making. This study is particularly pertinent given the increasing reliance of patients on social media for healthcare information and healthcare professionals' need to navigate and influence these digital conversations effectively [15–18]. Thus, our investigation not only illuminates the current state of social media discussions on UAS but also can guide future strategies for accurate and ethical health communication in the digital age.

Recent years have seen a burgeoning interest in analyzing social media content to gauge public perception of various medical procedures. Previous studies have analyzed posts related to various surgical conditions and procedures, such as sinus surgery, pediatric scoliosis, and hip arthroscopy [19–21]. Similarly, research by other authors in areas such as pediatric tonsillectomy, rhinoplasty, and cochlear implants has emphasized the role of social media in shaping patient expectations and experiences [22–24], revealing a trend towards patient-authored narratives and educational content. This trend toward patient-centric narratives and the educational role of social media aligns with our investigation into the Inspire® UAS device, suggesting a common theme across different medical domains. OSA remains a relatively underexplored area in otolaryngology social media research.

In this study, we investigated the portrayal and reception of UAS on three of the most popular social media platforms, Instagram, TikTok, and Facebook, highlighting the influence of digital discourse on patient understanding. In examining the digital narratives surrounding UAS technology, we aimed to emphasize the physician's potential role in ensuring accurate and balanced online health communication. Moreover, we addressed potential gaps or misconceptions about UAS prevalent on social media, underscoring the imperative of an authentic and comprehensive representation of emerging medical technologies in the digital domain.

2. Materials and Methods

This investigation employed a mixed-methods research design, incorporating both qualitative and quantitative data collection methods. We systematically gathered public data from three prominent social media platforms: Instagram, Facebook, and TikTok. Quantitative data included engagement metrics such as likes, shares, and comments, while qualitative data encompassed thematic analyses of post content and authorship demographics. The research pivoted around five predefined search terms: #inspiresleep, #inspiresleepapnea, #inspiresleepapneaimplant, #hypoglossalnervestimulator, and #lifewithinspire. These search terms were neither sponsored nor designed by industry but were chosen by the authors given that these hashtags yielded the highest number of posts at the time of investigation. Data was collected over a defined span from April 2018 to April 2023 by four independent investigators. Posts that bore no relevance to the Inspire® UAS device or were written in non-English languages were excluded. Since this research hinges on publicly accessible social media content, it was deemed exempt from Institutional Review Board (IRB) approval per the extant guidelines of the IRB at our affiliated institution.

2.1. Multimedia Classification

Posts sourced from these platforms were systematically categorized based on their intrinsic multimedia elements: image, video, or text. Instagram accommodates either image or video uploads, TikTok specializes exclusively in video content, whereas Facebook allows users to post images, videos, or text.

2.2. Authorship Demographics

We thoroughly examined publicly available user profiles to determine the authorship of each post (Table 1). This process included assessing profile information, historical content, and any affiliations or disclosures provided within the account. This analysis enabled us to categorize authors into groups such as Inspire®'s official representatives, individual patients, family members of patients, practicing physicians, and other relevant categories. In cases where a patient created a post, classification was based on the user's self-identification and the content's context, indicating personal experiences or testimonials related to UAS. For posts potentially serving marketing purposes, we looked for indicators such as promotional language, links to commercial sites, or explicit affiliations with the Inspire® company (Golden Valley, MN, USA) or other commercial entities. This methodology, while relying on information made publicly available by users, provided a framework to categorize each post's origin accurately and assess the nature of its content.

Table 1. Classification and descriptions of social media post topics related to Inspire® Sleep Apnea.

Inspire® Social Media Post Topics	
Subject	**Description**
Inspire®	• Official posts from the company, often involving new research findings, advancements in therapy, patient success stories, or announcements about events such as webinars and conferences.
Patient	• Personal testimonials and experiences. These range from the initial diagnosis of sleep apnea and the decision to use Inspire® to the journey of adjustments and eventual improvement in sleep quality.
Patient's Family	• Observations and reflections from family members, noting the difference in their loved one's energy levels, mood, and overall well-being post-treatment.
Physicians	• Clinical insights and observations. This encompasses discussions about the efficacy of Inspire®, comparison to other treatments, or even patient recovery anecdotes.
Non-Physician Healthcare Providers	• These posts offer a unique perspective from healthcare providers who are not physicians but still interact with Inspire® patients. They discuss post-operative care, common questions they receive, or general feedback on the device.

Table 1. *Cont.*

Inspire® Social Media Post Topics	
Subject	**Description**
Media Outlet	• Posts highlighting the appearance of Inspire® in popular media. This includes articles, documentaries, interviews with patients or medical experts, and any other media feature.
Professional Organization	• Discussions or endorsements from reputed medical associations or groups. These posts focus on the technical aspects of the therapy, research collaborations, or recommendations for usage.
Academic Institution	• Posts from research institutions studying the effectiveness of Inspire®. These range from clinical trial announcements, research findings, or even student experiences working with Inspire® patients.

2.3. Subject Categorization

The content elicited from these platforms underwent thematic segregation and was delineated into four overarching paradigms: advertisements, educational posts, patient experience, and media coverage. These subjects were defined as:

- **Advertisement**: Strategically oriented posts promoting the Inspire® device, affiliated medical procedures, or ancillary resources.
- **Educational**: Scholarly content delving deep into the device's mechanism, indications, therapeutic potential, or expansive knowledge pertinent to the Inspire® Sleep Apnea Hypoglossal Nerve Stimulator.
- **Patient Experience**: In-depth chronicles delineating subjective encounters with the Inspire® device, encompassing both the procedure and post-procedural experiences.
- **Media Coverage**: Analytical content highlighting the portrayal of or discourse on the Inspire® modality within the broader media echelons, encapsulating news, documentaries, and similar channels.

2.4. Engagement Metrics

Engagement metrics, primarily the number of 'likes', were used to indicate audience interaction and post popularity. The 'likes' count, being a direct and quantifiable measure of engagement, offered a straightforward method to compare the impact of posts across different platforms. Although 'shares' and 'comments' were also considered, these metrics were not uniformly available or quantifiable across all platforms, limiting their utility in our analysis. For instance, while Facebook and Instagram display the number of shares a post receives, TikTok does not. Thus, our engagement analysis focused predominantly on the 'likes' metric, supplemented by qualitative observations of comments where available.

2.5. Data Collection Standards

We utilized a rigorous, standardized data collection guideline to ensure consistency and reliability in our data collection process (see Supplemental Materials). This guideline included detailed procedures for identifying relevant posts, classifying multimedia elements, determining authorship, and categorizing post subjects. It also provided clear definitions and examples for each category and variable, aiming to minimize subjective interpretation and enhance the objectivity of the data collected. This standardized approach was crucial to maintaining the integrity of our mixed-methods research methodology.

3. Results

This study included 423 social media posts related to UAS and the Inspire® UAS device extracted from three platforms (Table 2). Instagram was predominant, yielding 308 posts. This was followed by Facebook and TikTok with 92 and 23 posts, respectively.

Table 2. Distribution of Inspire® social media data by platform, type, author, subject, and popularity.

Inspire® Social Media Data					
		n (%)			
Platform		Instagram	Facebook	TikTok	**Total**
	Included Posts	308	92	23	**423**
Type					
	Image	221	64	0	**285 (67.4)**
	Video	87	9	23	**119 (28.1)**
	Text	0	19	0	**19 (4.5)**
Author					
	Inspire®	99	22	0	**121 (28.6)**
	Patient	72	20	15	**107 (25.3)**
	Patient's Family	4	0	0	**4 (0.9)**
	Physicians	109	20	7	**136 (32.2)**
	Non-Physician Healthcare Providers	15	12	0	**27 (6.4)**
	Media Outlet	1	3	0	**4 (0.9)**
	Professional Organization	2	5	1	**8 (1.9)**
	Academic Institution	6	10	0	**16 (3.8)**
Subject					
	Advertisement	133	34	2	**169 (40.0)**
	Educational	73	23	8	**104 (24.6)**
	Patient Experience	101	32	13	**146 (34.5)**
	Media Coverage	1	3	0	**4 (0.9)**
Popularity	Mean Likes Per Post	32.7	41.2	152.9	**41.1**

3.1. Multimedia Classification

Content dissemination based on media type indicated images as the prevalent format, accounting for 67.4% (285/423) of the posts. Videos constituted 28.1% (119/423) of posts. Text-only posts were exclusively found on Facebook, making up 4.5% (19/423) of the total.

3.2. Authorship Demographics

Physicians were the predominant authors in this cohort, contributing 32.2% (136/423) of the posts (Figure 1), with 28.6% (121/423) of the posts originating from the Inspire® company itself. Patients additionally represented 25.3% (107/423) of posts. Other contributors included non-physician healthcare providers, academic institutions, professional organizations, and media outlets.

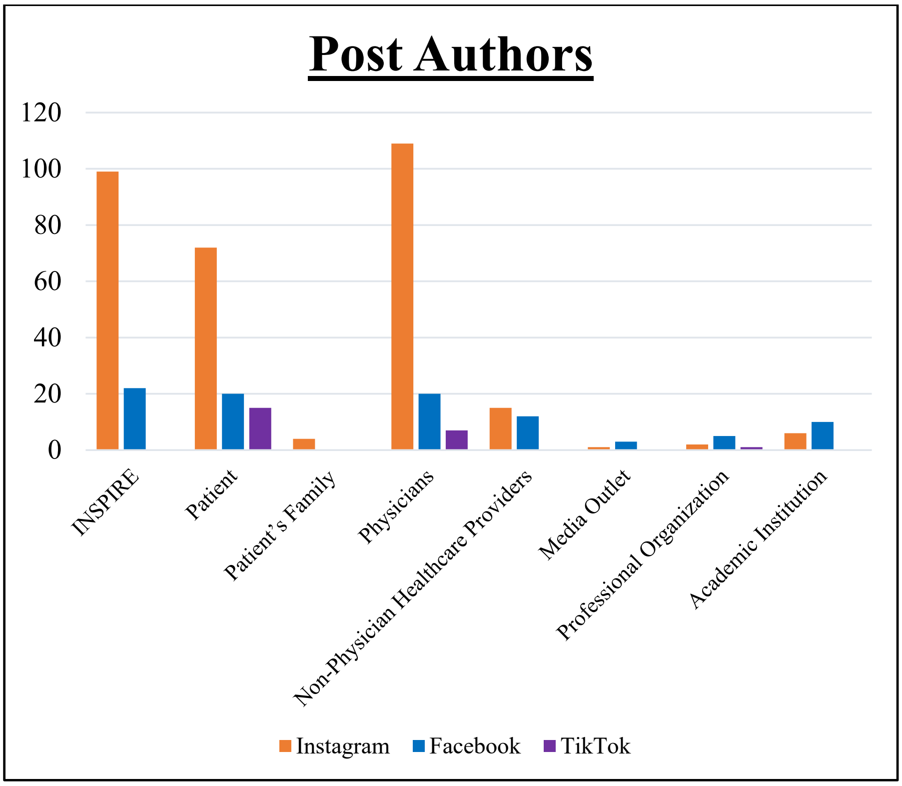

Figure 1. Social media post authors: Bar graph illustrating the distribution of social media post authors across platforms, highlighting a prominent presence of physicians, especially on Instagram.

3.3. Subject Categorization

Advertisements formed 40.0% (169/423) of the posts (Figure 2). Patient experiences made up 34.5% (146/423) of the content. Educational posts constituted 24.6% (104/423) of posts. Out of the Inspire® company's 121 posts, 79.3% (96/121) of posts were classified as advertisements, 9.1% (11/121) were educational posts, and 7.4% (9/121) were lifestyle-oriented posts.

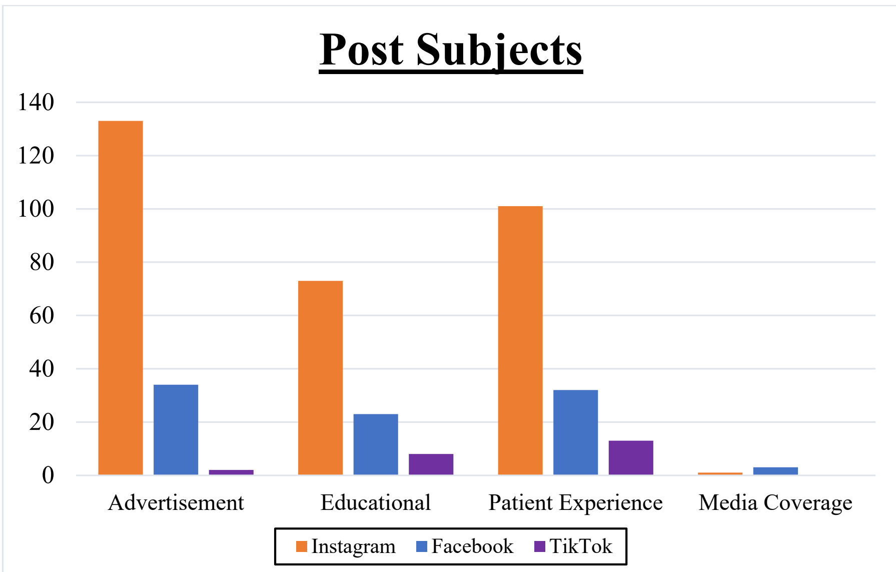

Figure 2. Social media post subjects: Graphical representation comparing subjects of social media posts across platforms, showcasing a high prevalence of advertisement and patient experience posts.

3.4. Engagement Metrics

Engagement, as gauged by mean likes per post, portrayed TikTok as the platform with the highest user interaction, averaging 152.9 likes per post (Figure 3). By contrast, Instagram and Facebook demonstrated mean likes of 32.7 and 41.2 per post, respectively. Overall, the mean likes across all platforms stood at 41.1. TikTok posts demonstrated a significantly greater mean number of likes than posts from either Facebook or Instagram ($p < 0.05$). Posts written by patients garnered 133.7 likes per post, the highest of any author. By contrast, posts authored by physicians had 24.1 likes per post, and those made by the Inspire® company averaged 27.5 likes per post.

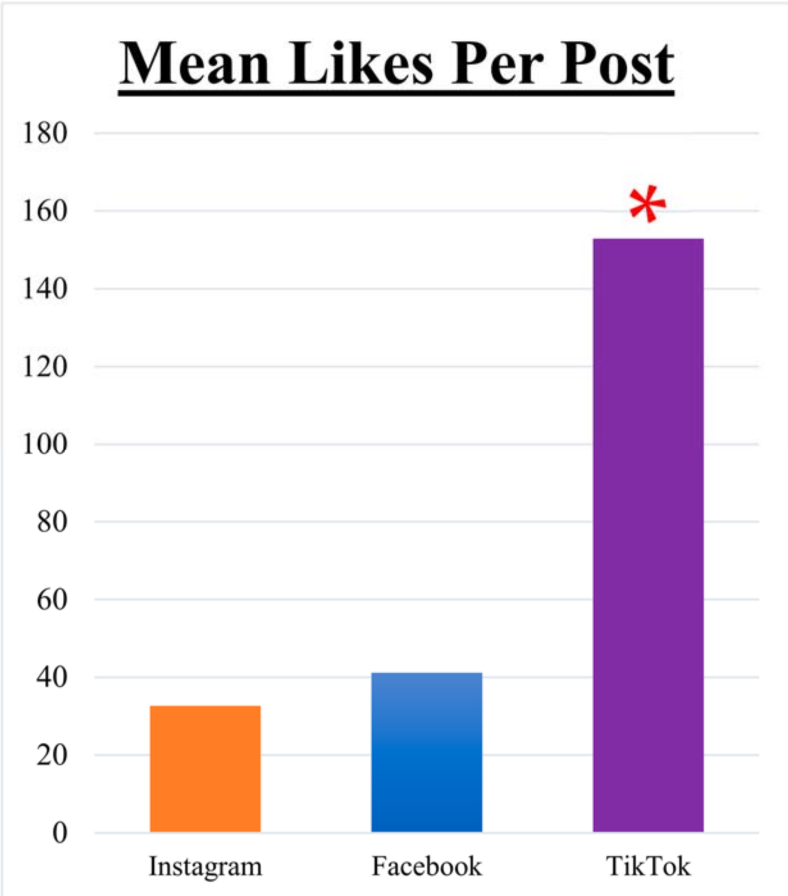

Figure 3. Mean likes per post: Bar graph depicting the Mean Likes Per Post for Inspire® Sleep Apnea content. Note that the red asterisk (*) indicates a significantly greater mean number of likes per post on TikTok than on Instagram or Facebook.

3.5. Hashtag Analysis

Posts tagged with #hypoglossalnervestimulator predominantly originated from formal entities such as the Inspire® company, physicians, or academic institutions, with an absence of this hashtag among patient posts. Furthermore, this hashtag garnered fewer likes compared to others. Multiple hashtag utilization within a single post was a common observation. The hashtag #inspiresleep was especially potent, resulting in the highest retrieval of posts related to the study's focus. Notably, 94.1% (96/102) of posts utilizing the hashtag #lifewithinspire were made by the Inspire® company.

4. Discussion

The Inspire® Upper Airway Stimulation (UAS) device has been a focal point of discussion in sleep apnea and sleep surgery literature, as hypoglossal nerve stimulation has gained traction as a popular option for surgical management of OSA [25–27]. The device has been commonly advertised on platforms such as television, radio, and social media, the latter of which physicians have assumed a proactive role, with 32.2% of all posts related to the UAS device being written by physicians. This substantial physician engagement is a deviation from other otolaryngologic procedures and diagnoses such as tympanostomy tubes, cochlear implants, and laryngectomy, where physicians' online participation has been significantly less [24,28,29]. This finding may suggest a growing recognition among the medical community about the benefits of the Inspire® UAS device and a desire to spread awareness to the public of its potential in sleep medicine [1,2,30].

In this study, TikTok greatly eclipsed the other platforms in user engagement with an average of 152.9 likes per post, compared with 32.7 and 41.2 likes per post for Instagram and Facebook, respectively. This finding underscores TikTok's potential burgeoning influence on healthcare conversations [31–33]. Further highlighting this trend is that patient-authored narratives garnered the highest average likes across posts. Such profound engagement with firsthand patient experiences may suggest an evolving appetite among the audience for genuine, personal insights into medical interventions while emphasizing the increasing role of newer social media platforms in shaping medical narratives. However, it is important to approach these findings with caution. TikTok's significant lead in engagement metrics may be influenced by its relatively low volume of posts in our study, which could amplify the impact of individual posts on the platform's average engagement figures. This fact necessitates careful consideration of the data, as a smaller sample size might not fully represent broader user interactions and may lead to overestimations of engagement levels.

Our study findings regarding the digital discourse surrounding the Inspire® Upper Airway Stimulation (UAS) device aligned with and expanded upon the existing literature examining social media's role in healthcare communication [6,17,34–36]. Our mixed-methods approach, combining both quantitative and qualitative data collection, provided a comprehensive understanding of the online narrative. Moreover, applying a rigorous, standardized data collection guideline also contributed to the robustness of our findings by ensuring the consistency and reliability of our analyses. The significant engagement of both physicians and patients in the social media discussion about UAS reflects trends observed in similar studies. For instance, prior analyses of social media narratives concerning other otolaryngologic procedures such as rhinoplasty, tympanostomy tubes, cochlear implants, and tonsillectomy revealed a pattern of diverse patient perspectives, mirroring our findings [22,23,29]. However, our study distinguishes itself by focusing on an emerging technology in sleep surgery, thereby contributing unique insights into how nascent medical innovations are discussed and perceived online. Furthermore, the predominance of advertisements in our study resonates with Moffatt et al. and Lahaye et al., who also reported a significant commercial presence in social media discussions on laryngectomy and new-age rhinology devices [28,37]. This observation underscores the increasing role of commercial interests in shaping public perceptions of medical technologies, a trend that necessitates a critical approach to evaluating online health information.

The high level of engagement on newer platforms like TikTok, as noted in our study, reflects a broader shift in digital health communication strategies [38,39]. Studies by Ramkumar et al. on shoulder and elbow surgery, cellular therapy, and joint arthroplasty using social media also highlighted the platform-specific dynamics of patient engagement and information dissemination [40–42]. Our research contributes to this discourse by emphasizing the significant impact such platforms have on shaping patient understanding and expectations, especially for novel treatments like UAS. Moreover, similar to Hairston and Haeberele's studies, which analyzed parental perspectives on pediatric tonsillectomy and patient perceptions of hip arthroscopy [20,23], our research highlights the evolving nature of patient narratives on social media. These narratives, as evidenced in our study, often focus on personal experiences and insights, providing a valuable, albeit subjective, view of patient journeys and satisfaction with medical interventions like UAS. Considering these parallels and distinctions in the existing literature, our study underscores healthcare professionals' need to engage proactively in digital spaces [43,44]. By contributing accurate, evidence-based information, physicians can help balance the narratives shaped by commercial interests and patient anecdotes. This approach is vital in ensuring that patients receive a comprehensive view of new medical technologies, aiding in informed decision-making.

While the active engagement of patients and physicians on social media underscores the increasing universal accessibility of healthcare discussions, ensuring the accuracy and integrity of disseminated information can be challenging [16,45,46]. The predominant role of advertisements and patient narratives emphasizes the need for a balanced portrayal, encompassing both the merits and potential risks of the UAS device. The distinct dynamics observed across platforms, particularly TikTok's ascendant influence, reflect a generalized shift in modern healthcare communication strategies. Physicians, as primary stakeholders and trusted voices, are encouraged to guide these narratives, ensuring that they remain both informative and evidence-based while resonating with the evolving digital milieu of their audience [8,47,48].

While several studies have examined various aspects of otolaryngology on social media [19,23,24,28,29,37,49], the presence of UAS on social media has not been thoroughly studied. In a 2021 study, Xiao et al. evaluated the usefulness and informativeness of YouTube videos for patients concerning UAS for OSA [50]. They found that many of these videos lacked comprehensive and quality information on the subject. Although YouTube is a popular source of information for patients, YouTube videos on UAS were considered insufficient in many content areas. Given the increasing demand for information among both the medical and lay public regarding UAS, there must be more high-quality and comprehensive resources for patients seeking knowledge on this topic.

In the age of information ubiquity, medical data sources play a pivotal role in determining its legitimacy and consequent patient actions. Given the substantial traction of advertisements and patient narratives on the Inspire® UAS device on social media, there is a pressing need to address digital trust and literacy [51,52]. Patients, when met with an influx of diverse information, must be able to discern evidence-based content from anecdotal accounts or commercial promotions. Likewise, physicians, as stewards of accurate health communication, should be equipped with the knowledge to evaluate and curate content in the vast digital expanse [53,54]. The challenge transcends content generation and helps foster a digitally literate audience that approaches online medical data with informed skepticism and critical engagement. This goal necessitates a multipronged approach, where physicians, medical institutions, and tech platforms collaborate to fortify the integrity of online medical narratives, ensuring they resonate truthfully within the rapidly evolving digital ecosystem.

The digital landscape presents both opportunities and challenges for sleep medicine practitioners. Given the potent influence of platforms like TikTok, sleep medicine specialists are encouraged to embrace these platforms proactively, promoting the emergence of authoritative, evidence-based narratives. A set of best practices could assist physicians in creating transparent content, distinguishing between patient anecdotes, research-backed findings, and commercial promotions. Collaborations with tech platforms could be explored to devise algorithms prioritizing verified medical information, especially for topics with substantial patient impact like the Inspire® UAS device [45,55]. Furthermore, continuous medical education programs must integrate modules on digital literacy and communication, equipping physicians with the tools to not only disseminate but also critically assess online content [56–59]. As digital health communication evolves, the sleep medicine community must lead with informed engagement, safeguarding the integrity of the information ecosystem in the digital age.

The significant presence of advertisements in our dataset, constituting 40% of the content, offers a critical perspective on the nature of information dissemination about medical technologies like UAS. The dominance of promotional material raises concerns about potentially skewing public perception, primarily when these advertisements emphasize the benefits of UAS while downplaying its risks or limitations [60,61]. This trend has implications for patient expectations and decision-making, highlighting the need for healthcare professionals to provide a balanced view encompassing both the advantages and potential drawbacks of such treatments. While our study focuses on a surgical device produced in the United States, the global reach of social media platforms suggests that these findings have wider relevance [52,62–65]. The interpretation and impact of social media content on UAS can vary significantly across different countries, influenced by cultural norms, healthcare systems, and regulatory environments. For example, in countries with restricted access to UAS or differing healthcare policies, the portrayal of UAS on social media might affect patient advocacy and demand differently than in the United States. Developing strategies that recognize diverse cultural and regulatory landscapes can ensure the accessibility of social media content on medical technologies as well as accuracy, balance, and cultural sensitivity [66–68]. As UAS continues to gain traction globally, understanding its portrayal on social media becomes imperative for shaping effective and ethical healthcare communication strategies worldwide.

This investigation is not without limitations. A primary constraint is that the methodology involved convenience sampling of public social media posts, which is inherently non-randomized and must be interpreted in the context of the specific posts examined. Our focus on the platforms Instagram, Facebook, and TikTok may narrow the study's generalizability, especially given the global popularity of other platforms [69–71]. Future research should broaden the scope to encompass a wider range of social media platforms such as Snapchat, LinkedIn, or Twitter, offering an additional lens into the UAS discourse. Employing technologies like artificial intelligence for data analysis, which was beyond the scope of this study, might further enhance the depth and breadth of our findings. Moreover, by surveying only public posts, we missed insights from private accounts or posts limited to specific user networks, a choice often made for privacy reasons. Additionally, the influence of industry stakeholders, who may act as de facto influencers, represents a further limitation. Their promotional activities might skew the representation and perception of UAS on social media, potentially overemphasizing benefits while underreporting risks or adverse outcomes. The subjective nature of post categorization, such as determining sentiment or intent, is another potential limitation. A different research group might derive varied conclusions due to individual biases or interpretations. Study findings can be influenced by the ever-changing nature of social media platforms, their algorithms, and user behaviors, as with any study involving dynamic platforms. Therefore, the clinical application of these insights should be approached judiciously and balanced with evidence-based practices and individual patient considerations.

5. Conclusions

The prominence of the Inspire® Upper Airway Stimulation (UAS) device on social media underscores the vital interplay between medical innovation and the digital realm, particularly on platforms like TikTok. This study highlights the dynamic nature of healthcare communication in the digital age, revealing a narrative landscape that blends patient experiences, educational content, and a significant proportion of advertisements. Such findings accentuate sleep medicine specialists' need to engage actively in these digital spaces with transparent, evidence-based narratives. This approach is crucial to counterbalance promotional content, fostering informed patient decision-making in an era where social media increasingly influences health-related perceptions.

Our investigation, while comprehensive, acknowledges the limitations of its scope and methodological approach, suggesting directions for future research. Expanding the analysis to more social media platforms and employing advanced analytical tools can offer deeper insights into the global discourse surrounding medical technologies like UAS. As the field of sleep medicine continues to evolve alongside digital communication channels, a collaborative and strategic approach is essential. By embracing digital literacy and working closely with tech platforms, healthcare professionals can ensure the integrity and effectiveness of the healthcare information ecosystem, catering to a globally diverse audience.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare11233082/s1, Data Collection Guidelines.

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Patent and Bibliometric Analysis of the Scientific Landscape of the Use of Pulse Oximeters and Their Prospects in the Field of Digital Medicine

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Abstract: This study conducted a comprehensive patent and bibliometric analysis to elucidate the evolving scientific landscape surrounding the development and application of pulse oximeters, including in the field of digital medicine. Utilizing data from the Lens database for the period of 2000–2023, we identified the United States, China, the Republic of Korea, Japan, Canada, Australia, Taiwan, and the United Kingdom as the predominant countries in patent issuance for pulse oximeter technology. Our bibliometric analysis revealed a consistent temporal trend in both the volume of publications and citations, underscoring the growing importance of pulse oximeters in digitally-enabled medical practice. Using the VOSviewer software(version 1.6.18), we discerned six primary research clusters: (1) measurement accuracy; (2) integration with the Internet of Things; (3) applicability across diverse pathologies; (4) telemedicine and mobile applications; (5) artificial intelligence and deep learning; and (6) utilization in anesthesiology, resuscitation, and intensive care departments. The findings of this study indicate the prospects for leveraging digital technologies in the use of pulse oximetry in various fields of medicine, with implications for advancing the understanding, diagnosis, prevention, and treatment of cardio-respiratory pathologies. The conducted patent and bibliometric analysis allowed the identification of technical solutions to reduce the risks associated with pulse oximetry: improving precision and validity, technically improved clinical diagnostic use, and the use of machine learning.

Keywords: pulse oximeters; patient safety; digital medicine; artificial intelligence; machine learning; telemedicine; patent

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1. Introduction

Patient safety remains a paramount concern across multiple fields of medicine, including anesthesiology, intensive care, resuscitation, surgery, and pediatrics. A critical diagnostic and prognostic factor for ensuring patient safety is the continuous monitoring of blood oxygen saturation levels. This metric serves as a comprehensive indicator of the respiratory and cardiovascular system functioning. Pulse oximetry has emerged as a non-invasive, safe, and highly informative method for monitoring the percentage of oxyhemoglobin in arterial blood [1].

Blood oxygen saturation monitoring is widely used in many areas of medicine, not only for patients but also for healthy individuals, to assess the cardiorespiratory status [2]. Pulse oximetry is a standard of mandatory monitoring protocols during anesthesia, as it detects episodes of hypoxia and allows timely medical intervention. During the awakening period and throughout patients' stay at the post-anesthesia care unit, pulse oximetry serves as a standard component of monitoring the restoration of vital functions, particularly adequate breathing and blood circulation [3]. Pulse oximetry does not only provide oxygen saturation levels, but also provides pulse frequency, pulse regularity, and respiratory variation in the amplitude of the plethysmographic waveform (as a predictor of fluid responsiveness), thus helping anesthesiologists decide whether a patient would benefit from intervening fluids.

It is worth noting that pulse oximetry is used in any setting where a patient's oxygenation may be unstable. This includes intensive care units, surgical theaters, recovery rooms, emergency departments, and general hospital wards. It is used to assess any patient's oxygenation, determine the need for additional oxygen, and detect life-threatening conditions in newborns and premature infants [4–7]. Additionally, pulse oximeters find utility in healthy people in the training and testing of pilots, firefighters, military personnel, professional athletes, and mountain climbers [8–11].

One of the biggest achievements in the history of clinical monitoring was the pulse oximeter [12,13]. For more than 30 years of application, pulse oximetry has not lost its relevance. The World Federation of Societies of Anesthesiologists, the American Society of Anesthesiologists, and the World Health Organization advise the use of pulse oximetry as part of standard intraoperative monitoring [14,15].

Marketing analysis data indicate that the market for pulse oximeters was valued at USD 2.1 billion in 2021 and is anticipated to increase to USD 3.9 billion by 2031, with a compound annual growth rate (CAGP) of 6.3% from 2022 to 2031 [16]. This market expansion is attributed to the rise of cardiovascular and respiratory diseases, diabetes, and aging populations. In addition, the increase in surgical procedures and hospitalizations, combined with technological advances in pulse oximeters, are additional factors driving market demand. The COVID-19 pandemic has further accelerated the adoption of pulse oximeters, both in clinical settings and for home use. In patients with respiratory conditions, oxygen saturation serves as a key metric for assessing the effectiveness of pulmonary gas exchange efficiency and treatment efficacy [17–21].

Optical oximetry methods are well-established and promising in the context of modern evidence-based medicine. They have a solid physical and mathematical foundation, and are based on the methods of physical measurements, i.e., they are a full-fledged branch of modern medical physics. Despite their robust foundations, questions remain regarding the accuracy and reproducibility of the results of such measurements related to the effects of pigmentation, race, fingernail polish, ambient light, and motion artifacts [22–25]. Notably, in November 2022, the US FDA recommended improvements to pulse oximeters following studies that indicated reduced efficacy in individuals with darker skin [26].

The implementation of digital technologies while using pulse oximeters is also promising, including remote monitoring, and artificial intelligence is an area of research interest today in major scientific centers around the world. This diagnostic direction, in the full sense of the word, is an evolving scientific frontier [27–30].

This study's objective was to conduct a patent and bibliometric analysis of the scientific landscape of contemporary innovative technological solutions for the development and application of pulse oximeters, including in the field of digital medicine, and identify technical solutions to reduce the risks associated with the use of pulse oximetry.

2. Materials and Methods

When investigating this topic, an analysis of patents and scientific information was carried out. General scientific and specific scientific research methods were applied (systematic approach, method of analysis, synthesis, induction and deduction, etc.).

2.1. Patent Analysis

Patents are indicators of technological activity and innovative potential. The information presented in the patents is unique and does not always appear in other publications. Patent databases store and constantly update huge amounts of invention data. Patent information is widely used to assess technology development, forecasting, and decision-making.

The research information base was an array of patent documents issued for the period of 2000–2023 (as of 31 August 2023), presented in the Lens database. To analyze patents reflecting the main trends in technical solutions in the field of pulse oximeters, a search was conducted using the following keywords "oximeter" and "oxygen saturation", using the OR operator. The request was limited to the sections of the Cooperative Patent Classification.

Keyword searches were performed in the title, abstract, or claims. The procedure for determining documents for patent analysis is presented in Figure 1.

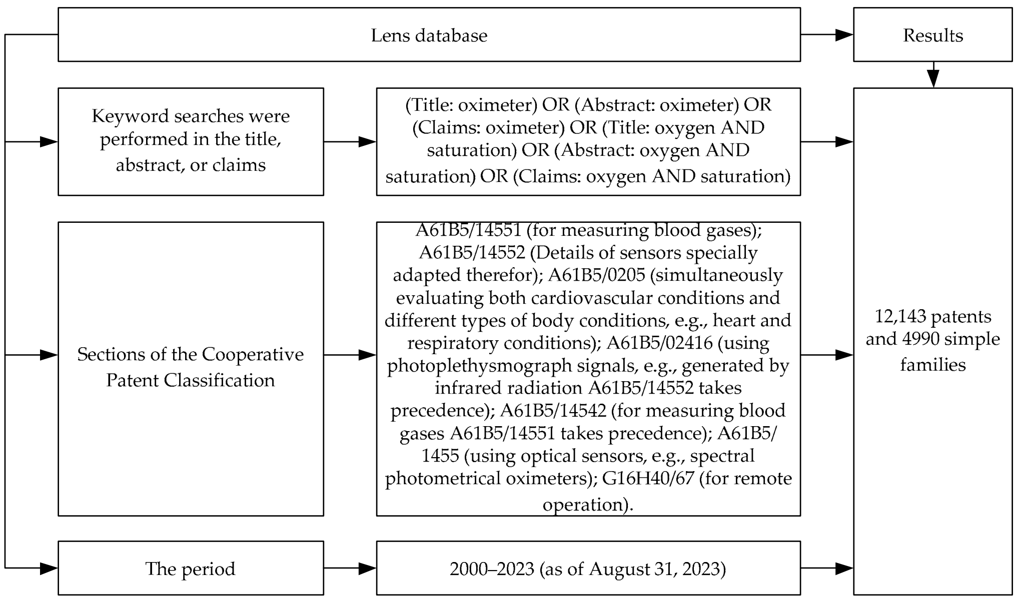

Figure 1. The procedure for determining documents for patent analysis.

2.2. Bibliometric Analysis

For the bibliometric analysis of scientific publications on pulse oximetry, the Web of Science database was used. The period of 2000–2023 (as of 31 August 2023) was also selected as the time interval for the analysis. In order to assess the prospects for using digital technologies in combination with pulse oximeters, the keywords "pulse oximeter", "oxygen saturation", "pulse oximetry", "digital", "artificial intelligence", and "machine learning" were used to search. The search field "Article Title, Abstract, Keywords" was used. The procedure for defining documents for bibliometric analysis is shown in Figure 2.

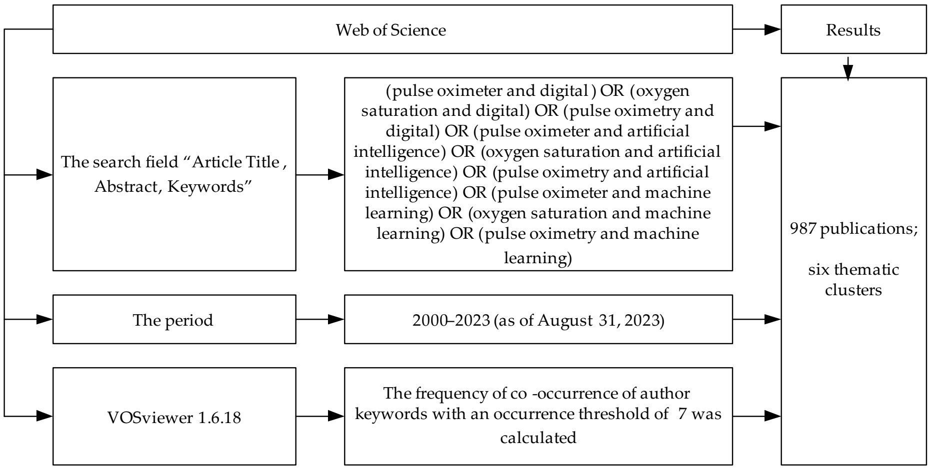

Figure 2. The procedure for defining documents for bibliometric analysis.

VOSviewer 1.6.18 [31] was used to analyze and visualize the results. The frequency of co-occurrence of author keywords with an occurrence threshold of 7 was calculated. VOSviewer allows one to generate bibliometric maps based on the analysis of the frequency of co-occurrences of keywords, co-citations, and other parameters. In particular, using VOSviewer, conceptual maps were created based on the frequency of co-occurrence of each pair of terms. The size of the circle reflects the frequency of occurrence of the term; the larger its area, the more often this word or phrase is found in the general list of author keywords. The distance between a pair of terms is an indication of their relationship. Colors are used to refer to clusters; terms of the same color (included in the same cluster) are more common with each other (i.e., more closely related) than terms labeled with other colors.

3. Results

3.1. Patent Analysis

Patent analysis using a search query of the study revealed 12,143 patents and 4990 simple families for the period from 2000 to 2023 (as of 31 August 2023). The dynamics of patenting inventions in the field of creating pulse oximeters in 2000–2023 are shown in Figure 3.

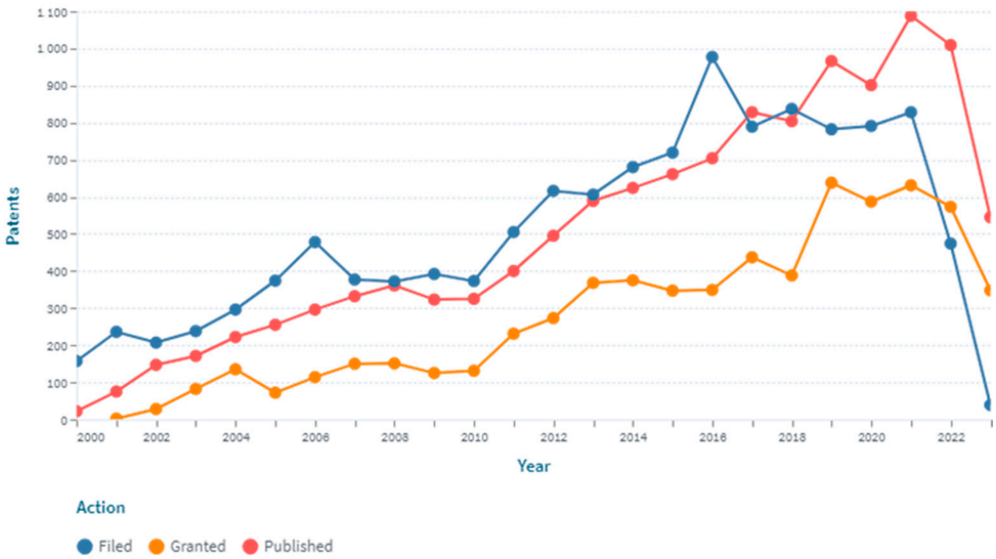

Figure 3. Dynamics of patent activity in the field of creating pulse oximeters for the period of 2000–2023 (as of 31 August 2023).

The presented data indicate the presence of a stable linear growth of patent activity in the field of pulse oximetry, which is probably due to the constant demand for pulse oximeters and the search for new solutions for their improvement. Noteworthy is the sharp increase in the number of published patents in 2021, which is possibly due to the widespread use of pulse oximeters during the COVID-19 pandemic for early detection of hypoxia, both by health personnel and patients at home.

Figure 4 shows the patenting activity in the field of creating of pulse oximeters in various countries. An analysis of the Lens patent database showed that the leading countries issuing patents on their territory were the United States, China, the Republic of Korea, Japan, Canada, Australia, Taiwan, and the United Kingdom. Applicants also made extensive use of the Patent Cooperation Treaty and a procedure for obtaining European patents.

Figure 4. Leading countries by number of patents issued (2020–2023, as of 31 August 2023).

The leading applicants in the field of pulse oximeters were evaluated. It was revealed that the top applicants in this field were Masimo Corporation, Covidien Lp, Fujifilm Corporation, Koninklijke Philips Nv, Vioptix Inc., Nellcor Puritan Bennett, Nihon Kohden Corporation, Medtronic Inc., etc. (Figure 5).

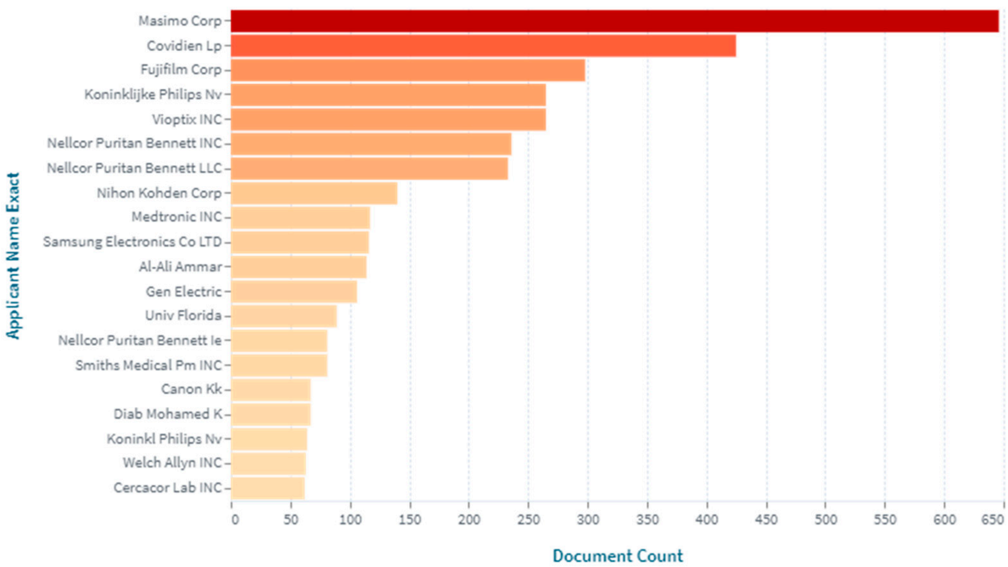

Figure 5. The top applicants in the field of creating pulse oximeters (2000–2023, as of 31 August 2023).

As shown by the patent analysis of innovative solutions for creating pulse oximeters, Masimo is one of the leading development companies. Masimo is an American company founded in 1989 that manufactures devices for non-invasive patient monitoring, including pulse oximeters. Based on earnings growth, revenue growth, and return on equity, Forbes included Masimo in its list of the 20 biggest billion-dollar public corporations in 2011. Joe Kiani, founder of the company, was honored with the Ernst and Young National Entrepreneur of the Year Award and the Life Sciences Award in 2012. In the development and marketing of non-invasive patient-monitoring devices, Kiani was recognized for "revolutionizing the healthcare business" [32]. Masimo received patents for pulse oximeters for different end consumers.

Using the example of a number of leading developers, we will consider the directions for creating technical solutions in the field of pulse oximeters.

The analysis revealed multiple classifications of pulse oximeters. Transmission and reflectance pulse oximeters are currently used in clinical practice. Their work is based on the ability of blood hemoglobin to absorb light emitted from the LED of various wavelengths, which is scattered, reflected by tissues and blood, and reaches the photodetector.

Depending on the end-user, there are a number of pulse oximeters (stationary, portable, for home use, pediatric pulse oximeters, etc.), each of which has its own purpose and features of use.

In a stationary version, pulse oximeters are often integrated into more complex devices (patient monitors, ventilators). Devices of this class are complex systems with extensive functionality. Most of the patient's monitors are equipped with a large graphic screen, which displays current information about the patient's condition: blood pressure, a cardiogram in real time, saturation value, and a photopletismogram of blood flow in the body site to which the sensor is attached. Stationary pulse oximeters are used exclusively in medical institutions and work from the electrical grid. These are the largest of all pulse oximeters, but they typically provide the highest accuracy. They are used during operations, in intensive care, and during critical procedures.

For example, Masimo has developed and implemented the Root with O3 Regional Oxymetry Stationary Device for use in adults, children, infants, and newborns for cerebral and somatic monitoring. The patent protection of the device is comprehensive, including protection of the following inventions: "Dual-mode pulse oximeter" (US6770028 [33]); "Low power pulse oximeter" (US7295866 [34]), "Pulse oximeter probe-off detector" (US7471969 [35]), "System and method for monitoring the life of a physiological sensor" (US7880626 [36]), "Robust alarm system" (US7962188 [37]), "Virtual display" (US7990382 [38]), "Plethysmograph pulse recognition processor" (US7988637 [39]), "Pulse oximetry data confidence indicator" (US8046040 [40]), and others [41–50]. The Root with O3 Regional Oximetry device can help doctors monitor brain oxygenation.

Portable pulse oximeters are used to evaluate oxygen saturation in the treatment of cardiovascular problems both in the hospital and at home. A portable pulse oximeter is placed on the finger, and the sensor is attached to a monitor mounted on the belt. With such a device, it is possible to obtain accurate measurement results during the day, continuously monitoring the patient's state. Continuous monitoring of saturation can be a key component in preparing for surgery or selecting the right treatment.

An example of a portable pulse oximeter is the iSpO2, developed by Masimo. When measured with an iSpO2 pulse oximeter, the accuracy of monitoring oxygen saturation and the pulse rate is guaranteed even during movement. It works with either iOS or Android devices. The Masimo Personal Health app, combined with the iSpO2 pulse oximeter, allows patients to monitor and change oxygen saturation, pulse rate, and perfusion index. The iSpO2 pulse oximeter is also protected by several patents [34,51–56].

A separate niche can be identified for pulse oximeters, focused on a quick assessment of the patient's condition rather than long-term monitoring. These devices have several features: their miniature size, limited functionality, and ease of use. Such pulse oximeters can be made with a sensor in the form of a clip, which is usually fixed on the index finger or earlobe of the patient. This type is well-suited for adults and adolescents when the patient is observed for a short time. It is inconvenient to wear a clip if one needs a long measurement (several hours or more), as it can shift during movements, distorting the results of the study. For use, it is necessary to be at rest and not move, which makes it impossible to use this type to obtain an average oxygen saturation value for some time.

As a leading development company, Masimo also developed the MightySat finger pulse oximeter to quickly assess a patient's condition, measuring five key vital signs:

oxygen saturation, pulse rate, respiratory rate, perfusion index, and plethistic variability index. These settings are displayed on compatible smart devices with Bluetooth LE models. Measurements can also be integrated into the Apple Health app. This development is protected by several patents ([57–61], etc.).

Pulse oximeters for rapid state assessment are also presented in the form of a wristwatch with a remote sensor that is attached to the finger, as in previous types. Such devices are more often used by athletes and people involved in climbing mountains.

Noteworthy is the development of the Masimo W1 (Advanced Health Tracking Watch). Numerous physiological measurements are provided by Masimo W1, including the hydration index, oxygen saturation, heart rate, respiration rate, pleth variability index, and perfusion index. The product is made for people who wish to track their health data on their own or with friends and family, make better fitness decisions, or follow their health information with more knowledge. The watch is protected by a few patents [62–65].

The company's products utilize Masimo SET technology, which should be highlighted. With the use of cutting-edge signal processing methods, SET sets Masimo apart from existing pulse oximetry systems by separating the arterial signal from noise sources. Masimo SET, when used in conjunction with clinical controls, has been shown in numerous studies to assist doctors in lowering the risk of blindness and eye damage (retinopathy of prematurity) in newborns [66], improving newborn critical congenital heart disease screening [67], and lowering the number of patient transfers to intensive care units and the activation of a rapid response team on the general hospital floor [68].

In a patient's physical data file, health care providers often record numerical parameter values together with other crucial data, such as time, other observational data, or remarks, and the identity of a health care professional. The file is frequently kept close by the patient, perhaps on a tablet. In this instance, the file is accessible to individuals who want to view the data. It should be mentioned that computer pulse oximetry is used in relation to this, where data processing from the device occurs through a microprocessor embedded into the device. This design is seen in many contemporary pulse oximeters.

Masimo is actively working towards the introduction of digital pulse oximetry technologies. A remote monitoring and notification system for doctors (Masimo Patient SafetyNet) has been developed, which displays information in almost real-time from any connected Masimo device or a third-party device at the central station. The system allows for the sending of alarms and alerts from bedside devices directly to doctors. The development is protected by a number of patents, including "Intelligent medical escalation process" (US10833983 [69]), "Physiological measurement logic engine" (US11399774 [70]), "Medical communication protocol translator" (US11145408 [71]), "Medical monitoring system" (US11133105 [72]), and "Alarm notification system" (US11488711 [73]).

Moreover, Masimo's Iris Gateway system bridges the gap between device data generated at the patient's bedside and documentation in patient data-management systems such as electronic EMR medical records. Masimo Iris contributes to simplifying interaction throughout the health care delivery process. The development is presented in a number of patents, including "Physiological measurement communications adapter" (US7844315 [74]), "Systems and methods for storing, analyzing, and retrieving medical data" (US8274360 [75]), "System for displaying medical monitoring data" (US9943269 [76]), etc.

Furthermore, Masimo has presented an original, innovative solution that uses pulse oximetry that is noteworthy and of great practical importance. This is an opioid overdose prevention and warning system disclosed in patent US10939878 [77]. Using a pulse oximeter at the tip of the finger attached to an intelligent mobile device, the physiological monitoring system tracks breathing based on oxygen saturation measurements and communicates opioid-monitoring data from an intelligent mobile device to an opioid overdose monitoring service.

Masimo also develops pulse oximeters for sports events. An application (US 2022/0218244 A1) has been made for the invention, which relates to methods and systems for combining physiological data from a pulse oximeter connected to a player playing a tennis match with match data corresponding to a tennis match [78]. The system can generate a visual alert for one or more spectators of a tennis match based on a trigger event corresponding to the received physiological data and match data.

It should be noted that the identified areas of development in the field of pulse oximeters for different groups of end consumers are also presented among the intellectual property portfolios of other leading companies.

The founders of the creation of pulse oximeters include Nellcor, created in 1981. In 1983, Nellcor introduced its first pulse oximeter. As a result of mergers and acquisitions involving Nellcor, the following companies were represented in the market: Puritan-Bennett, Nellcor Puritan Bennett, and Covidien. In 2015, Medtronic acquired Covidien and continues to promote the Nellcor brand [79]. As a result, the intellectual property market is widely represented by the above applicants.

The Nellcor pulse oximeter that has proven itself positively on the market is the Oxi Max N 560. It is designed to continuously and non-invasively monitor the degree of functional oxygen saturation of the arterial hemoglobin and the pulse rate. The device N-560 is intended for newborns, children, and adults both in and out of motion, as well as for patients in well-lit or poorly-lit rooms, such as hospitals, health facilities, in-hospital transport, and home settings. The Oxi Max N 560 is protected by a number of patents, including "Sensor with signature of data relating to sensor" (US6708049 [80]), "Method and circuit for storing and providing historical physiological data" (US6463310 [81]), "Method and circuit for indicating quality and accuracy of physiological measurements" (US6675031 [82]), "Pulse oximeter sensor with piece-wise function" (US6801797 [83]), "Oximeter sensor with digital memory recording sensor data" (US6591123 [84]), etc.

Of particular interest is the development of Covidien Lp, protected by the patent "Oxygen Saturation Monitoring Using Artificial Intelligence" (US11517226) [85]. The developed oxygen saturation-monitoring device determines that the oxygen saturation level of the patient has decreased before reaching the desaturation threshold and can predict whether the oxygen saturation level of the patient will rise again above the desaturation threshold within a predetermined period.

In the field of pediatrics, Covidien Lp has received a patent for a device for determining the risk of retinopathy of prematurity (US8374666) [86]. The processing unit is configured to determine the oxygen saturation level and trigger an alarm to receive timely information about the emerging risk.

Covidien Lp also applied for WO 2022/204668, "Autoregulation Monitoring Using Deep Learning" [87]. In anesthesia, that is particularly interesting in patients that are positioned with their heads elevated during surgery. The system is configured to determine, using a neural network algorithm, a model of cerebral autoregulation. A patient's cerebral autoregulation state is based at least in part on the patient's blood pressure and regional cerebral oxygen saturation in the patient for a certain period of time.

The leaders among the developers of pulse oximeters include Nihon Kohden. In 1972, the Japanese engineer Takuo Aoyagi developed a method for recording fluctuations in the absorption of light during the pulsation of the arteries. In 2015, he was awarded by the Institute of Electrical and Electronics Engineers with the "Healthcare Technology Innovation Medal," being the first Japanese to receive such an award. The first pulse oximeter was released in 1975 (model OLV-5100) by Nihon Kohden Corporation [88]. Nihon Kohden currently has a large portfolio of pulse oximeter patents, including "Pulse oximeter" (US 7206621 [89]), "Method and Apparatus for Measuring Pulse Rate and Oxygen Saturation Achieved During Exercise" (US 8649837 [90]), "Patient Monitor" (US 11291414 [91]), etc.

3.2. Bibliometric Analysis

Based on the entered search queries in the Web of Science database, the system provided 987 publications. Bibliometric analysis, as shown in Figure 6, revealed a time-stable growth trend in the number of publications and citations devoted to pulse oximetry using digital technologies.

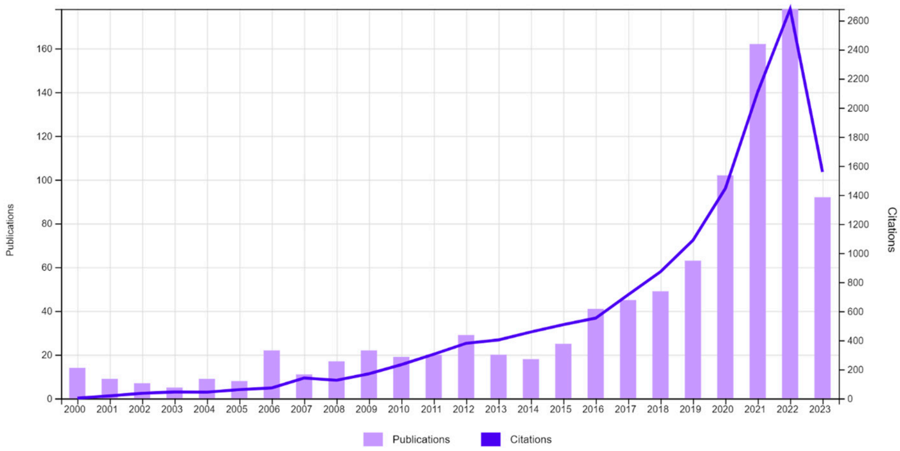

Figure 6. Dynamics of the number of publications and citations devoted to pulse oximetry using digital technologies in the Web of Science (2000–2023, as of 31 August 2023).

Figure 6 shows that 54% of all materials have been published since 2020. A total of 54% of scientific publications on pulse oximetry using digital technologies cover the following areas of knowledge: electrical engineering (13.982%), biomedical engineering (12.563%), general internal medicine (8.004%), medical informatics (7.497%), health care sciences services (6.180%), and instruments instrumentation (5.978%). Among the medical industries, leading positions occupy respiratory system (4.154%), surgery (3.951%), cardiac cardiovascular systems (3.850%), anesthesiology (3.749%), critical care medicine (3.546%), and clinical neurology (3.141%).

Among these 987 papers, 718 were articles, 67 were reviews, 195 were proceeding papers, and 6 were editorial materials.

The top five most productive affiliations and journals are listed in Table 1.

Table 1. Top 5 most productive affiliations and journals.

Entity	Record Count	%
Affiliations		
University of California system	35	3.57
Harvard University	34	3.47
University of Oxford	22	2.25
Massachusetts Institute of Technology	18	1.84
Massachusetts General Hospital	17	1.74
Journals		
Sensors	28	2.86
Proceedings of SPIE	23	2.35
PLOS One	18	1.84
Scientific reports	17	1.74
Physiological measurement	13	1.33

It was determined that the USA, China, England, India, Germany, Japan, Canada, Australia, Spain, and Italy are the countries in which the problems of pulse oximetry were worked out in the most detail. Three countries (the USA, China, and England) produced almost half of the total number of publications (50.8%).

The five most cited publications of authors studying pulse oximetry in combination with digital technologies in the Web of Science (2000–2023, as of 31 August 2023) are shown in Table 2.

Table 2. The top 5 most cited publications by authors studying pulse oximetry in combination with digital technologies in the Web of Science (2000–2023, as of 31 August 2023).

Title	Year of Publication	Average per Year	Total Citations
Ultraflexible organic photonic skin	2016	84.75	678
Photoplethysmography: beyond the calculation of arterial oxygen saturation and heart rate	2007	17.65	300
Prediction of sepsis in the intensive care unit with minimal electronic health record data: a machine learning approach	2016	28.25	226
Utility of the photoplethysmogram in circulatory monitoring	2008	14.13	226
Digital Health: tracking physiomes and activity using wearable biosensors reveals useful health-related information	2017	30.29	212

The most cited (678 citations) is the publication "Ultraflexible organic photonic skin" by Yokota et al. [92]. In this study, the authors reviewed the development of thin-film electronic devices for health monitoring. An ultraflexible reflex pulse oximeter was made.

In second place is the publication "Photoplethysmography: Beyond the Calculation of Arterial Oxygen Saturation and Heart Rate" [93]. It has been quoted 300 times. This study carried out a detailed analysis of photoplethysmography. In addition, the need to standardize and quantify the plethysmograph, device improvements, and well-designed prospective studies demonstrating the measurement of clinically-relevant information were emphasized.

In third place is the publication "Prediction of Sepsis in the Intensive Care Unit with Minimal Electronic Health Record Data: A Machine Learning Approach" by Desautels et al. [94], which has been cited 226 times. The paper proposed a method for predicting sepsis in intensive care using machine learning based on a minimal set of variables from electronic medical record data (including pulse oximetry data). The next highly cited publication [95] relates to the use of photoplethysmograms in blood circulation monitoring for new technological developments.

A highly cited study by Li et al. demonstrates that with portable devices, diverse measurements can be systematically obtained and used to monitor health-related physiology and activity [96]. These measurements are likely to be important not only in basic scientific research but also in clinical settings. It is likely that in the future, these devices will be used by physicians to assess health conditions and make recommendations and treatments.

The top 20 keywords by frequency of occurrence are presented in Table 3.

Table 3. The top 20 keywords of publications in the field of pulse oximetry using digital technologies in the Web of Science (2000–2023, as of 31 August 2023).

Keywords	Occurrences
Machine learning	200
Oxygen saturation	109
Pulse oximetry	100
COVID-19	76
Photoplethysmography	59
Oximetry	52

Table 3. *Cont.*

Keywords	Occurrences
Mortality	49
Prediction	46
Risk	46
Diagnosis	45
Artificial intelligence	41
Pulse oximeter	37
Management	35
Accuracy	34
Deep learning	30
Care	28
Telemedicine	28
Digital health	27
Sleep apnea	27
Outcomes	24

Using the method of clustering the keywords of the VOSviewer program, a conceptual map was created (Figure 7). It shows that terms form a complex network in which six thematic clusters can be distinguished.

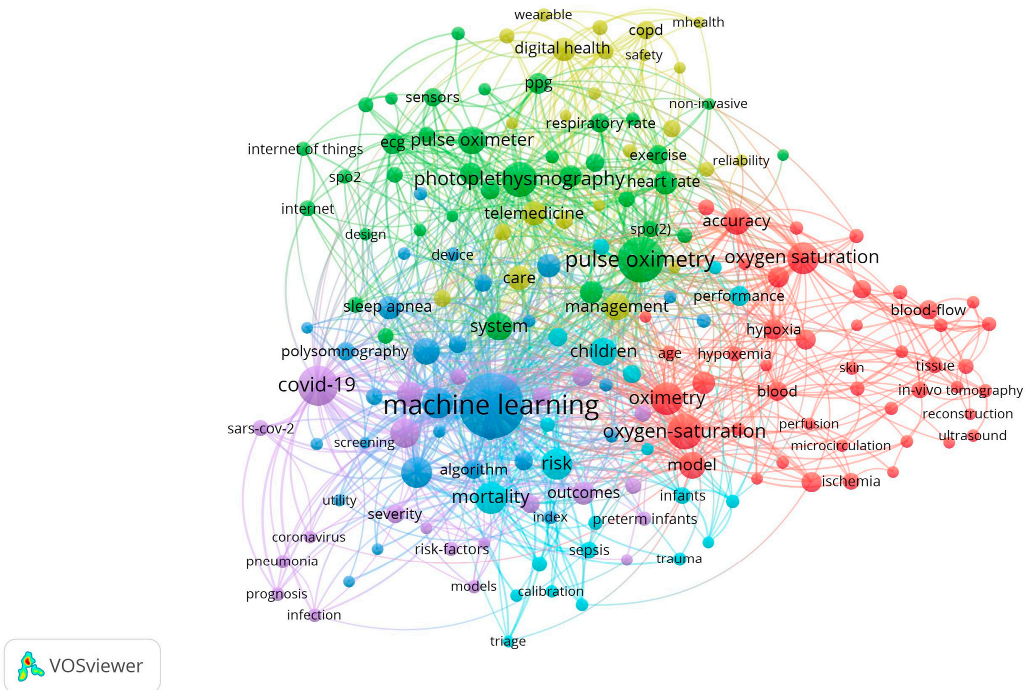

Figure 7. A conceptual map of the keywords of publications on pulse oximetry using digital technologies in Web of Science (2000–2023, as of 31 August 2023).

4. Discussion

The final stage in the development of devices, including innovative technologies for pulse oximeters, is their testing and introduction into medical practice. Thus, for example, Masimo Rad-97 and Accessories, Masimo Radical-7 Pulse CO-Oximeter and Accessories, Masimo Radius-7 Pulse CO-Oximeter and Accessories, Masimo Rad-67 Pulse CO-Oximeter and Accessories, and others have received FDA approval (https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfRL/rl.cfm (accessed on 24 September 2023)).

There must be a focus on the FDA guidelines, which determine the following types of pulse oximeters [26]:

- Pulse oximeters are used by prescription and have passed clinical trials. They are used most often in hospitals and doctors' offices, and less often for home use.
- Over-the-counter pulse oximeters. They do not pass FDA review and are more often intended for general wellness, sports, or aviation purposes.

Analysis of the results of patent studies revealed that modern innovative solutions for the creation and implementation of transmission and refractory pulse oximeters for different end-users (stationary, portable, for home use, for pediatrics, etc.) are often integrated into more complex devices. At the same time, the tendency to accompany them with digital technologies is clearly traced. Manufacturers emphasize the development of automated, wireless, and remote pulse oximeters, thereby reducing the number of hospitalizations and doctor's visits and improving diagnosis and treatment.

In order to analyze and systematize the available data on the experience of introducing pulse oximeters using digital technologies, bibliometric studies were carried out.

Ongoing studies reveal new beneficial effects of pulse oximetry in clinical practice. The bibliometric analysis of pulse oximetry revealed six areas of research, as well as technical solutions to reduce the risks associated with pulse oximetry.

The first cluster (marked in red) is associated with the accuracy of the measurement results obtained by pulse oximeters. The predominant terms include accuracy, age, blood flow, hemodynamics, circulation, hemoglobin, hypotension, hypoxemia, hypoxia, near-infrared spectroscopy, perfusion, reflectance, skin, temperature, etc.

Cabanas et al. systematized factors that may influence the accuracy and interpretation of pulse oximeter readings. Conditions of low perfusion, such as hypotension, hypothermia and vasoconstriction, anemia, hypoxemia, the use of dyes, nail polish, nerve-blocking medications, high altitude, or hypoxia training, can lead to SpO2 underestimation [97].

Although some older studies have not found any abnormalities associated with dark skin pigmentation [98,99], recent studies have shown that pulse oximeter devices have some limitations for dark-skinned subjects, especially in low-saturation or hypoxemia settings. Cabanas et al. note that factors that can lead to overestimation are darker skin pigmentation, hot skin temperature, hemoglobinopathy, high carbon monoxide levels, hyperbilirubinemia, and heavy smokers [23,97].

Additionally, the pulse oximeter's signal processing can be hampered by motion artifacts, HR >150 beats per minute, excessive ambient light, incorrect or loose placement of the probe on the finger or earlobe, electromagnetic interference, or irregular heart rhythms, all of which can lead to readings that are not accurate [97,100].

The FDA notes that some of the factors that may affect the accuracy of pulse oximeters include skin pigmentation, dyshemoglobinemia, severe anemia, low perfusion, dyes, nail polish, ambient light, motion artifacts, etc. [26].

In publications containing the above keywords, problems with the measurement accuracy of pulse oximeters and the usefulness of digital support are discussed. For example, Gokhale et al. have developed a non-invasive technology for measuring hemoglobin and oxygen saturation to eliminate racial bias [101]. The inventors use a special melanin-accounting algorithm and software. Non-invasive device scores were comparable to the invasive method.

The work of Matos et al. was also devoted to the study of the accuracy of pulse oximeters in a population with a darker skin tone [102]. The results of their single-center study suggest that SpO2 correction can be achieved with machine learning.

Other authors report that in neonatal intensive care units, 87.5% of monitoring system alarms are false and caused by neonatal movements. To reduce the level of false alarms, it is proposed to use machine-learning algorithms to analyze the data from standard physiological monitoring in combination with cerebral oximetry data [103].

The proposed digital technologies using machine learning might help solve the problems of the influence of pigmentation and motion artifacts on measurement accuracy.

There are other developments in pulse oximeters that use more wavelengths, which increase their accuracy. In the future, machine learning methods can be applied to these data. Thus, Rea et al. noted that the inclusion of various specific wavelengths allows the reliable use of noninvasive sensors by people of any race and/or skin type [104].

The second cluster (green) focuses on the capabilities of the Internet of Medical Things, including pulse oximeters. Biomedical monitoring, exercise, heart rate, Internet of Things, monitoring, motion, respiratory rate, sensor, SpO2, vital signs, wearable devices, and wearable sensors are the terms that are presented in this cluster.

Biosensors, as a general category of devices, collect information about different parameters and vital health signs by reading or measuring them and transmitting them using electrical signals to be interpreted. Pulse oximeters are of interest for the prevention and control of diseases, including those in elderly patients. They provide monitoring outside the hospital. At the same time, the indicators are more objective than those reported by patients during their visits to the doctor and can provide specialists with a real picture of the course of the disease in each specific case. The ability to connect sensors to mobile devices allows one to improve health management. It should also be noted that fitness trackers and smartwatches often include pulse oximetry indicators.

It is of interest to use sensors with digital technologies to detect early signs of drug overdose and respond in a timely manner. A review by Oteo et al. focused on technologies that can alert physicians to cases of drug overdose [105]. These technologies use sensors that monitor oxygen saturation levels, breathing rate, or movement in combination with smartphone applications.

Scientific evidence suggests that one in five Americans wears a fitness tracker [106]. The publications of this cluster are also devoted to the development and testing of smartwatches, including readings of pulse oximeters.

The main users of smart watches are professional athletes and sports fans, military personnel, and users monitoring health. Thus, Garmin Ltd. produces smartwatches for sports and the military sphere [107].

Mitro et al. developed and tested a smart bracelet with machine learning support for use in emergencies during the evacuation of large passenger ships [108]. The device allows one to monitor the pulse rate and oxygen saturation level in real-time and detect stress. An external review established an accuracy score of 76%.

Studies on the accuracy of oxygen saturation measurements using the Apple Watch (Apple Inc., Cupertino, CA, USA) were summarized [109]. A total of 973 patients had a 95% agreement of ± 2.7 to 5.9% SpO2 when using the Apple Watch Series 6. The limitations of the studies were heterogeneous measurement and reporting processes in comparison with non-invasive measurements at rest. The authors noted the need to study the effect of skin color on measurement accuracy. In the clinical setting, a 12-lead ECG is currently needed to diagnose a myocardial infarction (MI). Li et al. summarized data from a number of studies using the Apple Watch to record multiple leads to meet this requirement for a clinical diagnosis of MI. The researchers noted that there are still many limitations to achieving the goal of early detection of MI, and more clinical data are needed [110].

It is worth noting that the Apple Watch and other wrist devices are not class IIb medical devices. While class IIb devices are generally medium- to high-risk, this class is more complex due to stricter clinical data requirements [111,112].

The determination of oxygen saturation by these wrist devices is only punctual and not continuous, and the patient/user must remain still.

When using smart watches for medical purposes, scientists distinguish between the positive aspects of the high-tech functions of smart watches, which allow users to independently monitor their health, and the risks associated with the error of medical indicators recorded by smart watches. There is no doubt that the potential of smart devices will increase, and their data will be comparable to the results of stationary examinations.

The third cluster (blue) is associated with the study of the use of pulse oximeters with digital technologies in various pathologies. This cluster has the following terms: obstructive sleep apnea, diabetes, diagnosis, digital signal processing, machine learning, neural networks, polysomnoraphy, predictiob, screening, stroke, support vector machine, etc. In recent years, pulse oximetry using digital technologies has become actively used as a diagnostic tool in clinical practice and in functional diagnostics.

Pulse oximetry using digital technologies can be used as a screening method to determine sleep apnea. A systematic search by Bazoukis et al. revealed that machine-learning models performed well in the diagnosis of sleep apnea using electrocardiogram measures and pulse oximetry [113].

Wang et al. developed an apnea diagnostic system using a photopletismography sensor to synchronously collect human pulse wave signals and oxygenate the blood. Machine learning was used to process data [114]. The high accuracy of the system was revealed—more than 85%.

Pulse oximetry using digital technologies in combination with other indicators is a fast and simple, but to the same extent informative, method of studying the function of the cardiovascular system. Its use is possible both in emergency cases (operating room, ambulance) and in the diagnosis of chronic diseases. In the initial stages of the disease, in some cases, only hypoxemia may indicate a developing pathology.

Chu et al. proposed a transformer-based deep-learning architecture that uses photopletysmogram signals to conduct personalized blood pressure assessments and oxygen saturation [115]. The model meets clinical standards and can improve the accuracy of blood pressure and oxygen saturation measurements (n = 1732).

Huang et al. presented a machine-learning model predicting 28-day all-cause mortality in hypertensive ischemic or hemorrhagic stroke patients [116]. Indicators included age, ethnicity, white blood cells, hyperlipidemia, mean corpuscular volume, glucose level, oxygen saturation, serum calcium, red blood cell distribution width, blood urea nitrogen, and bicarbonate (n = 4274).

Kerexeta et al. proposed an artificial intelligence model predicting the risk of cardiac decompensation events [117]. The prognostic indicators selected were weight gain, oxygen saturation in the last few days, and heart rate.

Pulse oximetry using digital technologies has found application for detecting hemodynamically significant disease of peripheral arteries of the lower extremities in patients aged 50 years and older with type 2 diabetes [118].

The use of pulse oximetry with digital technologies in various areas of medical practice improves the work of identifying episodes of reduced oxygenation and thereby significantly increases the timeliness and quality of diagnosis of threatened conditions and the quality of medical care. Machine learning methods are increasingly being used to mine data characterizing the clinical status of patients.

The central topics of the fourth cluster (yellow-green color) are telemedicine and mobile applications to ensure the safety of patients in the provision of medical care, including using pulse oximeters. In this cluster, the keywords are asthma, COPD (chronic obstructive pulmonary disease), digital heath, management, Mhealth, mobile health, patient monitoring, physical activity, prevention, reliability, remote monitoring, safety, telehealth, telemedicine, therapy, validation, and wearable.

Telemedicine and remote monitoring contribute to improving the quality and safety of the medical care provided, taking into account continuous modifications and improvements in diagnostic and therapeutic tools, including the growing number of chronic patients. This cluster presents publications related to the above topic.

Ashfaq et al. developed a prototype for the remote monitoring of cardiovascular patients using machine learning and artificial intelligence techniques [119]. The device allows the monitoring of vital human functions, including oxygen saturation, heart rate, and body temperature.

It was reported that the remote monitoring of vital parameters and symptoms (blood pressure, respiratory rate, heart rate, temperature, dyspnea, and peripheral saturation) is safe and allows patients hospitalized for COVID-19 to be discharged from the hospital ahead of schedule [120].

The use of monitoring patients for asthma was analyzed [121]. Electrocardiogram and photoplethysmogram signals are widely used in smartwatches and breast bracelets, making it easy to integrate a more extensive body sensor system to predict asthma exacerbations. Blood oxygen saturation, temperature, blood pressure, verbal sounds, and pain responses are other vital indicators that are utilized to monitor asthma patients.

Digital pulse oximetry indicators are essential for determining the treatment tactics and prognosis for patients with respiratory pathology, particularly those with chronic obstructive pulmonary disease [122].

Telemedicine and mobile applications reduce the burden on medical staff and increase the safety of patients.

The fifth cluster (lilac color) is closely related to the third and focuses on the possibilities of applying artificial intelligence and deep learning to analysis and prediction in COVID-19 and neonatology, including using pulse oximeters. Key terms include: artificial intelligence, complications, coronavirus, COVID-19, deep learning, disease, deep learning, outcomes, pain, pneumonia, prediction model, preterm infants, retinopathy of premature, severity, and SARS-CoV-2.

The COVID-19 pandemic has contributed to a significant increase in interest in the use of digital technologies in general and artificial intelligence in particular in the context of healthcare [123–125]. The use of pulse oximetry using digital technologies is due to the fact that arterial hypoxemia is one of the main syndromes that develops in patients with pneumonia caused by COVID-19.

Using various machine learning approaches, the prognostic value for survival of COVID-19 patients based on known in-hospital mortality risk factors and chest radiographs was assessed. It was found that the indicators should include age, oxygen saturation, blood pressure, and some concomitant diseases, as well as image features related to the intensity and variability of the pixel distribution [126].

In connection with the COVID-19 pandemic, patients had to manually enter their daily oxygen saturation and pulse rate values into a health monitoring system. In order to optimize this process, a new PACMAN (pandemic-accelerated human–machine collaboration) structure with low-resource computer vision based on deep learning has been proposed and investigated. The structure is integrated into the patient monitoring system [127].

Considering that patients with COVID-19 may have significantly low SpO2 before obvious symptoms appear, Mathew et al. proposed neural network-based monitoring methods using smartphone cameras [128]. The device analyzes the participant's hand video for physiological indicators.

Due to the similarity of the symptoms of COVID-19 and other respiratory infections, the diagnosis of these diseases may be difficult. To solve this problem, a web application was developed that uses a chatbot and artificial intelligence to detect COVID-19, colds, and allergic rhinitis. The app also includes an electronic device that connects to the app and measures vital signs such as heart rate, blood oxygen saturation, and body temperature [129].

Pulse oximetry occupies a special place in neonatology. A prognostic algorithm has been created to detect late-onset sepsis in preterm infants [130]. The machine-learning model takes into account oxygen saturation and heart rate data with a per-minute sampling rate.

In order to reduce the development of retinopathy, the importance of using improved saturation monitors in the management of newborns in critical conditions is noted. The introduction of automated systems is promising, helping to regulate the oxygen blender based on digital oxymetry data in real-time [131].

Thus, pulse oximetry with digital technologies is highly specific for detecting critical conditions in COVID-19 and neonatology.

The sixth cluster (light blue) concerns the experience of using pulse oximeters with digital technologies in the departments of anesthesiology, resuscitation, and intensive care. Among the keywords, the following concepts can be distinguished: anesthesia, calibration, children, critical care, failure, in-hospital mortality, newborn, risk, sepsis, shock, support, surgery, and trauma.

To optimize the processes of diagnosis and treatment in intensive care, machine learning, accompanied by various devices, including pulse oximeters, can also be successfully used. In order to reduce the duration of intraoperative hypoxemia in pediatric patients, a machine-learning model has been developed and tested that could predict the events of intraoperative hypoxemia 1 min ahead in children undergoing general anesthesia [132].

A machine-learning model has been developed and tested that predicts short-term ICU mortality using trends in four easily collected vital signs [133]. Heart rate, systolic blood pressure, diastolic blood pressure, and peripheral capillary oxygen saturation datasets measured every hour for 10 h were used.

Hypoxemia often occurs in outpatients undergoing esophagogastroduodenoscopy under anesthesia. To predict the risk of hypoxemia, Fang et al. developed and evaluated four machine-learning models based on preoperative and intraoperative data. The models showed satisfactory prognostic characteristics [134].

A model for predicting mortality in critically-ill patients with cardiogenic shock (n = 8815) was developed using a machine learning method. The final risk assessment includes the following values during the first 24 h of intensive care unit stay: maximum blood urea nitrogen $\geq$ 25 mg/dL, minimum oxygen saturation <88%, minimum systolic blood pressure < 80 mmHg, use of mechanical ventilation, age $\geq$ 60 years, and maximum anion difference $\geq$14 mmol/L [135].

One of the problems in the departments of anesthesiology, resuscitation, and intensive care is sepsis, since its development not only worsens the course of the patient's underlying disease but also has a high overall mortality (approx. 30%). The development of machine learning technology and the use of big data in the departments of anesthesiology, resuscitation, and intensive care have prospects for solving this problem.

Thus, in the work of Strickler et al., statistically significant data on the prognosis of the development of sepsis were obtained [136]. A mechanism for interpreting machine-learning models using 17 features was proposed. The authors noted that age, chloride ion concentration, pH, and oxygen saturation should be further investigated for associations with the development of sepsis.

Machine-learning algorithms that analyze data, including pulse oximeters, in real-time are a means of predicting the development of adverse incidents in intensive care in advance, creating the possibility of adequate correction of the patient's condition in order to avoid further deterioration.

The VOSviewer program also allows researchers to display the time when the most-common terms in research appear. The closer to blue, the "older" the research (earlier publications); the closer to yellow, the more modern (recent publications). The data obtained are presented in Figure 8.

It should be noted that the time range was automatically reduced by the program due to fewer publications for 2000–2013. This analysis showed that the growth of publishing activity related to machine learning and telemedicine with the use of pulse oximeters actively began in 2020.

The conducted patent and bibliometric analysis allowed the identification of technical solutions to reduce the risks associated with pulse oximetry: improving precision and validity, technically improved clinical diagnostic use, and the use of machine learning. Generalized approaches to risk reduction when using pulse oximetry on the example of a number of patents and scientific articles are shown in Figure 9.

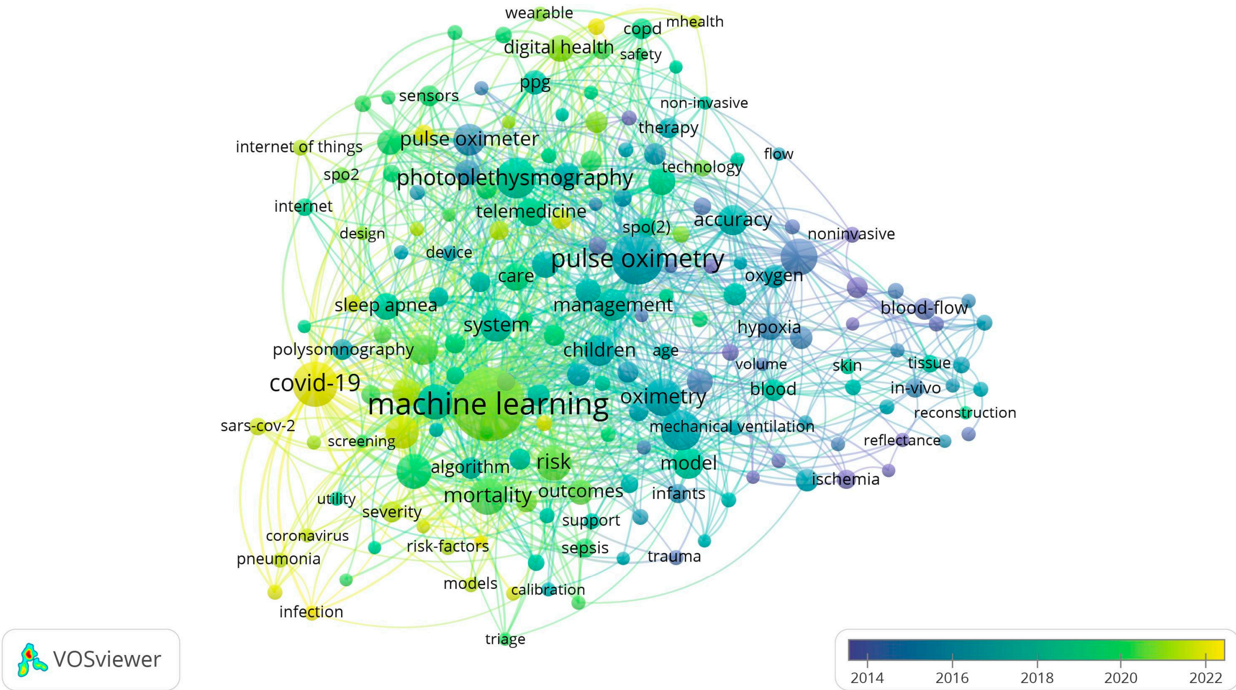

Figure 8. A conceptual map of the keywords of publications on pulse oximetry using digital technologies in the Web of Science in a time aspect.

Thus, the rational choice of strategy to reduce the risks associated with the use of pulse oximetry will allow developers and doctors to support and expand the quality and effectiveness of diagnostic, preventive, and therapeutic practices.

Our patent and bibliometric analysis of the scientific and intellectual property landscape of the use of pulse oximeters indicates their active development and implementation in medical practice. Currently, the large array of pulse oximeters can be classified according their application—from diagnostic to preventive (e.g., for a healthy lifestyle, a smart watch), and a trend in rehabilitation devices, such as monitoring of opioid overdoses.

The integration of digital technologies into pulse oximetry significantly enhances healthcare delivery by streamlining the flow of patient data, improving patient safety, enabling timely medical care, and augmenting the objectivity of clinical results and the accuracy of clinical outcomes, while reducing both the time and use of material resources.

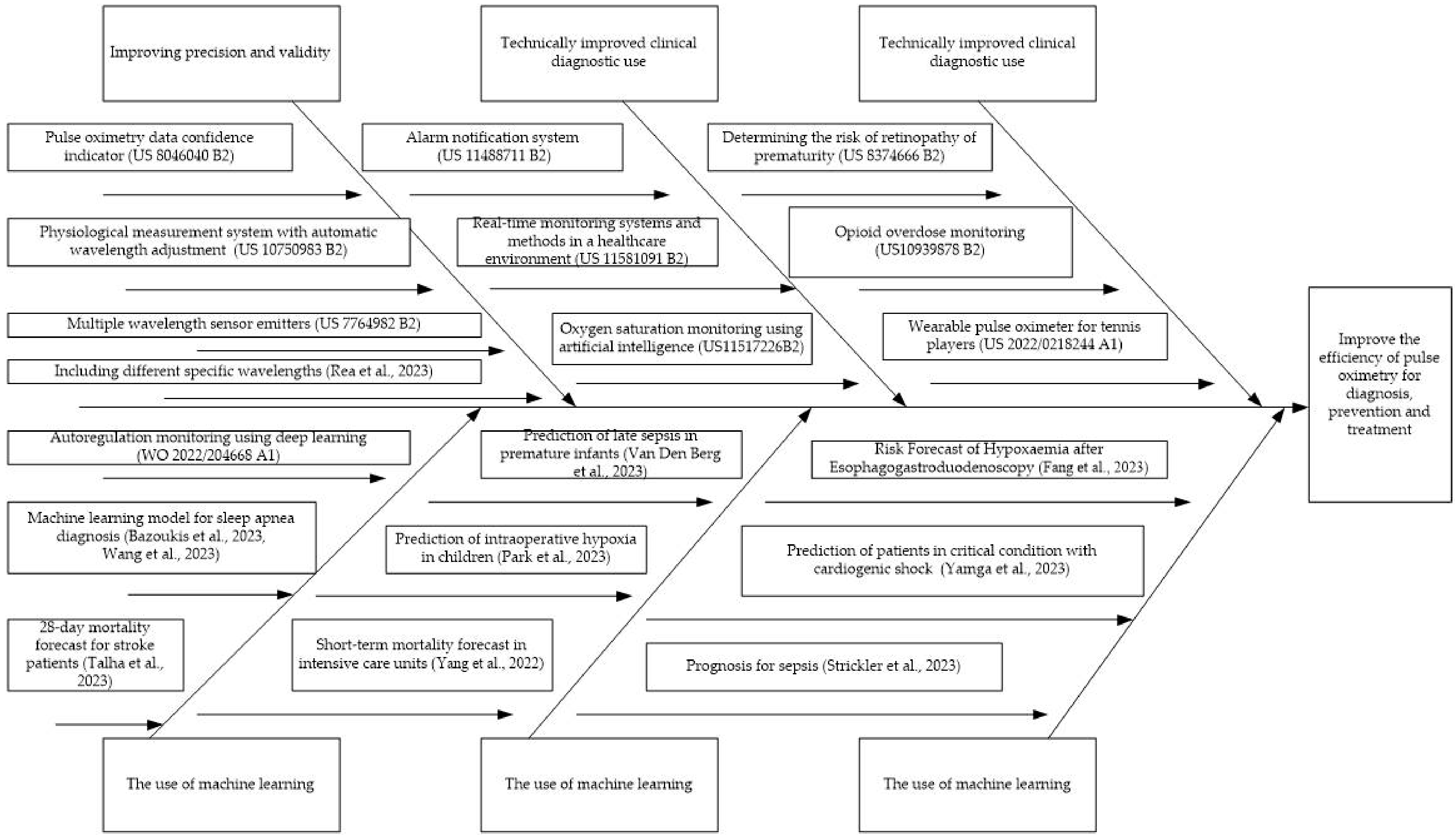

Figure 9. Generalized approaches to risk reduction when using pulse oximetry based on the example of a number of patents and scientific articles [104,113,114,120, 130,132–136].

5. Conclusions

(1) Patent analysis based on the Lens database for the period of 2000–2023 indicates the presence of a stable linear growth of patent activity in the field of pulse oximetry, with a sharp increase in the number of published patents in 2021, which may be due to the widespread use of pulse oximeters during the COVID-19 pandemic for early detection of hypoxia.

It was revealed that the United States, China, the Republic of Korea, Japan, Canada, Australia, Taiwan, and the United Kingdom are the predominant countries in patent issuance for pulse oximeter technology. Leading companies include Masimo Corporation (Irvine, CA, USA), Covidien Lp (Dublin, Ireland), Fujifilm Corporation (Tokio, Japan), Koninklijke Philips Nv (Amsterdam, Netherlands), Vioptix Inc. (Newark, NJ, USA), Nellcor Puritan Bennett (Carlsbad, CA, USA), Nihon Kohden Corporation (Tokio, Japan), Medtronic Inc. (Dublin, Ireland), etc. A number of their developments have received FDA approval.

It has been revealed that modern innovative solutions for creating and introducing pulse oximeters for various end-users (stationary, portable, for home use, pediatrics, etc.) are currently being integrated into more complex devices with a clearly traceable trend of accompanying them with digital technologies, which makes it possible to reduce the number of hospitalizations and visits to a doctor, as well as improve diagnosis and treatment.

(2) Bibliometric analysis in the Web of Science database for the period of 2000–2023 revealed a consistent temporal trend in the volume of both publications and citations, underscoring the growing importance of pulse oximeters in digitally-enabled medical practice.

The University of California system, Harvard University, the University of Oxford, the Massachusetts Institute of Technology, and the Massachusetts General Hospital were the most productive affiliations. The USA, China, England, India, Germany, Japan, Canada, Australia, Spain, and Italy were the most productive countries. Three countries (the USA, China, and England) produced almost half of the total number of publications (50.8%). The journal "Sensors" was the most productive journal. The most cited literature focuses on measurement accuracy and machine learning.

Using the VOSviewer software, we discerned six primary research clusters: (1) measurement accuracy; (2) integration with the Internet of Things; (3) applicability across diverse pathologies; (4) telemedicine and mobile applications; (5) artificial intelligence and deep learning; and (6) utilization in anesthesiology, resuscitation, and intensive care departments. The findings of this study indicate the prospects for leveraging digital technologies in the use of pulse oximetry in various fields of medicine, with implications for advancing understanding, diagnosis, prevention, and treatment, including intensive therapy. It enables clinicians to proactively identify high-risk patients, including premature infants, who may require more focused diagnostic and therapeutic interventions.

(3) The conducted patent and bibliometric analysis allowed the identification of technical solutions to reduce the risks associated with pulse oximetry: improving precision and validity, technically improved clinical diagnostic use, and the use of machine learning.

In summary, the future of digitally-augmented pulse oximeters is promising. These advances not only have great development prospects, but also contribute to enhancing patient safety and the overall quality of medical care.

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The RODI mHealth app Insight: Machine-Learning-Driven Identification of Digital Indicators for Neurodegenerative Disorder Detection

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Abstract: Neurocognitive Disorders (NCDs) pose a significant global health concern, and early detection is crucial for optimizing therapeutic outcomes. In parallel, mobile health apps (mHealth apps) have emerged as a promising avenue for assisting individuals with cognitive deficits. Under this perspective, we pioneered the development of the RODI mHealth app, a unique method for detecting aligned with the criteria for NCDs using a series of brief tasks. Utilizing the RODI app, we conducted a study from July to October 2022 involving 182 individuals with NCDs and healthy participants. The study aimed to assess performance differences between healthy older adults and NCD patients, identify significant performance disparities during the initial administration of the RODI app, and determine critical features for outcome prediction. Subsequently, the results underwent machine learning processes to unveil underlying patterns associated with NCDs. We prioritize the tasks within RODI based on their alignment with the criteria for NCDs, thus acting as key digital indicators for the disorder. We achieve this by employing an ensemble strategy that leverages the feature importance mechanism from three contemporary classification algorithms. Our analysis revealed that tasks related to visual working memory were the most significant in distinguishing between healthy individuals and those with an NCD. On the other hand, processes involving mental calculations, executive working memory, and recall were less influential in the detection process. Our study serves as a blueprint for future mHealth apps, offering a guide for enhancing the detection of digital indicators for disorders and related conditions.

Keywords: neurodegenerative disorders; mHealth apps; machine learning; digital indicators

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1. Introduction

The human brain undergoes structural changes throughout life, impacting individuals' cognitive abilities. Cognitive decline in older adults is particularly worrisome due to its medical and socioeconomic implications. Dementia, a prevalent condition among the elderly, affects approximately 5% of the elderly worldwide, while it is projected to increase due to population aging and longer life expectancy [1–3]. Biological and environmental factors play a significant role in determining outcomes, ranging from healthy cognitive aging to the development of Neurocognitive Disorders (NCDs), which can manifest years before clinical symptoms appear [4,5]. Moreover, cognitive performance does not follow a specific age pattern for peaking, as the onset and progression of cognitive decline can vary [6]. Interventions aimed at healthy adults with typical cognitive functioning are essential for promoting healthy aging and potentially reducing the risk of cognitive decline. By harnessing brain plasticity and cognitive reserve, these interventions enhance cognitive skills and resilience throughout the aging process [7,8].

The evaluation, diagnosis, and monitoring of cognitive function have traditionally been conducted in clinical settings using standardized neuropsychological assessments and interviews. However, barriers such as limited access to healthcare services and lengthy waiting lists can pose challenges for individuals, potentially deterring them from seeking necessary medical care. These deterrents restrict the vital early detection of cognitive deficits and the timely implementation of the appropriate cognitive interventions [9]. Moreover, regular monitoring is essential for accurately assessing changes in cognitive status, enabling the provision of suitable intervention strategies and support to individuals.

The integration of new sensors in mobile and wearable digital technology has revolutionized the development of a diverse range of assistive applications, addressing various needs and challenges across different domains of everyday living. Mobile health (mHealth) leverages these technologies to enhance healthcare and public health, with the potential to transform patient care, accessibility, affordability, and personalization [10]. The integration of mHealth technologies into healthcare practices is revolutionizing the way that patient care is delivered. mHealth technologies are reshaping healthcare by making medical services more accessible and efficient [11]. These tools enable patients to access care remotely, manage their health more effectively, and help healthcare providers monitor patient health in real time. This not only empowers patients but also has the potential to reduce healthcare costs and improve outcomes through better data analysis and patient management.

The acquired digital health data can be employed to develop innovative user function biomarkers, enhance the accuracy and timeliness of diagnosis, monitor treatment responses, identify individuals at risk of relapse, and provide a more objective and continuous assessment of outcomes compared to conventional methods, thereby facilitating the evaluation of intervention effectiveness [12]. The employment of mobile health applications (mHealth apps) has emerged as a promising approach to aid individuals with cognitive deficits. These apps provide interventions that leverage the capabilities of the Internet of Things (IoT) and facilitate big data analysis. By combining these technologies and focusing on vital cognitive domains, targeted mHealth apps are developed to enable the delivery of personalized and effective interventions [13]. These applications facilitate continuous evaluation and feedback, allowing users to trace their performance, identify areas for progress, and collaborate with clinicians in order to make informed decisions about their mental health.

2. Recent Developments in Mobile Platforms for Digital Evolution of Cognitive Assessment

Recent advances in mobile technology, particularly the integration of embedded sensors for passive data collection, have given rise to innovative mHealth applications for various health-related issues [14]. These innovations have been extensively used among older adults, addressing conditions like diabetes, chronic obstructive pulmonary disease, Alzheimer's disease (AD), dementia, osteoarthritis, and fall risk, employing diverse sensor and implementation approaches [15–19]. Furthermore, the use of mobile technology, particularly in the context of mental health, highlights its versatility, support features, and adaptability in addressing various health issues, further emphasizing the potential of mHealth in healthcare. These interventions have demonstrated effectiveness in alleviating depression symptoms and addressing anxiety in adults, utilizing elements like gamification, user customization, and anonymous feedback [20,21]. Mobile-based cognitive behavioral therapy has shown promise, enhancing adherence and reducing depression symptoms, especially for individuals with limited access to traditional mental healthcare [21,22]. Additionally, mHealth leverages passive sensing technology to predict mood states and improve depression and anxiety symptoms [23], offering benefits for older adults, including those with cognitive decline. Interventions employing virtual reality, serious, and interactive video games have the potential to improve accessibility, user experience, and cost-effectiveness and provide a means of remotely administering cognitive training and rehabilitation programs while monitoring cognitive health through the utilization of new data streams and identifying indicators sensitive to detecting subtle transitions in cognitive function.

In line with the current trend of leveraging mobile and wearable digital technology, various assessments that were originally paper-based have been converted into mobile-appropriate versions, such as the eSAGE, e-CT, and eMoCA. These mobile-appropriate digital versions have demonstrated high diagnostic accuracy in distinguishing Mild Cognitive Impairment (MCI) and AD patients from healthy older adults. In addition, they offer several advantages over traditional paper-based tests, including enhanced reliability and efficiency [24–27].

However, it is essential to acknowledge the emphasis placed by researchers on the need to establish new normative standards that are specifically designed for digital assessments, particularly when validated cognitive assessments are converted into mobile-appropriate digital formats. This recommendation stems from a comparative study that revealed notable differences in both overall scores and individual item scores between mobile-appropriate digital assessments and traditional paper-based examinations [28]. These findings underscore the significance of developing appropriate benchmarks and reference points to ensure an accurate interpretation and evaluation of cognitive performance using digital assessment tools. By establishing standardized norms, the field can effectively leverage the potential of digital assessments in enhancing the assessment and management of cognitive function.

Mobile-appropriate digital versions of cognitive assessments have gained acceptance not only compared to traditional paper-based assessments but also in comparison to digital computer-administered counterparts. In particular, users report a superior experience with the digital version for mobile devices, considering their performance to be superior to the corresponding one through the evaluation conducted on desktop computers [29]. Additionally, the research emphasizes the accessibility and user-friendly nature of mobile devices, particularly for individuals facing physical challenges such as arthritis or tremors, as well as those with limited familiarity with traditional computer interfaces [29]. These findings highlight the enhanced user experience associated with mobile platforms and provide further support for the strong preference for mobile versions of cognitive assessments.

In the field of cognitive assessment, significant advancements have been made in the development of tests specifically for mobile devices and in the utilization of novel data streams [30–32]. These innovations aim to identify and distinguish different stages of cognitive decline [33–35]. Mobile screening tests and test batteries have emerged as effective tools, enabling the active participation of older adults in their cognitive assessment and monitoring [36–38].

Furthermore, mobile-appropriate cognitive evaluations have demonstrated strong correlation with validated cognitive assessments [34,37–39]. Their ability to provide high-quality cognitive screening without the need for clinician input is a notable advantage of these assessments. They also demonstrate the potential to be effectively deployed in both clinical and non-clinical settings, thereby promoting improved health outcomes and supporting individuals' independence [39]. This feature enables their suitability for a wide range of healthcare settings, including community-based initiatives involving non-clinical personnel [39]. The integration of mobile platforms with person-centered care principles has allowed for the provision of individualized features [40]. Continuous and repeated evaluation is facilitated by suitable mobile assessments allowing for the collection of digital biomarkers of cognitive impairment, leading to the detection of patterns and changes that are often difficult to detect [41,42]. Moreover, the integration of data derived from mobile assessments with electronic health records holds promise for further enhancement of cognitive evaluation practices [37].

However, the accessibility of mHealth apps that effectively cater to a broad spectrum of cognitive domains, operate within user-selected environments and timeframes, enable unsupervised self-administration, function on a single user mobile device, and assist the purpose of training, evaluating, and monitoring, while also facilitating discreet data collection, is currently limited [13,43].

Additionally, expanding the target population beyond individuals with cognitive deficiencies to include all adults presents a significant challenge. To address this significant gap, we recently published a mHealth application, the RODI app [44], tailored to meet these multifaceted needs. The RODI app is a mobile application designed to enhance cognitive function, seeking to uplift the user's overall well-being and psychological state (further information in the following section). In this study, we utilized the RODI app on both healthy participants and those diagnosed with NCDs to identify their unique features and the primary elements that differentiate them.

In this context, the RODI application [44] was presented, which is an intervention specifically designed for mobile devices with a dual objective. Firstly, it aims to provide process-based training to enhance function and address deficits across various domains. The application offers a user-friendly experience on mobile devices, enabling active engagement with tasks and thereby fostering motivation and enjoyment [44]. In addition, the RODI app offers several advantages in the context of assessment. It facilitates continuous and repetitive evaluations while discretely collecting data. The obtained data allow for trend identification, enabling the monitoring of changes in users' performance. This approach provides a more comprehensive understanding of abilities and their fluctuations, which may be challenging to discern through traditional assessment methods.

Harnessing the features of the RODI app, users can enhance their monitoring and analysis of performance, resulting in more informed decision making and personalized interventions. Primarily targeting older adults with cognitive deficits, the app is also suitable for healthy adults aiming to assess and enhance their reserve. It allows individuals to self-administer cognitive tasks in their preferred environments and timeframes. Operating on a single mobile device and presenting a variety of tasks and difficulty levels, the RODI application intends to offer users a challenging and stimulating experience that supports cognitive health.

The RODI app was developed using a user-centered approach, which involved pilot testing the application in a sample of cognitively healthy adults ranging in age from 21 to 88 years old. The feedback collected from this pilot testing was then used to refine and optimize the application to better meet the needs of its users. The app's pilot usage revealed that adults were willing to use mobile technologies for cognitive stimulation, with participants acknowledging the importance and convenience of such technologies for cognitive awareness [44].

3. Materials and Methods

3.1. Case Study Description

Having originally pioneered the RODI mHealth app as an innovative approach for NCD detection, we assess its effectiveness and explore its full potential. We employed the RODI app in an extensive, methodologically robust study that encompassed a diverse cohort of 182 participants, including both individuals diagnosed with NCDs and healthy controls (Figure 1). Our primary objective was twofold: firstly, to harness advanced machine learning techniques to analyze the data, aiming to discern clear patterns and indicators representative of NCDs; and secondly, to interpret these findings biologically, providing a holistic understanding of the underlying mechanisms. Our aim is also to exploit the insights from this study to guide the evolution of the RODI app. Our ambition is to integrate the knowledge acquired, refining the app into a more robust version enhanced by artificial intelligence. Although RODI's cognitive tasks align with the standard criteria for NCDs [45], we believe that AI can contribute significantly to building an upgraded version for better detection of early signs of NCDs. In the subsequent subsections, we provide a detailed elaboration of the experimental study methodology and findings.

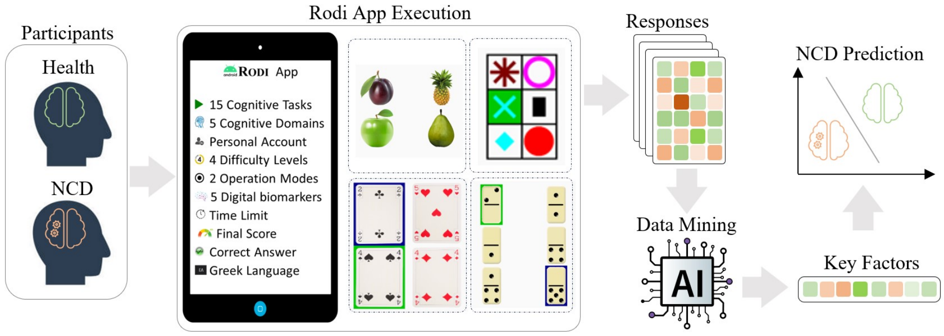

Figure 1. The figure illustrates the deployment of the RODI app in a robust study with 182 participants, including both NCD-affected individuals and healthy controls. Within the app, users engaged with 15 distinct cognitive tasks. We adopted an ensemble feature selection method to pinpoint the most significant tasks based on participants' performance data. This method utilized an ensemble Variable Importance (VI) metric derived from analyses conducted by three advanced classifiers: XGBoost, LightGBM, and CatBoost. Following data collection, we ranked these cognitive tasks using the Borda count technique to determine their relative importance. The final analysis revealed the key tasks that effectively differentiate between NCD and healthy cognitive states.

3.2. Participants

Several elderly care centers, open care centers for the elderly, day care centers for patients with dementia, and workplaces were approached for the recruitment of participants. The potential participants were introduced to the RODI mHealth app and the study's intentions, and they were informed about the research approval obtained from the Ionian University's Research Ethics and Deontology Committee (protocol number 3600). The research population included patients diagnosed with NCDs and healthy participants. This research was conducted from July 2022 to October 2022.

A total of 182 individuals participated in the study, with non-randomized and non-blinded selection criteria. Among the participants, eight (8) individuals had been diagnosed with NCD, including diagnoses of subjective cognitive decline, mild cognitive impairment, early dementia, and moderate dementia. The study included 99 female participants (54.4%) and 83 male participants (45.6%). The mean age of the participants was 46.1 years, with a mean of 15.58 years of education. The age of the participants ranged from 19 to 89 years old. Out of the total participants, 34 individuals (18.68%) were retired, while 148 individuals (81.32%) were still employed.

3.3. RODI App Execution

The mHealth RODI app comprises ten cognitive tasks, including three that present alternative response formats in either images or words. Additionally, one of these tasks is re-evaluated twice, increasing the total number of tasks to fifteen. The Back Task is intended to test the user's ability to recall a displayed integer and enter it via a keypad, with recall tested one and three tasks later. The New Object Task presents the user with a set of images, with one replaced, and requires identification of the new item. In the Object Series Task, the user is requested to identify the original items in a set of objects or words. The Colours And Shapes Task is a speeded selection task of a specific combination (shape/color). The Calculating Task presents numerical values as images for simple arithmetic operations. In the Shapes Task, the user must identify the original location of a missing colored shape. The Colour-Shape Task involves the user matching a colored shape to columns of different shapes and colors. The Descending Integer Task presents the user with three consecutive numbers in a descending sequence, with the user asked to calculate the next or second term. In the Name Task, the user is presented with a name in capital letters made up of straight segments and is required to find the number of segments used. The Who Task requires the user to match images of individuals with their corresponding names, with different shots of the images shown. The user's choices and responses, time taken, and accuracy are tracked and scored. Difficulty levels in all tasks increase with a growing number of elements or complexity, which helps to continuously challenge and stimulate users' cognitive abilities.

We utilized a tailored lighter version of the RODI app, specifically designed for one-time use per participant on personal or shared Android® mobile devices. The app was modified to a single protocol configuration to ensure consistency, operating in default Practice mode without a time limit, and displaying the correct answers after each task. Tasks were presented in random order with levels of difficulty alternating between Easy and Medium to accommodate this extended demographic of participants. To ensure variability in the required answer formats, tasks with different conditions, such as providing an image or a word as the answer, were presented in rotation. This approach allowed participants to encounter diverse formats in each task, contributing to a more comprehensive cognitive assessment and reducing potential biases in the data. The app's features were adjusted, disabling unnecessary features, while retaining essential functions like Sign In, Practice mode, Show Correct Answer, and Show Results.

Data collection was conducted utilizing Firebase Cloud Storage. This approach enabled discrete data collection while restricting access to authenticated users only. Participants granted digital consent before creating an account and receiving comprehensive information regarding the research's objectives, data collection procedures, anonymization processes, and subsequent analysis. During the study, several tablets were employed, each equipped with the pre-installed lighter configuration of the RODI app.

3.4. Methodology

We employed a Machine Learning (ML) workflow to analyze the data collected from the RODI application. ML algorithms were utilized to automatically discover patterns and relationships in the data, offering a unique perspective that can uncover non-linear relationships often missed by traditional statistical models. This ML approach is particularly advantageous for complex and unstructured data, providing valuable insights that are difficult to obtain through conventional statistical analysis. Leveraging ML techniques to analyze data collected from smartphones and tablets has the potential to significantly enhance the user experience, customizing it to individual needs and maximizing efficiency.

3.4.1. Dimensionality Reduction Techniques for 2D Data Visualization

The study specifically used dimensionality reduction techniques to project the RODI application's responses, aiming to differentiate between healthy individuals (Health state) and those diagnosed with Neurocognitive Disorders (NCD state). This visualization approach enabled the identification of patterns and trends within the data, potentially leading to the discovery of biomarkers and therapeutic targets. Three dimensionality reduction techniques, including t-SNE [46], UMAP SNE [47], and PCA SNE [48], were employed to assess the separability of the RODI outcomes, providing insights into the performance and predictive power of the reduced data.

3.4.2. NCD Prediction Performance

The study aimed to evaluate the prediction performance of RODI outcomes in binary classification, distinguishing healthy individuals from those with NCDs. To achieve this, five classifiers were employed: k-Nearest Neighbors (k-NNs), Support Vector Machines (SVMs), naive Bayes, decision trees, and Random Under Sampling and Boosting (RUSBoost) [49]. The latter was selected as the majority of samples belonged to the healthy class. K-NN is a supervised learning algorithm that classifies a new observation based on its nearest neighbors. SVMs find the best boundary to separate different classes. Naive Bayes is a probabilistic classification algorithm based on the Bayes theorem. Decision trees create a tree-like model of decisions, and RUSBoost is an ensemble method combining random under-sampling and boosting techniques to handle imbalanced datasets.

3.4.3. Feature Importance

In our experimental study, 182 participants engaged with the RODI mHealth app, completing 15 brief tasks, which resulted in a 182 × 15 data matrix. We implemented an ensemble feature selection strategy aimed at identifying the most dominant tasks regarding NCD identification. Our unique framework relies on the Variable Importance (VI) measure, extracted from three state-of-the-art classifiers: XGBoost, LightGBM, and CatBoost. We then systematically prioritized these 15 features by employing the Borda count. The integration of machine learning within our method unfolds immense potential, offering both precision and depth to our results. Machine learning, especially with robust classifiers like XGBoost [50], LightGBM [51], and CatBoost [52], can discern intricate patterns within large datasets, revealing relationships that might be obscured for conventional methods. In essence, the adoption of such an ML-driven approach not only amplifies the accuracy of our findings but also provides a richer, deeper understanding of the data, enabling us to draw more nuanced insights from the RODI app's results.

The logic behind this approach is to leverage the strengths of each classifier to gain a comprehensive understanding of the data. These classifiers evaluate the tasks based on their 'Variable Importance' (VI), which is a measure indicating how much each task contributes to the accuracy of the model in predicting NCDs. Feature selection is a critical process in machine learning that involves selecting a subset of relevant features (or variables) for use in model construction. Removing irrelevant features can lead to improved accuracy for machine learning models. Also, by eliminating redundant or irrelevant features, feature selection helps to reduce the chances of a model overfitting to the training data. More specifically, XGBoost operates on gradient-boosted decision trees. The variable importance in XGBoost is calculated by taking into account the number of times a variable appears in a tree across the ensemble of trees. Mathematically, for a given feature f:

$$VI_{XGBoost}(f) = \sum_{t=1}^{T} I(f \text{ appears in tree } t), \tag{1}$$

where T is the total number of trees and I is the indicator function. LightGBM, another gradient-boosting framework, computes feature importance by considering two aspects: "split" and "gain". While "split" counts the number of times a feature is used in a model, "gain" measures the contribution brought by a feature to the model. For a feature f:

$$VI_{\text{Light } GBM}(f) = \sum_{t=1}^{T} \text{ Gain } (f \text{ in tree } t), \tag{2}$$

where Gain represents the improvement in accuracy brought by a feature. CatBoost, a boosting algorithm built on categorical features, determines feature importance by tracing back through the trees in the model and measuring how much each split improves the loss function. For feature f:

$$VI_{\text{CatBoost}}(f) = \sum_{t=1}^{T} \Delta \text{ Loss } (f \text{ in tree } t), \tag{3}$$

where Δ Loss represents the change in the loss function due to the inclusion of the feature in tree t. From the above three classifiers, we exported the VI score for each task within RODI, reflecting their capability to differentiate between the NCD and Health states. Then, we applied the Borda count method [53], a rank-based approach that is employed to prioritize and rank features. In our context, for each classifier, features were ranked based on their variable importance, with the most important feature receiving the highest rank (e.g., 15 for the most important, 1 for the least). These ranks were then aggregated across all classifiers. For a feature f:

$$\text{Borda}_{\text{count}}\,(f) = \sum_{c=1}^{C} \text{Rank}_c(f), \tag{4}$$

where $\text{Rank}_c(f)$ is the rank of feature f in classifier c and C is the total number of classifiers. The features were then prioritized based on their cumulative Borda count, with higher counts indicating greater overall importance across classifiers.

4. Results

Before delving into the intricacies of machine learning, it is imperative to first understand the inherent nature and behavior of our data. Thus, we initiate a primary exploration focusing on the 15 feature tasks derived from the RODI app. By doing so, we aim to establish a foundational perspective on the inherent information within the data and discern any preliminary patterns or distinctions, setting the stage for subsequent, more advanced analyses.

Our first visualization, a violin plot (Figure 2), exhibits the distribution of each of the 15 feature tasks across the two states: Health and NCD. At a cursory glance, the plot illustrates a complex dataset where the boundaries between the two states are not distinctly demarcated. Such overlaps and intricacies in the data distribution underscore the need for a more sophisticated approach, positioning machine learning as an invaluable tool in extracting meaningful insights from such intricate datasets.

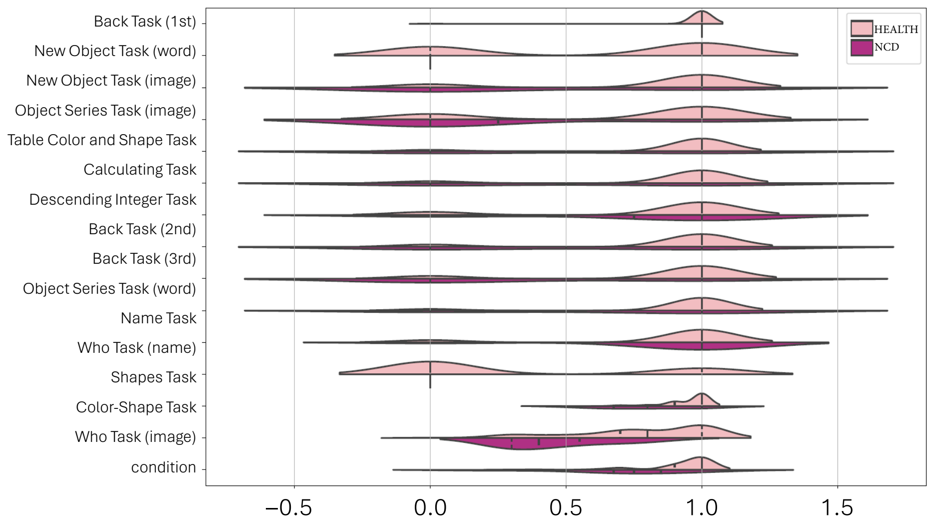

Figure 2. Violin plot illustrating the distribution of 15 feature tasks across two states: Health and NCD. The overlapping distributions highlight the complexity of the dataset and the challenges in distinguishing between the two states.

Subsequently, we turn our attention to a heatmap showcasing the correlations among the feature tasks (Figure 3). Interestingly, the heatmap does not highlight any significant correlations among the tasks. This lack of strong correlations further complicates the dataset, making traditional analysis techniques less effective in distilling knowledge. This emphasizes the challenge in our dataset, reinforcing the perspective that machine learning, with its advanced algorithms, stands as one of the few methods adept at effectively navigating and extracting meaning from such multifaceted data landscapes.

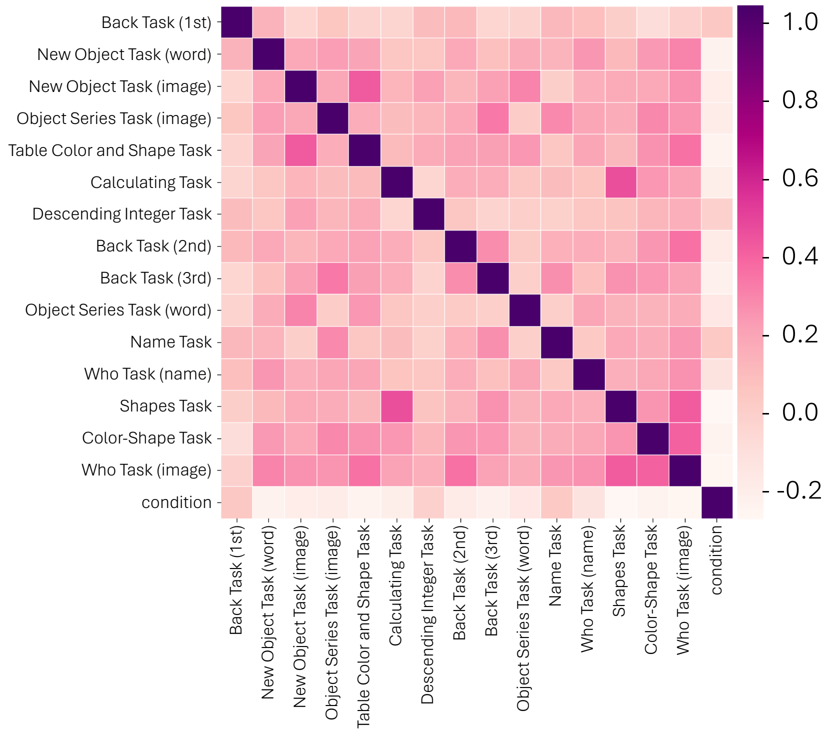

Figure 3. Heatmap displaying the correlations among feature tasks. The absence of significant correlations underscores the complexity of the dataset and the necessity for advanced machine learning techniques to decipher it.

The findings (Figure 4) suggest a noteworthy degree of overlap between the Health and NCD categories, which poses a considerable challenge in the clear differentiation of individuals. This intricate data complexity underscores the multifarious nature of the problem, emphasizing the requirement for machine learning techniques capable of handling the aforementioned limitations.

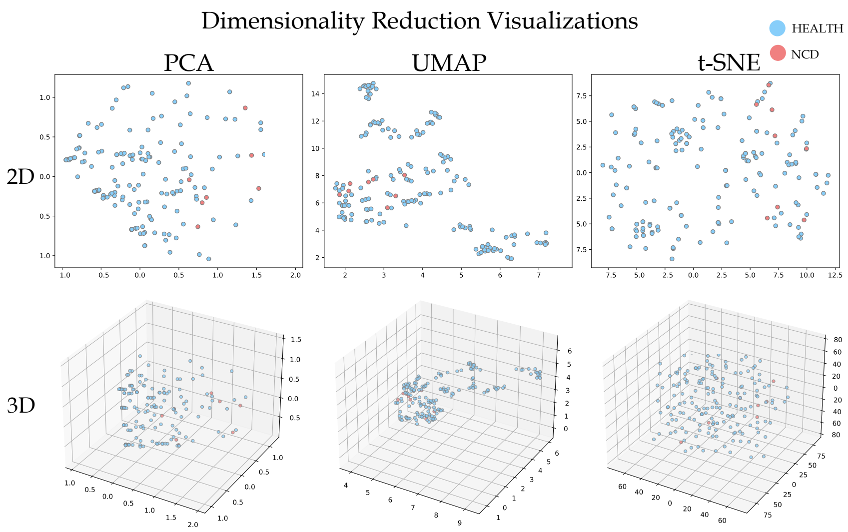

Figure 4. Visualization of RODI application responses using dimensionality reduction techniques: t-SNE, UMAP SNE, and PCA SNE. The projection aims to differentiate between the Health state and NCD state, highlighting patterns and potential biomarkers within the data.

Concerning the prediction performance, a 10-fold cross-validation technique was employed to evaluate the performance of the algorithms. The models were trained and tested 10 times independently to ensure the robustness of the results. The default parameter settings of each algorithm were utilized; however, a significant improvement in the performance metrics was observed through the variation in the parameters. All algorithms were examined using six measures: balanced accuracy, F1-score, specificity, sensitivity, precision, and false positive rate (Figure 5). Balanced accuracy was utilized as a metric to address class imbalance in the dataset by averaging the recall rate of each class. It is particularly useful for binary classification problems with under-represented classes. The F1-score is a measure of model accuracy that considers the harmonic mean of precision and recall. Precision is the ratio of true positive instances to the total number of true positive and false positive instances, while recall is the ratio of true positive instances to the total number of true positive and false negative instances. The F1-score is beneficial for imbalanced datasets because it equally emphasizes precision and recall. Specificity measures a classification model's ability to correctly identify negative instances in binary classification problems. It is defined as the proportion of True Negatives (TNs) out of all instances that are negative (TN + FP). Lastly, the false positive rate indicates the proportion of negative instances that were misclassified as positive. By examining all these measures, we adopted a systems view of the evaluation, ensuring a holistic understanding of the algorithm's performance across various facets of classification.

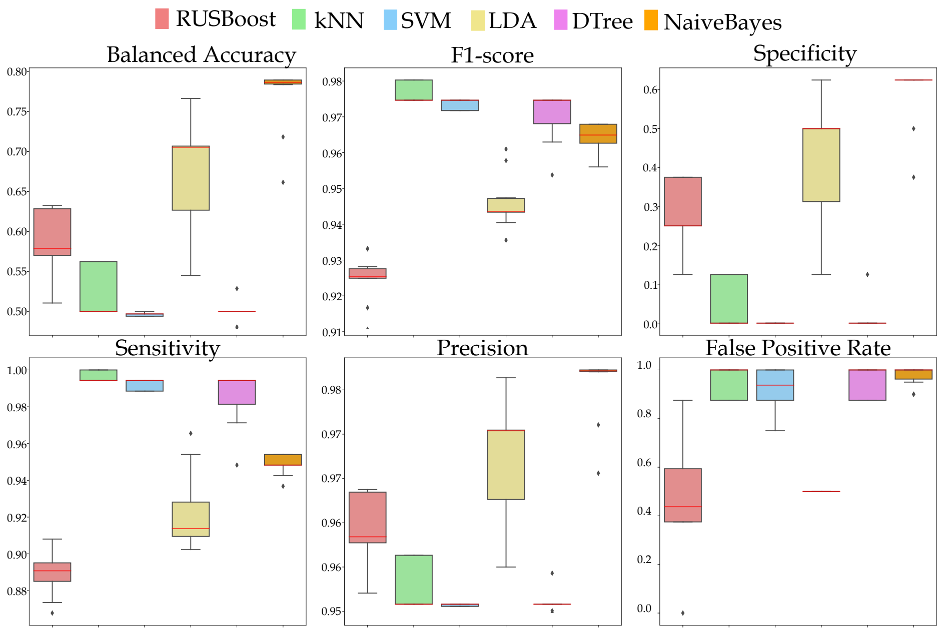

Figure 5. Boxplots illustrating the performance of five classifiers (k-NN, SVMs, naive Bayes, decision tree, and RUSBoost) in predicting RODI outcomes for binary classification of Health and NCD states. Using a 10-fold cross-validation, the models were trained and tested through 10 independent iterations. The evaluation assessed balanced accuracy, F1-score, specificity, sensitivity, precision, and false positive rate.

Our study revolves around a crucial factor, a novel ensemble method, which isolates the most critical elements in the classification of NCDs. The results of our analysis, which ranks the 15 tasks from the RODI mHealth app based on their importance in NCD identification using the Borda count ranking system and Variable Importance (VI) measures from XGBoost, LightGBM, and CatBoost classifiers, are presented in Figure 6. This ranking emphasizes the significance of tasks related to visual working memory in distinguishing between healthy individuals and those with NCDs.

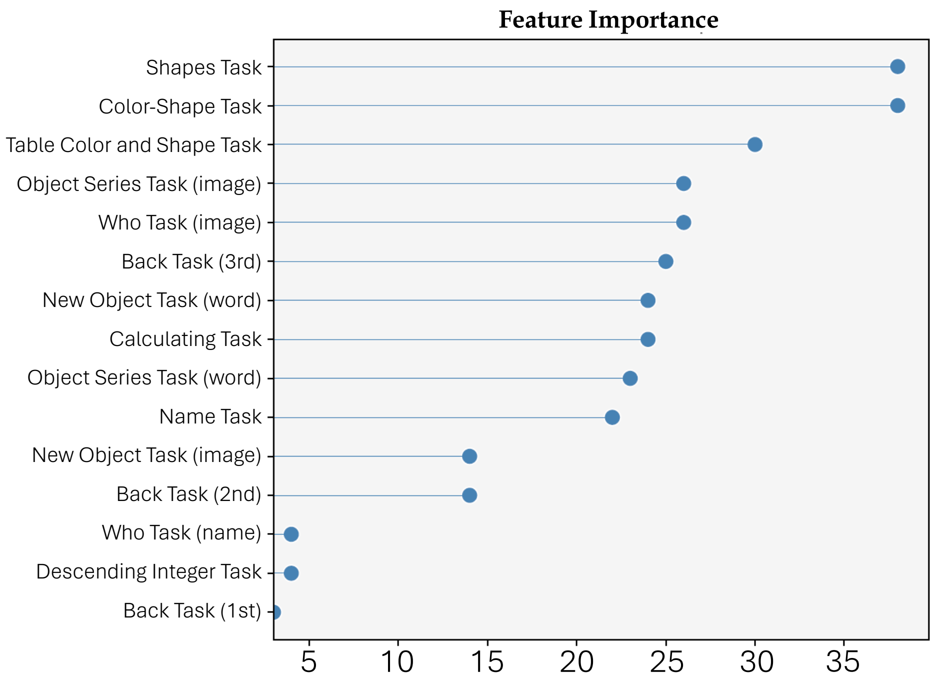

Figure 6. Dot plot ranking of the 15 tasks from the RODI mHealth app based on their importance in NCD identification. Features were prioritized using the Borda count ranking system, derived from the Variable Importance (VI) measure of three classifiers: XGBoost, LightGBM, and CatBoost. Our analysis revealed that tasks related to visual working memory were the most significant in distinguishing between healthy individuals and those with NCD. In contrast, processes involving mental calculations, executive working memory, and recall were less influential. This ensemble feature selection strategy showcases the potential of machine learning in discerning key patterns for NCD detection.

5. Discussion

The escalating global concern around Neurocognitive Disorders (NCDs) underscores the importance of early and effective detection methods. Early identification of NCDs is not just medically pertinent but is pivotal for optimizing therapeutic outcomes. With the evolution of technology, mobile health applications (mHealth apps) have burgeoned as potential tools to cater to this need, especially for those with cognitive deficits. In this evolving landscape, our study presents the RODI mHealth app, a tool that we developed to cater to this very demand. Designed in alignment with the diagnostic criteria for NCDs, the RODI app employs a series of concise tasks as an innovative approach to discern NCD patterns. Drawing from a sample of 182 participants, both with NCDs and healthy individuals, our comprehensive study ventured to probe the app's efficacy in differentiating between the two groups.

The focus was not only on the app's diagnostic ability but also on streamlining the app's features, identifying those most indicative of NCDs. To achieve this granularity, we leveraged an ensemble approach, utilizing the feature importance metrics from three cutting-edge classification algorithms. Our findings spotlighted tasks related to visual working memory as the most pivotal in distinguishing between healthy individuals and those with NCDs. Conversely, tasks related to mental calculations, executive working memory, and recall proved less essential. Interestingly, our results showed that participants, regardless of their technological proficiency and background, could navigate the app effectively, hinting at its user-friendly design.

The RODI app stands as a testament to the potential of mHealth apps in the sphere of NCD screening. Its ability to segregate healthy adults from those with NCDs amplifies its relevance as a screening tool, making it a promising candidate for future adaptations and wider clinical applications. This study sets the stage for future research, serving as a reference for mHealth app developments aiming to enhance the identification of digital markers for disorders and allied conditions. In the evaluation of performance differences between cognitively healthy adults and NCD patients, the feature importance scores obtained from the random forest algorithm were utilized to identify the critical features that differentiate between the two groups. The aim was to determine the most important characteristics that predict the outcome of interest, and the identified features were used to distinguish between Health and NCD conditions.

Furthermore, the study's findings indicate that the top five tasks that received the highest importance scores are dependent on visual working memory abilities. These results underscore the critical role of evaluating visual working memory skills to identify cognitive impairments and aid in diagnosing and tracking cognitive decline. These findings align with earlier research conducted on both individuals who are cognitively healthy and those who have cognitive disorders. The accurate recall of fundamental visual features, such as color, shape, brightness, size, orientation, and texture, heavily relies on memory capacity and the ability to associate them correctly in memory. The developmental trajectory of visual working memory abilities shows a peak around the age of 20, followed by a gradual decline. Immediate visual memory is poorer in individuals aged 55 and above compared to young children [54]. Additionally, aging differentially impacts short-term feature memory and binding memory, with a decline in short-term color–shape binding memory primarily attributed to a reduced capacity for retaining individual features [55].

Moreover, the Shapes Task obtained the highest importance score, surpassing the immediately following task by at least 0.6 and the third task by 1.40 in order of significance scores. This specific task combines visual working memory skills and spatial representations. The observation aligns with previous studies indicating that spatial abilities decline with normal aging, albeit not uniformly, and that visuospatial deficits can manifest in very early stages of dementia. Spatial information encompasses processes and data required for determining positions and directions in one's surroundings, including fundamental spatial abilities like object location memory. Humans utilize two primary frames of reference, namely the egocentric and allocentric, to encode and organize spatial information in memory [56,57]. Prior studies have indicated that allocentric representations operate at a slower pace compared to egocentric ones [58]. Visuospatial information and processes are essential for non-verbal cognitive functions that involve the representation and manipulation of information spatially [57]. The decline in spatial memory associated with healthy aging is influenced by coherent factors as well as attentional and executive [59]. In the early stages of AD, visuospatial deficits manifest as impairments in various cognitive abilities, including constructive skills, visuospatial intelligence, spatial short-term memory, and spatial orientation [59]. These spatial orientation difficulties are evaluated as early signs of dementia and are frequently attributed to hippocampal damage, which is crucial for both general and spatial memory [60–62]. Furthermore, research findings suggest that neurodegenerative processes affect visual neural pathways, potentially contributing to declines in other cognitive domains [63]. Some researchers proposed that visuospatial deficiencies may occur very early in the course of dementia, while the allocentric component of spatial memory has been suggested as a potential predictor of AD from MCI and early-onset dementia [64–66]. Overall, deficits in spatial memory are crucial in understanding cognitive decline and may serve as an indicator demonstrating departure from normal aging [59].

The task ranked second in terms of importance scores demonstrated superior performance compared to the third-ranked task by a margin of 0.60. Similarly, the third-ranked task outperformed the subsequent task by approximately 0.40. In addition to evaluating visuospatial working memory skills, these tasks also assess executive function, which Miyake and Friedman [67] describe as higher-order cognitive processes that allow individuals to adapt their behavior in response to contextual changes, with a particular focus on inhibition and cognitive flexibility. Diamond's model [68] identifies three main components of executive function, namely inhibition, working memory (including visuospatial working memory), and cognitive flexibility, that facilitate the development of complex cognitive processes. Previous research has reported deficits in inhibitory control [69,70] and partially in cognitive flexibility [71,72] in patients with AD. Additionally, it is indicated that individuals with MCI exhibit deficits in tasks that assess executive function, including inhibition and cognitive flexibility [73]. The findings suggested that these tasks may offer clinically relevant information about the decline in executive functions in individuals with MCI, providing diagnostic potential by assessing their discriminatory power. Similar results were observed in individuals diagnosed with dementia, indicating a clear executive deficit in inhibitory control and a partial deficit in cognitive flexibility [74]. The researchers suggested that there exists an executive functioning profile in AD, characterized by impairment in inhibitory control and cognitive flexibility, where performance variations may reflect differences in executive function deterioration levels during Alzheimer's disease progression. Furthermore, the researchers noted that the use of computerized versions of these tasks provides more precise measurements of reaction times and accuracy, which are more discriminative and sensitive in detecting executive function decline, indicating their usefulness in neuropsychological batteries for MCI diagnosis.

According to the importance scores, projects that assess visuospatial abilities rank higher than other visual projects, which is consistent with the findings of Alescio-Lautier et al. [64]. In their study, they examined whether visual or visuospatial modalities were more affected in early memory impairment in Alzheimer's disease by comparing AD and MCI patients with healthy controls. The results indicated that both MCI and AD patients exhibited impairments in short-term memory and visuospatial short-term memory when compared to the healthy control group. Notably, the impairment in spatial performance was more pronounced than in visual performance. MCI patients exhibited intermediate performance levels between the healthy controls and AD patients. Additionally, the cognitive memory profiles differed based on the modality tested, indicating distinct underlying processes. Specifically, AD patients exhibited more significant visuospatial deficits and were more impacted by experimental modifications, possibly due to a phenomenon known as the attentional blink. This phenomenon leads to temporary functional blindness when sequentially presented stimuli are presented rapidly. The researchers suggested that differences in visual recognition may result from deficits in attentional and executive resources, while scarcities in spatial recognition may be indicative of a genuine spatial disorder.

In terms of importance scores, the projects related to executive working memory rank from 8th to 12th, exhibiting a range of approximately 0.25. However, the Object Series Task (image) stands out as an exception, with an importance score exceeding 1 (namely 1.44) and securing the fourth rank. The unique characteristic in question can be attributed to the task's demand for identifying, in a random sequence, the precise arrangement of images that do not have explicit correspondences with identifiable objects that can be linked to language. The images employed in this task derive from mahjong and domino tiles as well as playing cards and dices, thus heightening its level of difficulty. Image memory tasks are employed to evaluate executive working memory, and their potential utility in assessing individuals with MCI and AD has been extensively explored. Studies have demonstrated that AD patients perform poorly on conventional tests of executive function [75] and working memory [76], which is attributable to impairments in the central executive function [77]. The prefrontal cortex primarily processes executive control [78] and the significant accumulation of plaques in the frontal lobes observed could account for the lower executive function scores in AD patients [79,80]. According to an exploratory study that investigated EEG changes during memory tasks, including word memory, it was observed that the picture memory task showed notable EEG differences between MCI patients and controls [81]. Moreover, in a study focused on identifying a potential biomarker for distinguishing between MCI and AD, multi-domain cognitive testing was used to evaluate executive working memory in patients with MCI and AD compared to control participants [82]. The study was consistent with previous findings that executive working memory is significantly impaired in both MCI and AD patients compared to controls. Furthermore, a positive correlation was found between executive working memory tasks (word and picture memory) and MCI, suggesting that better performance in these tasks may lead to improved global cognitive scores. Executive working memory was found to be more severely affected in AD patients compared to both MCI and controls. Additionally, a negative relationship was observed between word and picture memory tasks and Clinical Dementia Rating. Among the administered cognitive tests, picture memory was found to be more robust, exhibiting high sensitivity and specificity compared to controls. These findings indicate that the picture memory task may be a useful tool for distinguishing differences among all groups and therefore may aid in the early detection of cognitive impairment, enabling timely interventions.

In the context of image selection, the Who Task holds the fifth rank in order of score importance, whereas its counterpart with name selection ranks third from the end, with a minimum difference of 0.5 between them. The formation of face–name associations is a widely recognized challenging task, particularly among older adults, who frequently report difficulties in remembering proper names [83]. Conversely, the association of a face with other biographical information, such as occupation or hobbies, is relatively easier, primarily due to the inherent unrelatedness of a face with a name [84]. This specific task lacks contextual cues, making it difficult to form an associative link between a proper name and a unique face, thereby requiring higher cognitive effort. Successful performance on face–name association tasks has been linked to increased brain activity within memory-related networks in both young and older populations [85]. The rank of the Who Task in the case of image selection is consistent with the findings of previous studies. A review of studies exploring the use of a demanding test of face–name associative memory as a tool for early diagnosis of AD concluded that it may be a valuable diagnostic tool, and its performance is related to Aβ in brain regions associated with memory systems [86]. Additionally, a computerized, self-administered test was found to be suitable for discriminating between cognitively healthy and amnestic MCI individuals [87]. Performance on this test was associated with AD cerebrospinal fluid biomarkers, enabling the detection of memory-impaired cases resulting from other aetiologies. Furthermore, the researchers stated that the test can detect the AD endophenotype and is associated with AD-related changes in MRI and cerebrospinal fluid in patients with early-onset MCI.

In terms of tasks requiring the user to input answers using the device's built-in keyboard, the Back Task (3rd) ranked highest, appearing as the sixth task in descending order. This task involves delayed recall, occurring three tasks after the number to be recalled is presented. On the other hand, Immediate recall, Back Task (1st), ranked last, with a significance score of only 0.01. Back Task (2nd), a post-immediate recall task, was ranked eleventh in terms of importance score. These findings are consistent with prior research that has demonstrated an association between lower scores on delayed recall tasks and older age [88]. Delayed recall tasks have been shown to be the most effective neuropsychological predictors of conversion from MCI to AD [89,90]. Moreover, a study by Sano et al. [91] aimed at determining the usefulness of delayed recall assessment in clinical trials for MCI and AD showed that the addition of delayed recall increased the sensitivity to detecting changes in subjects with MCI, while it increased the variance in subjects with AD, even in those with mild impairment.

In the context of mental calculations, which involve arithmetic operations performed without the aid of devices or tools, the Calculating Task ranks seventh in terms of importance with a score of 0.73, followed by the Name Task in tenth place with a score of 0.65. Conversely, the Descending Integer Task is ranked second, but only has an importance score of 0.1. Mental calculation is a fundamental mathematical skill that is closely related to procedural fluency, one of the five main components of mathematical proficiency, which refers to the ability to perform procedures efficiently, accurately, and flexibly. According to an exploratory study that investigated EEG changes during memory tasks, including word memory, it was observed that the picture memory task showed notable EEG differences between MCI patients and controls [92,93]. With an aging population, the likelihood of cognitive deterioration is expected to increase, potentially affecting financial capabilities [94].

Such deficits in financial abilities within this demographic could also present societal risks. In particular, written arithmetical skills have been identified as the key predictor of financial capability across the various stages of dementia [95]. Patients with MCI may experience difficulties with mathematics that affect their everyday functioning. In a study investigating the brain changes and cognitive factors associated with these deficits, researchers noted that among MCI patients, issues with number comprehension and formal numerical performance were linked to variations in brain volume in the right middle occipital and right frontal gyrus region deficits [92]. These findings indicate that early neuropathological changes in various brain areas, including the frontal, temporal, and occipital regions, can lead to cognitive deterioration in MCI, affecting daily numerical functioning. As a result, they have significant implications for the diagnosis, clinical care, and at-home support of MCI patients.

Furthermore, a study investigated the numerical-information-processing ability of individuals with MCI but without dementia and those with mild dementia of the Alzheimer's type [96]. In particular the study evaluated the capacity of patients to perform simple numerical operations without added attentional or executive load and when required to switch between functions or control and inhibit automatic retrieval processes. The results showed that both patient groups could retrieve numerical knowledge from long-term memory without added load. However, under executive load, patients with dementia of the Alzheimer's type demonstrated compromised executive function, while patients with MCI exhibited difficulty inhibiting previously learned associations. The researchers emphasized the importance of assessing numeracy processing in a mixed condition that mimics everyday numeracy activities, as it highlights the contribution of attention and executive functions to numeracy. They also suggested that patients who score within the normal range on routine neuropsychological numerical assessments may still experience difficulties when additional non-numerical resources are required.

In summary, the study's findings support the potential of the RODI app as a screening tool for NCD, as it was able to distinguish between healthy cognitive adults and NCD patients. The analysis also revealed the feature importance scores obtained from the random forest algorithm, indicating the most salient features that differentiate between the two situations. The "Shapes Task" feature exhibited the highest level of importance, while the "Back Task (1st)" feature displayed the lowest level of importance. The low importance of "Back Task (1st)" suggests that its exclusion would not significantly impact the overall performance of the model. The importance of certain features, specifically those related to visuospatial abilities, in discriminating between the two situations is noteworthy. The observation that the four features with importance scores above 1 are related to visual working memory further reinforces this finding. These results suggest that future research may benefit from focusing on these features.

Furthermore, future research should address the primary limitations of this study, which include various aspects. Firstly, the sample selection process was non-randomized and non-blinded, relying on a convenience sample. Additionally, the study faced challenges with a relatively small sample size, especially concerning the NCD cohort. While the preliminary findings from the current study seem favorable, there is a compelling need for further research to comprehensively establish the application's effectiveness. The app's tasks align with criteria for neurocognitive disorders, target related domains, and offer diverse tasks. Despite positioning RODI as a promising tool for identifying deficits, rigorous scientific investigations are necessary to confirm its validity and effectiveness.

It is worth mentioning that the naive Bayes classifier outperformed other machine learning algorithms, including RUSBoost, kNN, SVM, LDA, and decision trees, for the specific problem that we addressed. One possible explanation for the superior performance of the naive Bayes classifier is its independence assumption. This classifier assumes that features are conditionally independent given the class label. This simplification can make the naive Bayes classifier more robust and efficient when handling high-dimensional or noisy data. If our dataset exhibits relatively independent features, this characteristic may have contributed to the strong performance of the naive Bayes classifier compared to other algorithms. Additionally, the probabilistic nature of the naive Bayes classifier may be more suitable for our specific problem. As a probabilistic classifier, it can manage uncertainty effectively and provide probabilities associated with each class. These probabilities can be valuable for decision making in our application. The study's findings provide substantial evidence supporting RODI's potential as an assessment tool for Neurocognitive Disorders (NCDs), given its effectiveness in distinguishing between healthy adults and NCD patients. The analysis also yields importance scores, shedding light on the most critical attributes contributing to this differentiation. Notably, tasks associated with visuospatial abilities stand out as the most crucial, with the four related to visual working memory achieving the highest importance scores. These findings suggest that future research endeavors may benefit from prioritizing investigations into these specific characteristics.

There are additional areas of investigation to explore, including the use of the full version of the RODI mHealth app with its active features. Furthermore, analyzing the comprehensive dataset collected by the app, including user demographics, task completion times, screen time, and any corrections made, would provide valuable insights. Exploring the interaction of the app with other technological tools that provide biomarkers is also promising. The app's potential as both a cognitive training intervention and an evaluation tool highlights its value for future research and clinical applications. These investigations can enhance our understanding of the app's efficacy and its clinical utility.

RODI has the potential to be directed toward younger older adults with normal cognitive function who have not displayed any cognitive impairment. This approach can facilitate the detection of cognitive disorders in the earliest stages or can be utilized to evaluate cognitive reserve. Furthermore, RODI can be aimed at individuals who do not have access to appropriate healthcare services or those living in territories with prolonged waiting lists for such services, thus discouraging them from seeking medical care.

The engaging nature of mobile cognitive interventions and their potential of self-administered screening without imposing extra limitations on the healthcare system present an opportunity for extensive screening and alleviating the strain on primary healthcare services. Incorporating screening into apps that the elderly are inclined to use, particularly self-administered tasks, could prove to be an effective approach. However, the inclusion of such mHealth apps into healthcare systems, information policies, and awareness campaigns requires additional investigation [97]. It is also essential to study the perspectives and requirements of application users in order to develop more effective apps that encourage older adults to self-monitor and enhance their cognitive functions.

Remote assessment and cognitive training utilizing mHealth apps allow for unsupervised sessions. However, sessions conducted in the presence of clinicians provide the benefit of professional judgment. Therefore, it is essential to emphasize that these interventions are not meant to substitute for regular visits to specialists but rather to supplement them by offering data and insights into individuals' progress and cognitive status.

6. Conclusions

Our study underscores the pivotal role of mHealth applications, particularly the RODI app, in the early detection and assessment of Neurocognitive Disorders (NCDs). The study's outcomes demonstrate RODI's effectiveness in distinguishing between NCD-affected individuals and healthy controls, emphasizing the relevance of tasks associated with visual working memory. These tasks emerged as the most critical indicators in identifying the presence of NCDs, overshadowing other cognitive tasks in predictive significance. The importance scores derived from our machine learning analysis provide a valuable roadmap for prioritizing features in future mHealth tools. Our research opens the road for the advancement of digital health technologies and sets a strategic direction for subsequent explorations into neurocognitive assessment.

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Institutional Review Board Statement: This study has received formal ethical approval from the Ionian University's Research Ethics and Deontology Committee under protocol number 3600. The approval ensures that the research conforms to recognized ethical standards and principles, safeguarding the rights, well-being, and dignity of the participants.

Informed Consent Statement: Informed consent was obtained from all individual participants included in the study. Potential participants were provided with detailed information about the study's intents, the RODI mHealth app, and their rights as participants, ensuring their understanding and voluntary agreement to participate. Participants were made aware of their right to withdraw from the study at any time without facing any consequences, ensuring the autonomy and respect of each individual involved in the research. Consent for publication was obtained from all participants involved in the study. Participants were informed that the collected data would be used for publication and scholarly purposes, with the assurance that all published data would be anonymized to maintain confidentiality and protect the participants' privacy. Any identifying information has been removed or altered to prevent the identification of individual participants in the published work, ensuring adherence to ethical standards and respect for participant rights.

Data Availability Statement: The data for the experiment can be accessed online at: https://www.dropbox.com/scl/fo/vx7ovu6i8uaqi9maaqqpm/h?rlkey=5gkeyaularf0vteszcna5sggw&dl=0.

Conflicts of Interest: The authors have no competing interests to declare that are relevant to the content of this article.

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healthcare

Review

Promoting Universal Equitable Accessibility: An Overview on the Impact of Assistive Technology in the UN, UNICEF, and WHO Web Portals

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Abstract: The number of people with disabilities and frailties who need support and assistance is increasing. Assistive technologies (ATs) are increasingly playing a central role in supporting people with disabilities and frailties. The study investigated the impact of the ATs on the websites of the UN, UNICEF, and WHO in terms of proposed activities and actions. The methodology proposed was based on two points of view: (1) A formal process to directly select elements in the institutional webs of the UN, UNICEF, and WHO. (2) A formal process for a complementary literature narrative review based on an *umbrella review* of Pubmed and Scopus. A standard checklist and a qualification process were applied. The outcome reported 35 documents from the direct search on the web and 19 systematic reviews for the complimentary literature overview. The direct search returned documents related to initiatives focused on the following: The tailoring of the ATs to a person based on international guidelines and specific monitoring initiatives of the AT introduction/access based on surveys both at the population and system/government level with the publication of the data/metadata in an observatory. Dissemination initiatives of both the culture of ATs (e.g., catalog, guidelines, reports, congresses) and of recommendations. The literature overview contributed more specifically to the use and effectiveness of categories of ATs. Both direct research and the literature overview have shown a consistent growth in interest in ATs. The initiatives of the UN, UNICEF, and WHO have been consistent with the institutional role and aimed at improving the diffusion of ATs through capillary monitoring, which is not free from obstacles, and a diffusion of the culture and rational use of ATs. The narrative review shows also the important role of research in monitoring the development, use, and effectiveness of devices, strategies, and support of international institutional initiatives. Important initiatives have been launched internationally on AT in terms of monitoring, dissemination, and improvement in access. However, it is necessary to consider and face the obstacles that limit these initiatives.

Keywords: assistive technology; accessibility; WHO; UNICEF; UN; ISO; need; disability

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1. Introduction

1.1. Background and Key Questions

The terrific development of information and communication technology (ICT), together with the high technological Assistive Technologies (ATs) [1–3], has the potential to improve the quality of life and integration into society of many people with the most diverse disabilities.

In recent years, we have assisted in the following ways:

1. The breadth of technologies on offer. Over the course of a century, technical and technological aids for disabled and frail people have greatly improved, and now the focus and attention is on expanding ATs' accessibility both from economic/social and technological points of view by providing free supplies.

2. The evolution of technological tools themselves. We have gone from rudimentary mechanical supports, such as the first prostheses and the first wheelchairs, up to modern tools that make extensive use of electronic and information technology components.
3. The perception of society towards aid for disabled and frail people, both from a common point of view and from an institutional point of view. In recent years, for example, the United Nations Convention on the Rights of Persons with Disabilities established that every member state should compulsorily guarantee and offer its citizens access to mobility aids, assistive devices, and assistive technologies for disability.

It must be highlighted that the demand for these ATs is increasing due to the aging of the population, which is leading to a growth in people with disabilities in need of support. The ATs that are being developed are increasingly following the indications of the International Classification of Functioning, Disability and Health (ICF) [4–6] that are tailored to an individual.

However, there are disparities in AT access and allocation worldwide both at the level of social categories and at the level of more and less developed countries. It is important to understand how this problem is being addressed internationally and to understand what actions are being implemented. The United Nations (UN), with its main institutional components that deal with health—the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF)—plays a leading role in this area [7–12].

This overview focuses on the UN and its institutional components dedicated to the health domain and analyzes the evolution of the approach towards ATs and the activities implemented in this context with reference to monitoring, dissemination, and recommendations.

The overview aims to answer the key questions:

"How has the approach to ATs evolved in these international bodies according to the WEBs?"

"What are their monitoring initiatives in this area?

"What are their dissemination initiatives both in terms of data and metadata and of contents and information?"

"What are the problems and bottlenecks?"

1.2. Organization of the Study

The study is arranged into five sections.

The *first section* is the introduction that presents the problem to be addressed through a review and the questions to be answered and reports the organization of the study

Section 2, "Methods", illustrates the study design, which has two polarities.

The first polarity is reported in *Section 2.1, "Web Search in Detail"*, describing the search method in the institutional sites of the UN, UNICEF, and WHO, including the formal process based on an algorithm. *Section 2.2, "The Narrative Review Designed as an Umbrella Review"*, reports the methodology carried out in an umbrella review around these themes, including the formal process based on a checklist and a qualification procedure.

Section 3, "Results", reports the outputs of these two searches.

Section 3.1, "The Evolution of the Inclusion of the Assistive Technologies in the Websites", traces the evolution of the frequency of occurrence of the term AT in the three sites over time.

Section 3.2 "The Outcome of the Web Search", is dedicated to the output of the search on websites. It has been organized into four themes structured editorially in the following four subparagraphs:

- *3.2.1 Role and Mandate of the United Nations, UNICEF, and the WHO on Assistive Technologies*
- *3.2.2 The Focus on the Individual on the Basis of the ICF*
- *3.2.3 Monitoring and Dissemination Initiatives*
- *3.2.4 Recommendations*

Section 3.3 "The Outcome of the Narrative Review Based on the Umbrella Review" reports the outcome of the umbrella review organized into the following themes structured editorially in five subparagraphs:

- *3.3.1 Exploring the Interconnection between Assistive Technology and the Environment.*
- *3.3.2 The Crucial Role of Internet and Electronics in Enhancing Assistive Technology.*
- *3.3.3 Empowering Motor Disabilities through Assistive Technology Solutions.*
- *3.3.4 Enhancing Independence for Individuals with Cognitive and Communication Disabilities through Assistive Technology.*
- *3.3.5 Addressing the Accessibility Gap: Improving Access to Assistive Technologies in Low-Income and Middle-Income Countries.*

Section 4 is dedicated to discussion and is organized into two discussion topics. The first topic, reported in *Section 4.1, "Interpretation of results"*, addresses and interprets, on the one hand, the evidence of the direct research on the websites (*Section 4.1.1 Direct Evidence from the UN, UNICEF, and WHO Websites*), and on the other hand, it discusses the contribution of the umbrella review to the general analysis and to a more complete interpretation of the first research (*Section 4.1.2 "The Contribution of the Umbrella Review"*). The second topic in *Section 4.2, "Final Thought: The Bottlenecks"*, reports the bottlenecks that emerged.

Section 5 draws the conclusions of the study.

2. Methods

This review used a standardized checklist designed for the narrative category of reviews (see at https://it.scribd.com/document/434616519/ANDJ-Narrative-Review-Checklist (accessed on 6 September 2023)).

The literature review was essentially based on web searches of institutional sites. Furthermore, to verify whether an added value could be obtained from international publications compared to direct searches on the webs of international institutions, a narrative review designed as an *umbrella review* (which considers the produced systematic reviews) was performed based on targeted searches using specific composite keys on Pubmed and Scopus. This double approach has also the following rationale.

From one side, it is useful in this emerging field to interrogate the 'grey literature', specifically websites, to look at actions related to ATs from global bodies. This could offer the evidence base and be useful to the actors in the health domain to spread findings divided into role and mandate and monitoring and dissemination initiatives. However, this gives a non-exhaustive and complete picture compared with the peer-reviewed evidence base if not supported enough by the peer-reviewed literature. The complementary narrative review may also serve to validate the findings when confirming them and/or to suggest attentiveness when this confirmation is not found because, for example, the theme was not studied in depth by scholars.

This research ended on 30 June 2023.

2.1. Web Search in Detail

The search focused on institutional sites to analyze how the issue of assistive technologies is addressed. The search applied targeted searches on the Institutional websites of the United Nations, UNICEF, and WHO, selecting documents according to a formal process based on a specific algorithm. Information technology provides tools to achieve this.

It was therefore decided to use the Google search suite, which has its own presentation selection and sorting tools based on an algorithm that uses an automatic ranking based on five parameters: *meaning, relevance, quality, usability, and context* [13]. An algorithm was proposed which foresees two phases. The first selection phase was based on Google ranking (N.1–N.6), and the second phase of further synthesis and refinement (N.7–N.11) of the research included: (a) Selection based on our parameters evaluated by means of a graded score ranging from 1 = minimum to 5 = max. These parameters have been identified as *priority, pertinence, completeness, and effectiveness* of the transmitted message. Only items with all 4 parameters with a rating higher than 3 (in AND logic) were taken into consideration. (b) An overlapping check between the various documents followed by a further synthesis operation.

Algorithm Used in the Web Search

1. *Start* by selecting the websites *un.org*, *who.int*, and *unicef.org*.
2. Perform three searches using the following queries:

    2.a-> site: unicef.org assistive technology
    2.b-> site: un.org assistive technology
    2.c-> site: who.int assistive technology

3. Collect the results from the first 10 pages of each search, ordered by the priorities of the *Google ranking (meaning, relevance, quality, usability, and context)*
4. *Exclude the commercial content.*
5. *Analyze the chronological evolution* of the results within each site, with a focus on the entire history, the last ten years, and the last three years (pandemic period) ordered according to the Google ranking.
6. *Select documents* with a focus on assistive technology, including web publications and documents that can be reached by means of ramifications starting from these websites.
7. *Assign a personal score from 1 (min) to 5 (max)* to each selected document based on the following parameters:

    Priority;
    Pertinence;
    Completeness;
    Effectiveness.

8. Select only those documents that exceed a threshold of three on all parameters defined in step 7.
9. *Check for overlaps* among the selected documents and *select those with higher scores*.
10. *Carry out a synthesis* of the selected documents.

2.2. The Narrative Review Designed as an Umbrella Review

The literature overview accompanying the main survey was conducted using both a qualification checklist and a qualification methodology based on the proposed quality parameters described in [14] used to decide the inclusion of the study in the overview.

2.2.1. Algorithm Used in the Literature Overview

1. Set the search query to:

    "defined search query"

2. Conduct a targeted search on Pubmed and Scopus using the search query from step 1.
3. Select studies published in peer-reviewed journals that focus on the field.
4. For each study, evaluate the following parameters:
    - N1: Is the rationale for the study in the introduction clear?
    - N2: Is the design of the work appropriate?
    - N3: Are the methods described clearly?
    - N4: Are the results presented clearly?
    - N5: Are the conclusions based and justified by the results?
    - N6: Did the authors disclose all their conflicts of interest?
5. Assign a graded score to parameters N1-N5, ranging from 1 (minimum) to 5 (maximum).
6. For parameter N6, assign a binary assessment of "Yes" or "No" to indicate if the authors disclosed all their conflicts of interest.
7. Preselect studies that meet the following criteria:

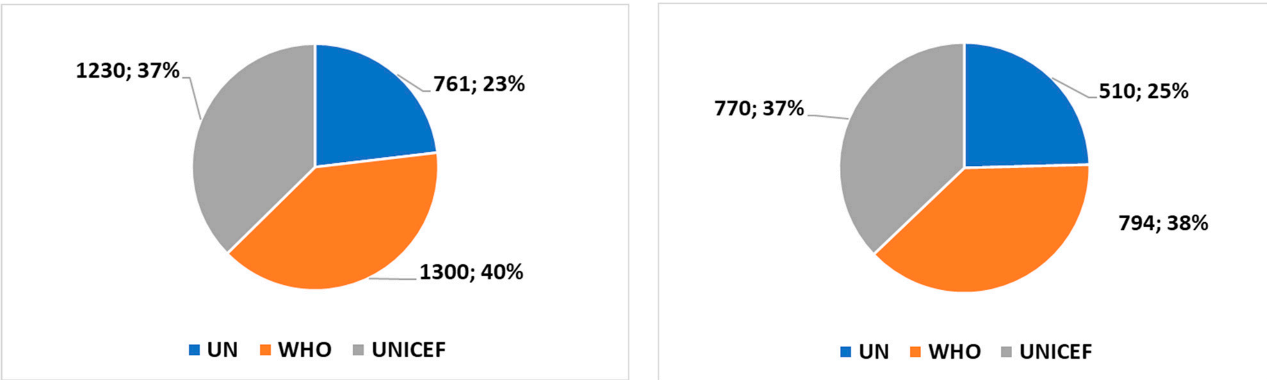
- Parameter N6 must be "Yes".
- Parameters N1-N5 must have a score greater than 3.

8. Include the preselected studies in the overview.

3. Results

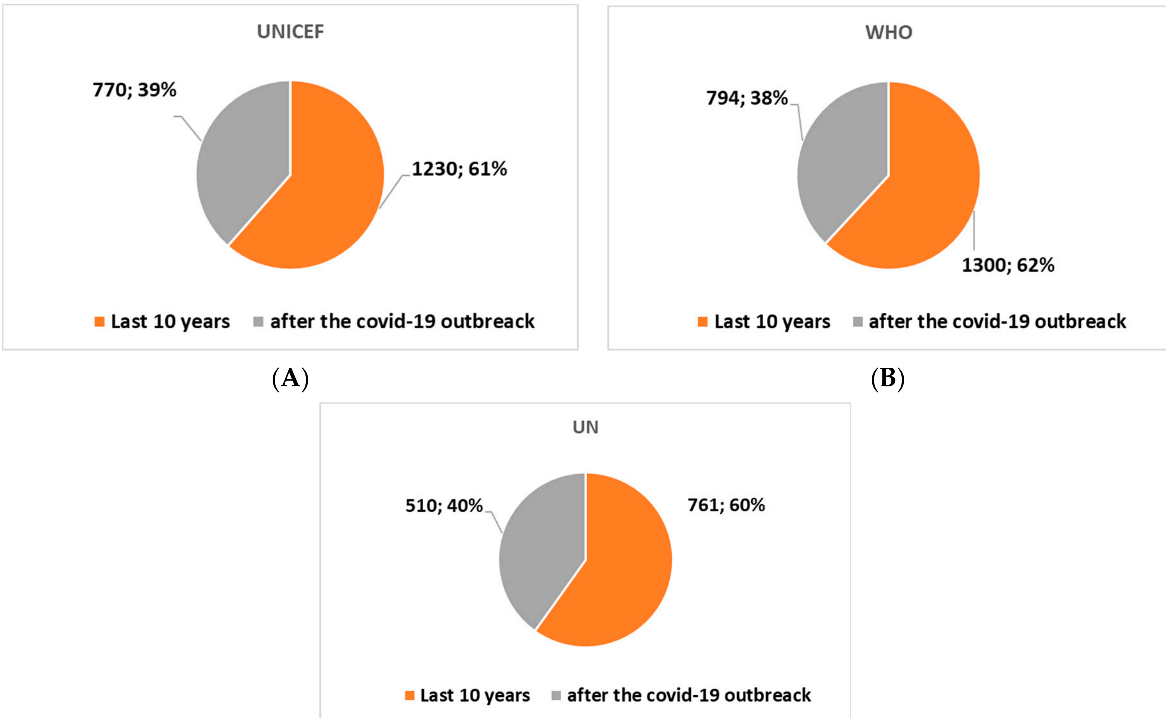
3.1. The Evolution of the Inclusion of the Assistive Technologies in the Websites

The application of the algorithm highlighted the trends in the three websites un.org, who.it, and unicef.org. First, the analysis showed that the first citations were as follows: UN site, on 15 October 1998. WHO site, on 15 October 1992. UNICEF site, on 16 June 1995. Figures 1–3 show the trends in the last ten and three years. The analysis shows that (Figure 1), even if not predominantly, the major citations are recorded on the WHO website.



(**A**) (**B**)

Figure 1. History of citations on "assistive technology" on the UN, UNICEF, and WHO websites in the last 10 years (**A**) and after the outbreak of the pandemic (**B**).



(**A**) (**B**)

(**C**)

Figure 2. History of assistive technology citations for each separate site over the past 10 years and since the outbreak of the pandemic. (**A**) WHO website. (**B**) UNICEF website. (**C**) UN website.

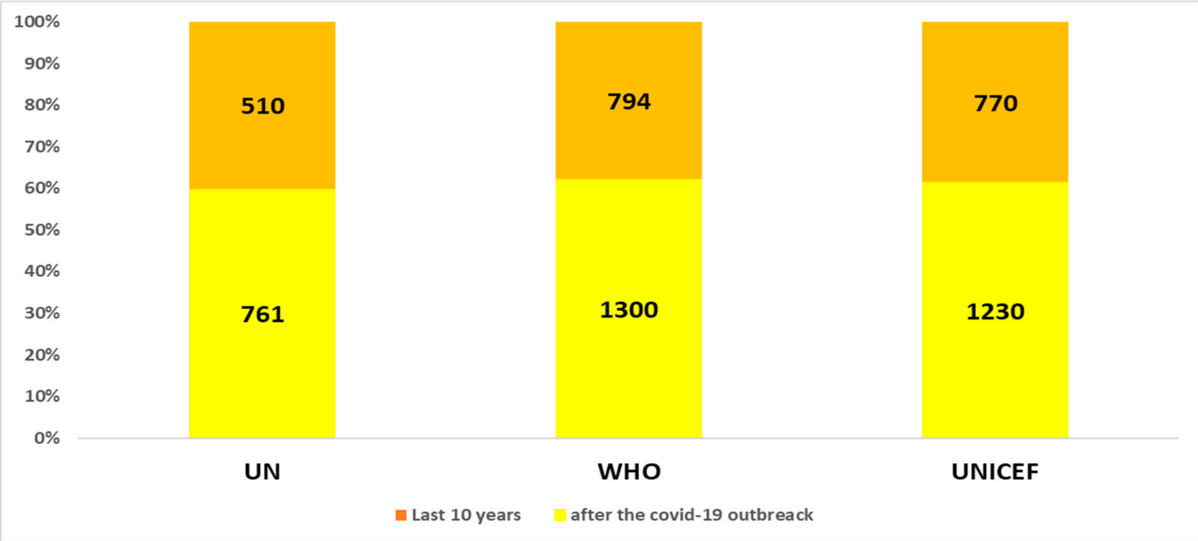


Figure 3. Historical detail for each site in percentage with reference.

In general, if we consider the last ten and three years (Figures 2 and 3), the analysis shows an increase in the citations of all the institutions' websites in the period following the outbreak of the COVID-19 pandemic (the last three years). In fact, there is an acceleration in interest over the past three years, presumably due to the push of technological innovation due to the COVID-19 pandemic. In fact, Figures 2 and 3 show that in the last three years, there has been an increase in citations of all three websites. The number of citations has increased by around 40% compared to the ten-year period.

In summary:

- In the last ten years, the term "assistive technology" was cited 1300, 1230, and 761 times, respectively, on the WHO, UNICEF, and UN website.
- After the COVID-19 pandemic outbreak, the term "assistive technology" was cited 794, 770, and 510 times, respectively, on the WHO, UNICEF, and UN website.

3.2. The Outcome of the Web Search

The analysis showed that from time to time, initiatives were activated that absorbed the previous ones. Therefore, an important and strategic parameter was certainly that of priority. The defined algorithm search returned 35 documents on the WHO, UNICEF, and UN websites [3,4,6–12,15–42].

The analysis, also considering the aims and sub-aims, suggests a division according to the following themes:

○ *Role and mandate of international institutions in assistive technologies;*
○ *The focus on the individual on the basis of the ICF;*
○ *Monitoring and dissemination initiatives;*
○ *Recommendations.*

3.2.1. The Role and Mandate of the United Nations, UNICEF, and the WHO on Assistive Technologies

Research on ATs clearly redirects to the role of international actors operating in this area: the UN, UNICEF, and WHO. The application of the algorithm in *Section 2.2.1* is also traced back to the system information relating to these institutions. It was considered essential to bring them back as they clarify the role and mandate of these institutions in relation to assistive technologies.

The United Nations (UN) was founded on 24 October 1945. Today, virtually every nation on the planet is part of the UN—193 countries in total [7,8]—and must follow the UN Charter. According to the provisions of the UN Charter (see at https://www.un.org/

en/about-us/un-charter/full-text (accessed on 30 June 2023)), the United Nations has four purposes reported in Art. 1 that can be briefly summarized as follows:

- *To maintain international peace and security.*
- *To develop friendly relations among nations.*
- *To cooperate in solving international problems and in promoting respect for human rights.*
- *To be a center for harmonization of the different national initiatives.*

The role of the UN in the *health domain* (and therefore around the ATs) is touched upon by point (3) and by point (4). In fact, the right to health is an integral part of the internationally recognized fundamental human rights, as mentioned in point (3). Health is also an undisputed part of the various national initiatives, which the UN has the task of harmonizing, as referred to in point (4). For this task, the UN makes use of two international institutional entities: the WHO and UNICEF.

The World Health Organization (WHO) [9,10] serves as the primary guiding and harmonizing institution for health at an international level. The WHO's overarching goal is to ensure that all individuals achieve the highest possible level of health. As per the WHO constitution, health is characterized by complete physical, mental, and social well-being, transcending the mere absence of disease or infirmity, with assistive technologies (ATs) playing a pivotal role.

The United Nations Children's Fund (UNICEF) [11,12] was initially proposed after World War II to support mothers and children with food and healthcare provisions in nations suffering from devastation. The UN enlarged UNICEF's role in 1950 in all the nations to face long-term needs. AT is clearly a long-term need.

3.2.2. The Focus on the Individual Based on the ICF

ATs are those devices or tools capable of improving the functional abilities of people with disabilities, including hardware, software, and mechanical devices. These can support people who have both communication difficulties, for example, hearing, seeing, feeling, memorizing, pointing, and typing, and difficulties with movement. They can be used in domestic environments, in social life environments, and in the workplace. ATs can have high technological components regarding mechanics, information technology, and electronics. According to the WHO, an AT can be defined as both a product and a service [3]. Therefore, according to the WHO, the definition of AT can be extended to the service. The International Organization for Standardization (ISO), which strictly collaborates with the WHO in the WHO Family of International Classifications Network, gives an exhaustive definition of an assistive product (https://www.iso.org/standard/72464.html (accessed on 4 october 2023)), clearly identifying the inclusion. Assistive products, according to the ISO classification, are also those products utilized by an individual to enhance functionality and minimize disability, yet necessitating assistance from another individual for their operation, and are encompassed within the classification. The following items, for example, are expressly not covered by the classification: items utilized for installing assistive products; solutions resulting from combinations of assistive products that are classified individually in the ISO document; medications; assistive products and tools exclusively used by professionals in the health domain or professors; guide dogs; financial support; implanted devices. An important aspect related to AT is the correct assignment to a person with need. These needs are identified by means of a careful analysis of the health components of the person. A globally consolidated guide to identifying the components of health has been identified in the International Classification of Functioning, Disability and Health (ICF) [4–6]. Evolving from the earlier International Classification of Impairments, Disabilities, and Handicaps (ICIDH) established by WHO in 1980 for research purposes [15], the ICF signifies a major revision. The ICF's final text received approval during the 54th *World Health Assembly* (WHA) on 22 May 2001. Subsequently, it was highly recommended to member states for extensive utilization in diverse domains such as research, population studies, and reporting. The classification has also been activated by the WHO based on the actors involved [16].

The ICF (a) allows you to identify the health components of an individual—it has universal use and does not only concern people with disabilities, but everyone can be associated with one or more qualifiers related to "functioning"; (b) takes into consideration the entire span of life; and (c) takes into consideration the environment and social life surrounding an individual. From the point of view of assigning an AT, the ICF leads to greater attention on the individual and to tailoring of the device, which must consider the state of all health components.

Recently, some international initiatives are trying to make the ICF tool more useful. The AT Service Method (ATSM) seems promising for this. It is an evidence-based process framework to efficiently manage the several parameters required for the efficient provision of an AT. The ATSM is based just on the ICF to establish a universal and internationally appropriate, "person-centred, cross-disability, interdisciplinary, trans-environmental methodology supporting data collection to inform practice and policy on AT interventions" [17]. However, the ATSM has not received an evident interest from scholars in scientific publications.

A second promising initiative at the international level is linking the Global Burden of Disease (GBD) [18]. to the ICF and ISO 9999

Diseases are classified according to the International Statistical Classification of Diseases and Related Health Problems (ICD-10). The ICD-10 is the international standard diagnostic classification for all general epidemiological purposes, many health management purposes, and clinical use [19]. GBD is based on the ICD-10. ICF practically complements the ICD-10 but does not contain the functional status in the classification. ATs used to improve a person's functioning are classified by ISO 9999.1. It is a classification at an international level of ATs. So, this action by the WHO is strategic to put the person at the center by linking the key strategic documents ICD-10, ICF, and ISO 9999.

3.2.3. Monitoring and Dissemination Initiatives

The development of articulated and structured initiatives based on different levels is recorded at an international level. Monitoring actions based on specific surveys are intended for both citizens and various actors and are combined with uploading actions and dissemination of structured data and metadata on portals visible to all at an international level. Of course, we are witnessing the dissemination of guidelines, book catalogs and congress types. News aimed at achieving specific objectives also falls within this ambit. According to the UN, disability can increase poverty and widen social inequalities between countries. ATs are directly included in the sustainable goals of the UN (SDG 1: no poverty, SDG 3: good health and well-being) [20,21]. To achieve these objectives, it is necessary to pay attention to the most defenseless populations in the world, including people with disabilities. According to the UN, there are some factors that prevent the osmosis of ATs between rich and poor countries [22]. Among these factors, the most important is that technological innovation has focused on highly technological products that are marketed at high cost in rich countries and do not meet the needs of people with disabilities in poor countries.

We must record that the UN also gives specific indications on the use of high-tech ATs to its collaborators and guests with disabilities at events. The UN supply model in this case is described in [23,24], where it is highlighted how accessibility is merely guaranteed through high-tech devices.

Basically, on the one hand, the UN suggests the types of high-tech ATs (HT-AT) as part of its institutional activities but recognizes that these ATs, at least in part, are not suitable for use in the field in less developed countries and communities, where both costs and environmental conditions have to be taken into account. The message that clearly appears in the news shared in the grey literature is that it would be necessary to overturn this paradigm and develop projects aimed at providing a low-tech alternative AT (LTA-AT), adaptable to the environments of these countries and more convenient than the traditional devices available. This point is very important and challenging to address. Specific studies should help us answer how to address this issue, which, in a certain sense, interrogates the usefulness of LT-ATs versus HT-ATs in low- and middle-income countries. International initiatives, such as AT2030 (described below), should, as highlighted in the message, give space to these themes.

The WHO and UNICEF have the prerogative to be engaged in monitoring initiatives in this field. The WHO plays a leading role in monitoring both the needs and diffusion of ATs and the policies adopted for their usability within countries, addressing/guiding the national policies towards a better assignment and diffusion of ATs. UNICEF, which focuses on children and everything that revolves around them, including motherhood, has an important role in monitoring their needs, even in the medium and long term, and ATs represent an indispensable need for many children. *It can be affirmed that the WHO and UNICEF operate in complementarity and synergy.*

The WHO identified five major challenges for the ATs at the international level, as reported in the online documents [1,3,10]:

- *The policy*. It must be considered that in many countries, a policy on ATs is not available.
- *The products*. More focus on the person is needed. Based on the ICF [4,5], every individual is unique.
- *The provision*. The process of provision of an AT must be more effective. Often, these services are not optimized and citizens must follow several often-unconnected passages in order to obtain the right AT.
- *The personnel*. The training of the personnel is also a key issue to ensure both a correct prescription and a well-organized follow-up.
- *Assistive technology within universal health coverage*. This is the most ambitious goal of the WHO. Everyone must access both products and services with no restrictions from an economic point of view.

In line with these challenges, the WHO has designed and developed a global health observatory [25]. A section of this observatory is dedicated to the ATs [26].

A specific WHA resolution (WHA71.8) [27] is focused on ATs; on the one hand, it pushed all countries to improve access to ATs, and on the other hand, it asked the WHO to monitor and collect scientific evidence in the form of a global report. This resolution calls for such reports to be issued in the years 2022, 2026, and 2030 to monitor progress in this area. In response to these requests, the WHO has acted and taken steps to gather this evidence. Data are collected using two main tools based on specific questionnaires designed by WHO [26]:

- The *first tool* is the rapid Assistive Technology Assessment tool, which runs at the level of the population to obtain population data on access to ATs (https://www.who.int/publications/i/item/WHO-MHP-HPS-ATM-2021.1 (accessed on 6 September 2023)) [28]. It is a questionnaire focused on the population designed to assess, based on a self-reporting methodology, the perceived barriers to access to an AT, the need, the use, and the met need.
- The *second tool* is a questionnaire for obtaining the progress indicators for access to assistive technology that runs at a system level to obtain *specific indicators on the state and advancement of the ATs* (https://www.who.int/publications/i/item/WHO-MHP-HPS-ATM-2022.01 (accessed on 6 September 2023)) [29]. It is a questionnaire allowing to measure, with reference to an AT, the preparedness in terms of several issues, such as the service provision attention, the workforce obtainability, the training governance, the regulation, the national budget, the funding mechanisms, the standards, the projects, and the activities.

Data are stored and available in two windows of the observatory [26]. They are available publicly and separated into two related collections. The first collection is related to the survey at the system level (progress indicators). The second collection is related to the population survey. The data and metadata available in the observatory show that 70 countries provided progress indicators, while 29 furnished the results of the questionnaire. Key global results available on the observatory are as follows: 2.5 billion people are in need of ATs. It is expected that this number will increase to 3.5 billion in 2050. Two-thirds of people with an age $\geq$ 60 need an AT. Among the 70 countries providing progress indicators, 62 have specific legislation on ATs. In total, 63 countries have measures designed to cover users' AT costs partly or fully.

As a further initiative, the WHO is developing another tool (not yet available) [30]. It is a population-based questionnaire aimed to assess the impact of an AT on citizens. It will assess the enjoyment of human rights and the people's empowerment/dignity/participation/quality of life/inclusion.

The WHO also provides *scientific dissemination of data and metadata as per outcomes from the administration of these questionnaires*. The data include, but are not limited to, the following: data on the availability of government/registered services for assistive technology, which may be viewed online [31]; data on the existence of regulations/standards/guidelines/protocols on assistive technology [32]; data on the availability of education/training for assistive technology [33].

Another level of scientific dissemination by the WHO consists of specialized volumes on specific issues related to ATs.

Three have been identified (all accessible online) by relevance, priority, interoperability, and functional interconnection. Together they address the subject of priority ATs at reasonable prices, process and development specifications, and third-party supply through tenders.

The first volume reports and describes those ATs that are highly needed and are fundamental to preserving or increasing an individual's functioning and, very importantly, need to be available at an affordable price for the community/country [34].

The list of these ATs is called the World Health Organization (WHO) Priority Assistive Products List (WHO APL). These ATs cover six key areas of functional difficulties: mobility, hearing, vision, cognition, communication, and self-care.

The second volume is dedicated to ATs' specifications [35]. In detail, it reports the model specifications as a reference for the procurement by working groups. These specifications support these groups in the design and development of their own procurement specifications suitable for their settings. In total, 26 AT specifications are included. These ATs are those included in the WHO APL [34]. Particular care is dedicated to the description of the minimum requirements related to both the technological performance and functionality that an AT in the list must meet for safety and effectiveness of use.

The third volume is dedicated to public procurement, precisely to proffering ATs, accessories, auxiliary components, and connected services [36]. The document aims to:

- Overview the procurement and supply management for ATs.
- Describe essential principles of AT procurement.
- Categorize the diverse participants related to the procurement process.
- Detail the phases of the AT procurement process.
- Report other ways of obtaining ATs (e.g., donations of used ATs).

The WHO also proposes itself as an observatory of the dissemination experiences of the various member states of the UN. From this point of view, it represents a real catalog of shared experiences in the field of ATs. See, by way of a non-exhaustive example, the experience in Buthan shared in [37]. UNICEF [38] is working on ATs with objectives aligned with those of the WHO with particular reference to children, mothers, and related living environments. It is also dedicated to the advocacy of ATs. Regarding this aspect, UNICEF fought for the introduction of 24 new AT products into the catalog, including specific models of wheelchairs for children and innovative hearing aids [39]. Thanks to this initiative, UNICEF can distribute innovative acoustic and motor support devices both in international development projects and to various governments of the United Nations. Together with the WHO, it has focused on the development of guidelines for the actors in the AT supply process. Especially important in this direction is a book that represents a guide dedicated to 26 priority AT products, which also contains the specifications and requirements of the production in quality [35]. Also worth mentioning is a global initiative, called AT2030 [40], that works to improve access to life-changing assistive technology (AT) for all. In this context, workshops were held in South Africa and Tajikistan at the end of 2019, and a webinar on ATs was held in September 2020 [41] in collaboration with the WHO and the Clinton Health Access Initiative.

3.2.4. Recommendations

UNICEF and the WHO developed the "The Global Report on Assistive Technology" in synergy [42], addressing the WHA 71.8 resolution in May 2018 [27] on the international improvement of access to ATs.

The report on ATs gives a complete vision of international access to ATs, with a focus on several issues, including the need and the expected economic benefits.

It is clearly a disseminative product. However, most importantly, it is dedicated to providing recommendations. The key message of each recommendation (see [42] for the extended text) is reported in Table 1.

Table 1. The recommendations from the Global Report on Assistive Technology.

Recommendation #	Description
1	Improve access to assistive technology within all key development sectors.
2	Ensure that assistive products are safe, effective, and affordable.
3	Enlarge, diversify, and improve human resource capacity.
4	Actively involve users of assistive technology and their families.
5	Increase public awareness, garner political support, and combat stigma surrounding assistive technology use.
6	Invest in data- and evidence-based policy.
7	Invest in research, innovation, and an enabling ecosystem.
8	Develop and invest in enabling environments.
9	Include assistive technology in humanitarian responses.
10	Provide technical and economic assistance through international cooperation to support national efforts.

3.3. The Outcome of the Narrative Review Based on the Umbrella Review

A search of scientific publications was carried out to complement the overview carried out on the web. It was based on an *umbrella review*.

The composite key in Box 1 was used.

The application of this key led to the identification of 675 published works on Pubmed with a starting date of 1990.

An analysis of the last 10 years shows a number of papers equal to 510 (76%). Instead, if we consider the last three years characterized by the COVID-19 pandemic, we find 238 papers (35.3%). This highlights a rapid acceleration in publications in this area over the past decade. This acceleration becomes terrifying if we consider the last three years characterized by the COVID-19 pandemic. In fact, more than a third of the papers published in this area have been published in the last three years.

In line with the objectives of the study, the investigation focused on the publications in the systematic review category in order to provide an *umbrella review* of the systematic reviews, which, in evidence-based medicine, have a higher hierarchy level and are the first step at the national and international level for the formation of guidelines and recommendations.

The research reported 19 systematic reviews [43–61]. Almost all the reviews dealt with aspects of effectiveness and/or acceptance in some way, and several also dealt with multiple issues at the same time. It should be noted that only one review [49] addressed the issue of disparity in the assignment and use of ATs. The following issues emerge from the analysis.

- *Exploring the interconnection between assistive technology and the environment.*
- *The crucial role of the internet and electronics in enhancing assistive technology.*
- *Empowering motor disabilities through assistive technology solutions.*
- *Enhancing the independence of individuals with cognitive and communication disabilities through assistive technology.*
- *Addressing the accessibility gap: improving access to assistive technologies in low-income and middle-income countries.*

Box 1. The proposed composite key.

"assistive technology"[Title/Abstract] AND ("UN"[Title/Abstract] OR "WHO"[Title/Abstract] OR "UNICEF"[Title/Abstract])

3.3.1. Exploring the Interconnection between Assistive Technology and the Environment

Three studies [43,48,57] highlight the significance of the environment in the International Classification of Functioning, Disability and Health (ICF) as a crucial factor for protection and participation. In the study referenced as [43], the effectiveness of environmental interventions in preventing falls among older adults living independently was examined. Home fall hazard reduction interventions were shown to notably decrease overall fall rates by 26% in older individuals. However, interventions targeting improved vision or other assistive technologies did not exhibit a substantial impact on fall rates. The review emphasized tailoring home fall hazard reduction strategies for those at higher fall risk, underlining robust evidence supporting their efficacy. Yet, further investigation is needed for other intervention types and population groups. The overview presented in [48] evaluated rehabilitation interventions for middle-aged individuals with long-term physical disabilities. The interventions addressed various aspects such as fall risk reduction, functional capacity, and community mobility. Wheelchair skill training programs (WSTPs) for manual wheelchair users and post-stroke limb exercises were strongly supported by evidence. These interventions should be routinely offered to this population, with calls for tailored interventions due to the unique challenges they face. The review presented in [57] aimed to gauge the impact of occupational therapy on post-stroke adults' abilities to perform daily activities. Occupational therapy targeting activities of daily living (ADL) demonstrated enhancements in performance scores, decreased risk of poor outcomes, and improved extended ADL independence. However, the evidence's quality was compromised by methodological flaws and data gaps. While suggesting potential benefits, the review emphasized the necessity for more rigorous research in this domain.

3.3.2. The Crucial Role of Internet and Electronics in Enhancing Assistive Technology

Five systematic reviews [44,45,53,55,60] emphasize the significance of the interplay between electronics, the internet, and assistive technologies (ATs).

The review in [44] delves into the creation of an internet-based intervention for remote monitoring and support of older adults and caregivers using assistive technology. Through an evidence-based, user-centered, and pragmatic approach, the study demonstrates the complexities of crafting such interventions. By combining intervention mapping and participatory processes, the development team established a link between evidence, user needs, and practicality. This work serves as a guide for future developers, shedding light on challenges and considerations. In [45], the research explores the experiences of older Western adults with chronic illnesses and their families using digital technology for aging in place. The study presents a conceptual model depicting how these individuals reflect and decide on using digital devices. Understanding these experiences informs assistive technology development and provides guidance for healthcare professionals supporting older adults and their families. A specific review [53] investigates electronic assistive technology (EAT) effects on the well-being of older adults living alone. EAT displays potential for enhancing physical and mental well-being, though social well-being evidence is limited. Personalized designs, interventions, and user engagement are recommended for EAT design. More evidence is necessary for a comprehensive understanding.

The overview [55] examines ATs and internet access technologies for the deafblind. Early-stage technologies show promise, yet their efficacy remains untested. Bridging the gap between research and real-world implementation is crucial, requiring user involvement and focused development to cater to the unique needs of the deafblind population.

Lastly, [60] focuses on EAT effects on reading, educational outcomes, and quality of life for visually impaired children and young individuals. Despite an extensive search, no relevant randomized controlled trials were found. The study calls for high-quality evidence to assess EAT's utility for visually impaired children, suggesting that research protocols should consider various outcomes relevant to families and educators.

3.3.3. Empowering Motor Disabilities through Assistive Technology Solutions

Two studies [46,50] specifically addressed the empowerment of people with motor disabilities using assistive technology solutions. However, the studies reported in *Section 3.3.1* [43,48,57] also touched on this field, although to a lesser extent and from a different angle.

In the study detailed in [50], the impact of motor neuroprosthesis (MN) on post-stroke individuals' independence in activities of daily living (ADL), limb-related activities, health-related quality of life (HRQoL), exercise capacity, balance, and adverse events was examined. The evidence indicated that MN did not provide superior benefits compared to other assistive technology devices for improving limb-related activities like walking speed, balance, exercise capacity, and HRQoL. Insufficient evidence existed to assess MN's effect on ADL independence. The study found that MN did not increase fall risk or serious adverse events, but dropout rates during the intervention period were potentially higher. The overall certainty of evidence ranged from low to moderate.

The review discussed in [46] analyzed wheelchair design, particularly in terms of navigating stairs and flat surfaces. It revealed a gap in meeting wheelchair users' functional needs, as the existing literature primarily concentrated on stair-climbing ability while neglecting safety, comfort, and maneuverability. The review stressed the importance of designing assistive technologies like wheelchairs with empathy, addressing users' physical and emotional requirements. Overall, it underscored the necessity for comprehensive wheelchair design beyond stair climbing, encompassing a wide array of user needs. By prioritizing safety, comfort, and user-friendly features, designers can create assistive technologies that offer optimal accessibility and functionality.

3.3.4. Enhancing Independence for Individuals with Cognitive and Communication Disabilities through Assistive Technology

Most of the systematic reviews, seven in total [47,49,52,54,56,58,61], dealt specifically with AT in cognitive and communication disabilities. In addition to these works, others, reported in *Section 3.3.2* [44,45,53,55,60], have addressed the importance of the internet and electronics in TA and touched on this topic.

In [47], a study assessed the efficacy of technology aiding braille literacy education for blind or visually impaired children and youth. Despite braille's importance, limited research on technology for braille literacy education exists. The study emphasized the need for technology evaluation standards, promoting real-time feedback, independent study, editing, user-friendliness, and engagement. Developing such a technology and consistent evaluation standards could significantly impact the rehabilitation and education of visually impaired youth. The review described in [49] aimed to identify variables influencing AT use among individuals with deafness and blindness, contextualized within the International ICF framework. Usability challenges emerged, especially for devices relying on non-visual and non-auditory senses. The lack of research on haptic and tactile aids highlighted the urgent need for technology development catering to this marginalized population. An overview [52], based on a structured review protocol [51], investigated the experiences of carers of dementia patients using ATs. Positive and negative findings were reported across various ATs, emphasizing the importance of a standardized classification system and a family/carer-centered approach in future research. Another overview [54] focused on ATs for tinnitus care, using mixed methods. The study incorporated evidence of efficacy and patient priorities, aiming to facilitate shared decision-making between clinicians and patients and meeting quality standards for decision aids. The review detailed in [56] explored haptic sensory substitution technologies for individuals with sensory disabilities. Such technologies showed potential in alleviating language, communication, and navigation deficits, though acceptance issues persisted. The study highlighted the need for miniaturized, custom-designed, and affordable haptic interfaces to integrate with personal devices like smartphones. In [58], an overview examined robots for rehabilitating and educating children with cerebral palsy (CP) and autism spectrum disorder (ASD). The study called for more valid research and a user-centered design approach to develop affordable robots for these populations, suggesting interdisciplinary involvement and low-cost robotic systems. Finally, the study presented in [61] conducted a systematic review of assistive technology for cognition (ATC) interventions in clinical populations. It categorized cognitive domains and tasks supported by ATC, finding effectiveness in various cognitive functions. The study contributed a framework for ATC prescription based on cognitive deficits, introduced a novel ATC classification, and identified future research and development directions.

3.3.5. Addressing the Accessibility Gap: Improving Access to Assistive Technologies in Low-Income and Middle-Income Countries

Only the study detailed in [59] directly addressed the issue of limited access to assistive technologies (AT) in low-income and middle-income countries (LMIC), particularly concerning aging populations. The researchers conducted a literature search across six countries—Brazil, Cambodia, Egypt, India, Turkey, and Zimbabwe—all of which had ratified the UN Convention on the Rights of Persons with Disabilities and were anticipated to experience rapid growth in the 65 and above population. The findings demonstrated that while these countries possessed AT solutions tailored for older adults with existing impairments and disabilities, there was a notable lack of AT options focused on preventing impairments and disabilities among older adults without current impairments. The study underscored the urgency of a comprehensive, integrated approach within the health and social systems of LMIC to enhance AT availability for aging populations. This approach should encompass promoting low-cost AT initiatives, increasing awareness and AT capacity, bridging the gap between AT policy and practice, and promoting targeted research on AT.

4. Discussion

4.1. Interpretation of Results

4.1.1. Direct Evidence from the UN, UNICEF, and WHO Websites

We are witnessing both population growth and gradual aging. This is leading to the growth in people with disabilities who need support and assistance.

ATs will increasingly assume a central role [1–3,62] in this area and will have to be increasingly centered on the needs of people and their living environment. In fact, from the analysis of the scientific dissemination of ATs in international sites in the last three years (connected with the explosion of the pandemic), there has been a growth in interest in these devices, which, in the critical phases of the pandemic, proved fundamental. In general, it can be observed, on the one hand, that thanks to the actions of these international bodies, the ICF is increasingly guiding us towards a greater tailoring of these ATs to the individual [4–6,16–19]. On the other hand, this centering must take into account the development disparities of the various countries and the relative peculiarities of their living environments, particularly taking into account that development models based on high technology and costs are ill-suited to poor countries [22]. The UN with its operational branches, the WHO and UNICEF, is taking various actions in this area to improve the diffusion of ATs and monitor their progress. The actions of the WHO and UNICEF are in some respects synergistic and complementary. The WHO [1] has identified five *challenges* in the field of ATs (*the policy, the products, the provision, and the assistive technology within universal health coverage*), for which it is taking international action. In line with these and with the WHA71.8 [27] resolution, it has set up an observatory [26] in this area and has activated continuous monitoring at the population and system levels through two dedicated tools [28,29]. The data and metadata *are disseminated and updated* online and currently cover a portion of the population and governments. *Another level of scientific dissemination* by the WHO consists of the online publication of contents and guidelines through specific volumes dedicated to key strategic issues related to ATs. Three have been identified (all accessible online) that together address the subject of priority ATs at reasonable prices, the process and development specifications, and third-party supply through tenders [34–36].

UNICEF has also been active in specific initiatives in collaboration with the WHO. These initiatives concerned, for example, the introduction of 24 new products to the catalog, the indication and guidelines for specifications and essential requirements for the development of 26 priority products, and the global awareness of ATs through dissemination activities and workshops [24–28].

Of great scope and impact is the "Global Report on Assistive Technology" developed by UNICEF and WHO [29]. The report on ATs gives a strategic vision [42,63,64] for international access to ATs, with a focus on several issues, including the need and the expected economic benefits. Among the most important outputs of the document are 10 recommendations. Table 2 shows the opportunities that emerged from the analysis.

Table 2. Opportunities emerged from the analysis.

#	Opportunities
1	Increased awareness of and interest in assistive technology devices due to the pandemic.
2	Greater focus on tailoring assistive technology to the individual needs of people with disabilities.
3	International bodies such as the UN, WHO, and UNICEF working to improve the diffusion of assistive technology devices and monitoring their progress.
4	Online dissemination of guidelines and contents related to assistive technology devices.
5	Introduction of new products in catalogs and global awareness through dissemination activities and workshops.
6	The Global Report on Assistive Technology providing a strategic vision of international access to assistive technology and economic benefits.
7	Collaborative work among governments, institutions, and population.

4.1.2. The Contribution of the Umbrella Review

In addition to the direct analysis of the contents of the institutional sites of the UN, UNICEF, and the WHO, an analysis was carried out by means of an *umbrella review* [62,65] of the systematic reviews produced in this area, which represent, as is known, the highest level of publications for the formation of evidence-based medicine.

This analysis has revealed a growth in interest in this theme in the recent period. The most relevant issues that have been addressed, including the effectiveness and usage, are the importance of the internet and EAT in ATs [44,45,53,55,60], AT technologies for cognitive and communication disabilities [47,49,52,54,56,58,61], and for motor disability [46,50]. An important space has been dedicated to the ICF, in line with what has been shown by direct research. The ICF comes to the fore both when issues of interconnection of ATs with the environment and activities are dealt with [43,48,57], and as a formal approach methodology [49,61]. Little space was given, for example, to the relevant issue of unequal access. Only one review addressed the limited access to ATs in LMIC [59]. The findings revealed there were limited AT options to prevent impairment and disability among older adults without current disabilities in the investigated countries (Brazil, Cambodia, Egypt, India, Turkey, and Zimbabwe). The study emphasized the need for a comprehensive, integrated approach within the health and social systems of LMICs to increase the availability of ATs for aging populations, promote low-cost AT initiatives, raise awareness, and build the capacity of ATs.

The literature overview highlights how consolidated scientific topics are influenced more by an interest in devices and their environment of use, passing through the importance of electronics and the internet. Support for raising awareness of access issues is a topic that has less extensive coverage. Now, the *umbrella review* does not report systematic reviews dedicated to monitoring initiatives at the three levels of system, needs, and satisfaction for ATs. This could have two explanations. The first, more reasonable, is that not enough data have yet been accumulated for the development of these reviews given that the monitoring tools of the WHO have only been released in recent times. The second, less probable, is that there is less interest from authors on these issues. On the other hand, if we focus on recent scientific articles conducted by the WHO experts themselves, the need to echo this issue [66] and the need to study critical aspects of the diffusion of the culture of ATs in some nations (which is also reflected in the participation in the surveys themselves carried out by the WHO and UNICEF) is particularly emphasized [65]. Furthermore, the importance and central role of ATs with regard to the realization of the Convention on the Rights of Persons with Disabilities [63] and the central role of monitoring tools are highlighted in the recent scientific contributions conducted by the WHO experts, both at the system level and at the need level of the ATs made available by the WHO [64,66,67].

Overall, the *umbrella review* shows an imperfect overlap of the domain of interventions of the ATs on the WHO/UNICEF/UN websites and in the scientific literature referring to these international bodies. This is partly due to the different roles of the contributors: the former have a more institutional role while the latter have a key role in development and research. Surely, actions linking the two sectors could be useful to enhance AT initiatives on issues dear to the WHO/UNICEF/UN.

4.2. Final Thought: The Bottlenecks

Surely, the actions of the considered institutions at the international level are multifaceted and of an important level of concreteness; think of the observatory [26] and the Global Report on ATs [42].

However, it must be borne in mind that the work ahead of us is considerable. For example, 70 out of 193 countries provided responses on the progress indicators tool, and not all of these (62) have specific legislation (see the data and metadata available online at [26]). However, in the administration of these tools, there is always a need for collaboration on the part of governments, and presumably, the neediest populations find themselves with governments with less evolved legislation and less collaboration toward these initiatives.

Greater collaboration between national and international institutions and between themselves regarding the dissemination of research activities could also be of great importance in tackling the hot topics in the AT field as they emerged in the first part of the overview of international sites. Table 3 shows the problems and bottlenecks that emerged from the analysis.

Table 3. Problems/bottlenecks emerged from the analysis.

#	Problems/Bottlenecks
1	Population growth and gradual aging lead to a growth in people with disabilities who need support and assistance.
2	Development disparities of various countries and the relative peculiarities of living environments affect the adoption of assistive technology devices.
3	High technology and costs may not be suitable for poor countries.
4	Lack of specific legislation in some countries hinders the progress and adoption of assistive technology devices.
5	Need of collaboration from governments, particularly those with less-evolved legislation and less collaboration toward initiatives.

5. Conclusions

In conclusion, it should be noted that important initiatives have been undertaken in the AT field by the United Nations through its institutional operational arms, the WHO and UNICEF. These initiatives range from the set-up of an observatory, the improvement of catalogs, the design of guidelines, and the dissemination of the culture on ATs, up to the design and submission of survey tools (both at the population and at the government level) and the planning of new ones. From a general point of view, the overview conducted on the websites of the WHO, UN, and UNICEF highlighted that the initiatives are concrete and potentially have a high impact. However, there are also bottlenecks. Information campaigns on ATs are very important, but the effectiveness must also be monitored through specific targeted scientific investigations. In this, scholars have an important role. Indeed, not all countries are responding to these actions; the neediest populations, often with governments with less evolved legislation, seem to be less collaborative towards these initiatives. From another point of view, an *umbrella review* highlighted how consolidated scientific topics are influenced more by an interest in devices and their environment of use and digitalization. The support for raising awareness of access to ATs has less extensive coverage as a theme of interest. The need to echo the issue along with the need to study critical aspects of the diffusion of the culture of ATs in some national systems (which is also reflected in the participation in the surveys themselves carried out by the WHO and UNICEF) is particularly remarked in very recent targeted studies. All of this highlights the need to better bring together the institutional world (national and international) with the world of dissemination of the scientific literature.

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Review

Leveraging Motor Imagery Rehabilitation for Individuals with Disabilities: A Review

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Abstract: Motor imagery, an intricate cognitive procedure encompassing the mental simulation of motor actions, has surfaced as a potent strategy within the neuro-rehabilitation domain. It presents a non-invasive, economically viable method for facilitating individuals with disabilities in enhancing their motor functionality and regaining self-sufficiency. This manuscript delivers an exhaustive analysis of the significance of motor imagery in augmenting functional rehabilitation for individuals afflicted with physical impairments. It investigates the fundamental mechanisms governing motor imagery, its applications across diverse disability conditions, and the prospective advantages it renders. Moreover, this document addresses the prevailing obstacles and prospective trajectories in this sector, accentuating the necessity for continued investigation and the invention of cutting-edge technologies that optimize the potentiality of motor imagery in aiding disabled persons.

Keywords: disability; motor imagery; rehabilitation; motor skills

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1. Introduction

Motor impairments can substantially affect an individual's quality of life by restricting their capacity to conduct daily tasks, participate in social interactions, and sustain independence. Conventional rehabilitation methods such as physiotherapy and assistive apparatuses have demonstrated efficacy, but often encounter limitations in achieving optimal results [1,2]. In recent years, people have been paying more attention to the idea that imagining themselves doing physical movements could be a helpful addition to rehabilitation for individuals with disabilities [3,4].

By understanding how motor imagery can be valuable in disability rehabilitation, a diverse group of healthcare professionals, researchers, and people with disabilities can work together to use this innovative approach to improve functional outcomes and enhance the overall well-being of individuals with disabilities.

Motor imagery Figure 1, also referred to as mental imagery or kinesthetic imagery, denotes the cognitive procedure of mentally simulating or rehearsing a movement without physically enacting it [4]. It encompasses the formation of vivid and elaborate mental depictions of motor actions, integrating sensory, perceptual, and proprioceptive facets [5]. By engaging in motor imagery, individuals can mentally "practice" movements, triggering neural networks analogous to those involved in actual physical execution [3]. Motor imagery functions through an intricate interplay of neural mechanisms. Neuroimaging studies have disclosed that during motor imagery, corresponding brain regions accountable for planning and implementing physical movements are activated, including the primary motor cortex, premotor regions, supplementary motor area, and parietal areas [6,7]. This activation culminates in the production of internal motor representations which can impact the subsequent performance of motor tasks [8].

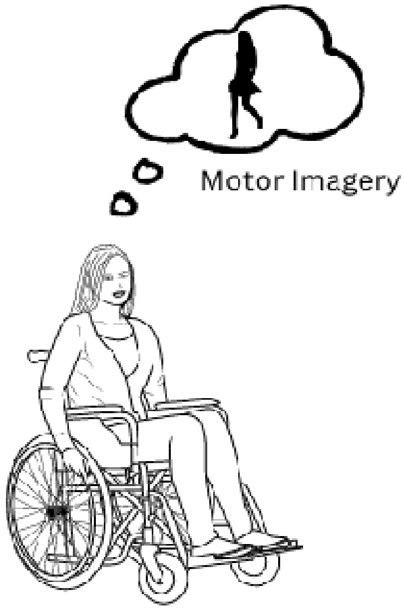

Figure 1. Motor imagery.

Motor imagery is intimately connected to motor learning—the process of attaining and refining motor skills via practice [9]. Empirical evidence indicates that motor imagery can bolster motor learning by facilitating the consolidation and refinement of motor representations [5]. Studies show that through mental rehearsal of movements, individuals can enhance their motor planning, coordination, and precision, resulting in more proficient motor execution [10]. This attribute of motor imagery renders it an invaluable resource in rehabilitation, where motor learning is a crucial component in functional recuperation [11]. This manuscript aims to investigate the utilization of motor imagery in relation to various disability circumstances such as stroke rehabilitation, spinal cord injuries, traumatic brain injuries, Parkinson's disease, cerebral palsy, and musculoskeletal disorders [6,9]. The advantages of motor imagery in enhancing motor functionality, cognitive capability augmentation, psychological well-being promotion, and fostering neuroplasticity for motor recuperation will be examined. Additionally, the manuscript will delve into diverse motor imagery techniques and training protocols including mental practice, virtual reality applications, biofeedback modalities, and brain–computer interfaces while analyzing their respective strengths and drawbacks. The obstacles and restrictions linked to the integration of motor imagery into clinical practices—variability in imaginative faculty and technological restraints—are also assessed [12]. Conclusively, the manuscript will expound upon future research trajectories encompassing the formulation of tailored training regimens, refinement of neurofeedback methodologies, breakthroughs in both virtual reality and brain–computer interface technologies, and the significance of longitudinal follow-up and persistence within motor imagery interventions [11]. This paper aims to offer a comprehensive understanding of the function of motor imagery in ameliorating motor performance and augmenting the rehabilitation process for individuals with disabilities (having impaired motor functions) [3,4]. By investigating the fundamental mechanisms, scrutinizing its applications across various disability conditions [6,9], and deliberating on prospective advantages and challenges [12], this paper endeavors to illuminate the importance of motor imagery as an inventive strategy for disability rehabilitation [10,11]. Section 2 presents the mechanism of motor imagery, then the physiological mechanism of motor imagery is discussed, which is followed by motor learning and rehabilitation using motor imagery. Then, different protocols are discussed before identifying challenges and opportunities and offering concluding sections.

2. Mechanism of Motor Imagery

Motor imagery is a complex cognitive process encompassing the mental simulation and rehearsal of movements without engaging in their physical execution. This allows individuals to generate and manipulate mental representations of motor actions, incorporating sensory, perceptual, and proprioceptive elements. The concept is based on the premise that the brain can produce internal motor representations that share similarities with those activated during actual movement [6,7].

There are several key components involved in motor imagery:

2.1. Mental Simulation

This component requires individuals to mentally simulate the performance of a specific movement or action, generating a mental image or representation of themselves executing the desired action. This process necessitates visualization of the body and its respective movements [5].

2.2. Kinesthetic Imagery

Kinesthetic imagery pertains to the subjective experience entailing emulation of bodily movement sensations without any physical execution. This component encompasses a sense of body position, movement, and effort, empowering individuals to mentally perceive the kinesthetic sensations concomitant with the intended action [4].

2.3. Visual Imagery

This aspect involves the generation of mental images or visual representations pertinent to movement. It encompasses visualization of bodily movements, environmental context, and any relevant objects or obstacles within said environment [9].

2.4. Temporal Imagery

Temporal imagery pertains to the process of mentally representing timing and sequencing aspects of movements. Individuals imagine attributes such as duration, rhythm, and coordination of actions, therefore allowing them to mentally practice and refine their motor skills [13].

3. Neurophysiological Mechanisms

Exploring the neural mechanisms underpinning motor imagery offers valuable information regarding its influence on motor learning and rehabilitation processes. Neuroimaging studies employing techniques like functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) have elucidated brain regions and networks associated with motor imagery [12,14,15].

Regions such as the primary motor cortex (M1) and premotor cortex, accountable for motor planning and execution, are activated during motor imagery sequences [6,7,14]. These regions generate neural signals analogous to those produced during actual movements. The supplementary motor area (SMA) also participates in this process, contributing to the initiation and coordination of motor plans Figure 2.

Parietal regions like the superior parietal lobule and inferior parietal lobule play a crucial role in sensorimotor integration during motor imagery. These regions combine visual, proprioceptive, and kinesthetic information to formulate a coherent mental representation of the movement [10]. The Mirror Neuron System (MNS) constitutes a fundamental component in the realm of motor imagery. Initially identified in macaque monkeys and subsequently in humans, mirror neurons represent a unique class of neurons that exhibit activation both during the execution of a specific action by an individual and while observing another individual performing the same action. The MNS contributes significantly to motor imitation and comprehending the intentions of others. Moreover, it is postulated to play an essential role in motor imagery by facilitating the internal simulation of observed movements [8].

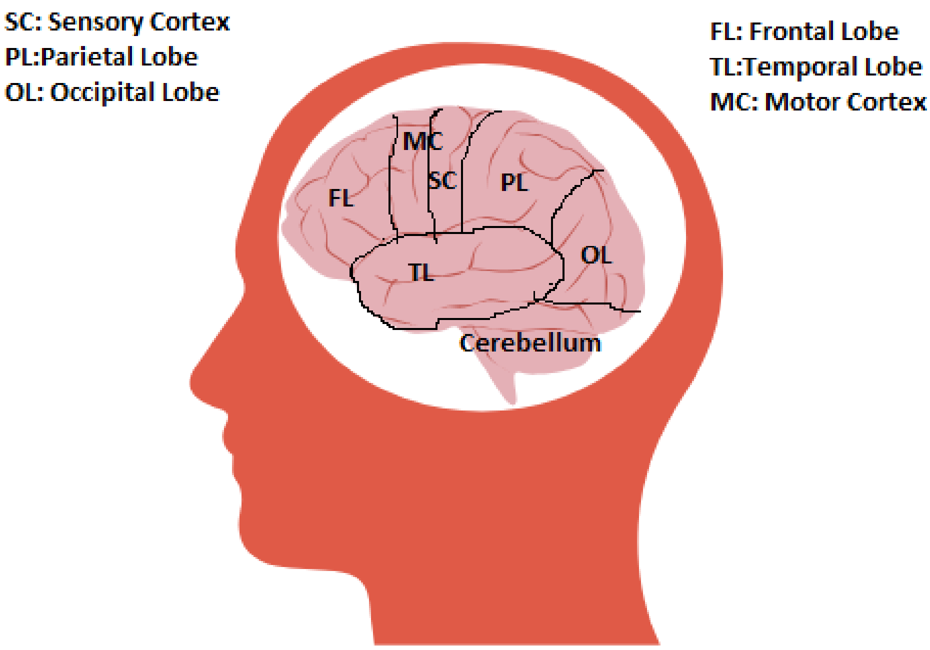

Figure 2. Regions of human brain.

4. Motor Learning

Motor imagery is intricately interconnected with motor learning, which refers to the process of acquiring and refining motor skills through repetitive practice. Current findings propose that motor imagery can augment motor learning through various mechanisms. Motor learning using motor imagery typically involves three phases Figure 3:

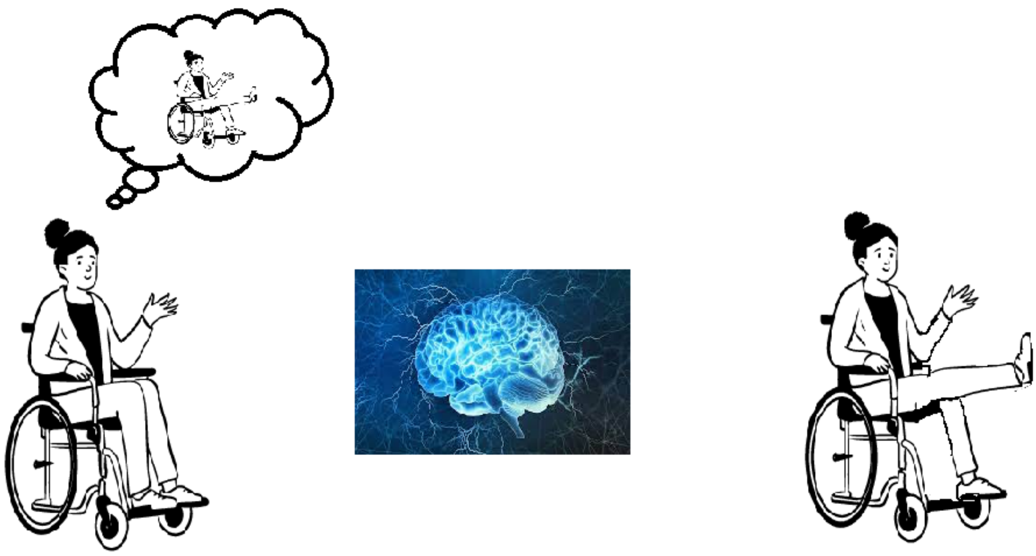

Figure 3. Motor Learning Phases: Cognitive rehearsal, Neural activation and Skill Transfer.

4.1. Cognitive Rehearsal

Motor imagery enables individuals to engage in mental rehearsal of movements, fostering cognitive planning and organization of actions. By repetitively engaging in the mental practice of the desired movement, individuals can optimize their motor plans, therefore enhancing accuracy, coordination, and timing [12].

4.2. Neural Activation

Motor imagery stimulates neural circuits analogous to those activated during physical execution, resulting in neuroplastic changes that support motor learning [16–18]. Repeated activation of these neural circuits through imagery can reinforce the associations and pathways related to the intended movement, ultimately contributing to skill acquisition and consolidation of motor [16].

4.3. Skill Transfer

Motor imagery possesses the capacity to bolster the transfer of learned skills from a cognitive domain to a physical domain. By mentally rehearsing specific movements, individuals can develop a more profound comprehension [10].

5. Rehabilitation Using Motor Imagery

Motor imagery has demonstrated significant potential in numerous disability conditions, providing possible advantages for functional rehabilitation. This section delves into the implementation of motor imagery in various disabilities, encompassing stroke rehabilitation, spinal cord injury, traumatic brain injury, Parkinson's disease, cerebral palsy, and musculoskeletal disorders [18,19]. Figure 4 and Table 1 shows different use cases of MI for rehabilitation.

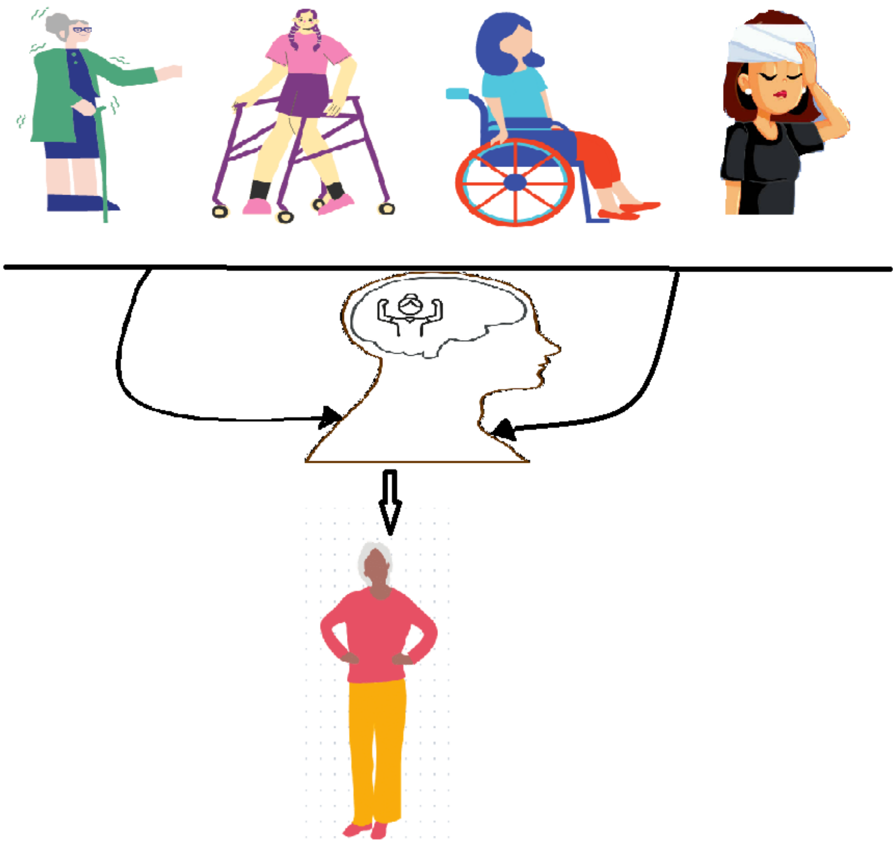

Figure 4. Rehabilitation using motor imagery.

5.1. Stroke

Stroke frequently leads to motor impairments and functional restrictions. As demonstrated by a randomized, placebo-controlled study conducted by [20], motor imagery has emerged as an efficacious supplemental therapy in stroke rehabilitation. Engaging in mental practice allows stroke survivors to mentally simulate movements, encouraging neural activation and expediting motor recuperation. Researchers [21] discovered that integrating physical therapy with mental practice resulted in superior outcomes compared to conventional physical therapy alone. Moreover, studies [22–24] established that motor imagery can contribute to functional improvements in activities of daily living and promote cortical reorganization in stroke-affected brain regions.

5.2. Spinal Cord Injury

Spinal cord injuries (SCI) often engender severe motor impairments and loss of voluntary movement below the injury level. Opsommer et al. [25] observed positive effects of motor imagery training in individuals with SCI. Through visualization and mental rehearsal of movements, subjects can activate cortical and subcortical areas associated with motor control. This activation may lead to enhancements in motor function, muscle strength, and spasticity, as demonstrated by studies conducted by Opsommer et al. [25]. Furthermore, motor imagery interventions can augment body awareness, stimulate neuroplasticity, and expedite the integration of prosthetic devices or assistive technologies [26,27].

5.3. Traumatic Brain Injury

Traumatic brain injuries (TBI) can manifest various motor impairments, including challenges with motor coordination, muscle weakness, and balance issues. Scientific investigations have indicated that motor imagery interventions can address these obstacles and ameliorate motor outcomes in individuals with TBI. Oostra et al. [15] determined that motor imagery can bolster motor planning and coordination, facilitating the reacquisition of motor skills. This finding is corroborated by research conducted by Liu et al. [28], who proved that motor imagery training can enhance motor performance, functional mobility, and balance in subjects with TBI.

5.4. Parkinson's Disease

Parkinson's disease (PD) constitutes a neurodegenerative disorder typified by motor manifestations such as bradykinesia, tremors, and rigidity. Motor imagery has surfaced as a promising therapeutic strategy for addressing motor deficits and augmenting motor control in PD-afflicted individuals. As reported by Nicholson et al. [17], motor imagery facilitates the enhancement of motor planning, coordination, and timing for individuals with PD. This amelioration is accomplished through the mental execution of movements and activation of neural networks pertinent to motor control. Furthermore, the study revealed that motor imagery interventions contribute to improvements in gait, balance, and overall motor performance for PD patients [29–31].

5.5. Cerebral Palsy

Cerebral palsy (CP) encompasses a collection of motor disorders originating from brain damage occurring during early developmental stages. Motor imagery has garnered interest as a potential supplementary therapy for CP rehabilitation. Research conducted by Ragunath et al. [32,33] determined that individuals with CP can benefit from motor imagery interventions, which foster enhanced motor planning, coordination, and overall motor performance. By mentally rehearsing movements, individuals can stimulate neural circuits associated with motor control while expediting the integration of novel motor patterns. The study exhibited improvements in upper limb functionality, gait, and balance among CP patients [34,35].

5.6. Musculoskeletal Disorders

Motor imagery techniques prove advantageous for those affected by various musculoskeletal disorders, encompassing conditions such as osteoarthritis, chronic pain, and limb amputation. Investigations have substantiated the efficacy of motor imagery in palliating pain intensity, promoting joint function, and expediting rehabilitation processes in those afflicted with musculoskeletal disorders [36]. Mental rehearsal generates effective modulation of pain signals while activating cortical regions pertinent to pain processing and fostering the reorganization of pain-related neural networks.

5.7. Amputations

Motor imagery can facilitate the adaptation to prosthetic limbs. By mentally controlling a virtual or real prosthetic, users can reinforce neural pathways associated with limb movement [37].

Table 1. Summary of Motor Imagery in Rehabilitation for Various Disabilities.

References	Disability	Key Findings in Research
[11–13,38,39]	Stroke	• Neural activation for motor recovery • Improved outcomes with mental practice • Enhances activities of daily living
[14,40,41]	Spinal Cord Injury	• Improves motor function and strength • Enhancements in muscle strength • Facilitates body awareness and neuroplasticity
[15,16]	Traumatic Brain Injury	• Enhances motor planning and coordination • Improved motor performance and mobility • Addresses balance issues and muscle weakness
[17,42,43]	Parkinson's Disease	• Improves motor planning and coordination • Enhancements in gait and balance • Augments motor control and timing
[18,44,45]	Cerebral Palsy	• Enhances motor planning and coordination • Improved upper limb functionality • Stimulates neural circuits for motor control
[19]	Musculoskeletal Disorders	• Reduces pain intensity and promotes joint function • Expedites rehabilitation processes • Neural network reorganization

The integration of motor imagery into rehabilitation protocols produces more extensive and efficacious interventions for individuals coping with disabilities. The referenced studies corroborate the potential of motor imagery to bolster motor function, facilitate motor learning, foster neuroplasticity, and elevate overall functional outcomes in the domains of stroke rehabilitation, spinal cord injury, traumatic brain injury, Parkinson's disease, cerebral palsy, and musculoskeletal disorders. Continued research and examination are requisite to optimize motor imagery techniques and generate customized interventions for specific disability conditions.

6. Effectiveness of Motor Imagery for Rehabilitation

The integration of motor imagery into rehabilitation programs can refine motor functions, amplify cognitive capacities, foster psychological well-being, and advance neuroplasticity and motor recovery. Persistent investigation of motor imagery techniques is essential to maximize their potential in rehabilitation contexts Figure 5.

6.1. Motor Function Improvement

6.1.1. Acquisition of Motor Skills

Studies [37,38] revealed that motor imagery fosters cognitive rehearsal, subsequently leading to an augmentation of skill acquisition and motor performance.

6.1.2. Motor Control and Coordination Enhancement

Hétu et al. [39] posited that motor imagery stimulates the neural networks responsible for motor planning and execution, thus improving motor control and coordination.

6.1.3. Rehabilitation Targeting Specific Motor Impairments

Caligiore et al. [40] corroborated that motor imagery can address certain motor impairments, such as muscular weakness or spasticity, resulting in improved motor functionality.

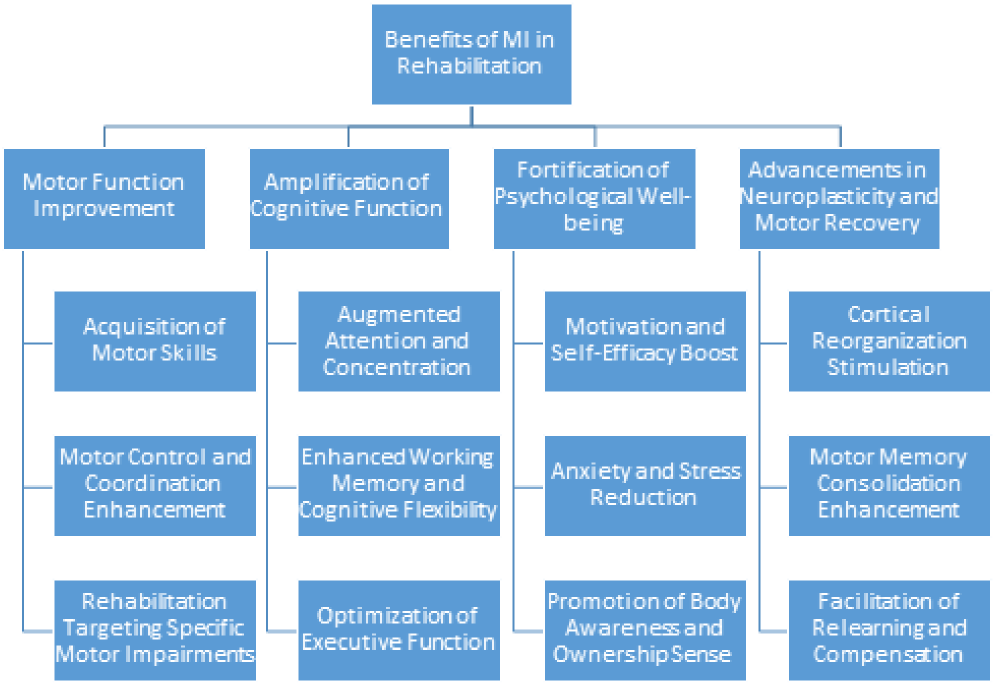

Figure 5. Benefits of using MI for Rehabilitation.

6.2. Amplification of Cognitive Function

6.2.1. Augmented Attention and Concentration

Di Rienzo et al. [41] elucidated that habitual practice of motor imagery bolsters attentional control and concentration capabilities.

6.2.2. Enhanced Working Memory and Cognitive Flexibility

Wright et al. [42] established that motor imagery promotes an increase in working memory capacity and cognitive adaptability.

6.2.3. Optimization of Executive Function

Holmes et al. [43] emphasized the engagement of executive functions through motor imagery, leading to refinements in planning, organization, and decision-making skills.

6.3. Fortification of Psychological Well-Being

6.3.1. Motivation and Self-Efficacy Boost

Malouin et al. [44] discovered that motor imagery intensifies motivation and self-efficacy during rehabilitation processes.

6.3.2. Anxiety and Stress Reduction

Di Rienzo et al. alluded to a decrease in anxiety and stress levels among individuals partaking in rehabilitation when utilizing motor imagery [41].

6.3.3. Promotion of Body Awareness and Ownership Sense

Sharma et al. [45] documented that motor imagery fosters body consciousness and a sense of personal body ownership, ultimately enhancing psychological well-being.

6.4. Advancements in Neuroplasticity and Motor Recovery

6.4.1. Cortical Reorganization Stimulation

Guillot et al. [46] presented evidence demonstrating that motor imagery stimulates cortical regions associated with motor control, subsequently resulting in cortical reorganization and motor recovery.

6.4.2. Motor Memory Consolidation Enhancement

Kundi et al. [47] substantiated that motor imagery elevates motor memory consolidation, leading to improved motor performance and recovery.

6.4.3. Facilitation of Relearning and Compensation

Braun et al. [48] advocated that motor imagery aids in the relearning of motor abilities and compensation for motor impairments.

7. Motor Imagery Techniques and Training Protocols

Motor imagery techniques and training protocols are essential for optimizing the advantages of motor imagery in rehabilitation processes [48,49]. This section delves into various motor imagery techniques and training protocols, including mental practice, virtual reality, biofeedback and neurofeedback, electromyography (EMG), brain–computer interfaces (BCI), and the efficacy of combined approaches.

7.1. Mental Practice

It constitutes the basis of motor imagery, encompassing the cognitive rehearsal of movements without physical execution. It can be performed independently or facilitated by a therapist or audiovisual cues, employing diverse methods such as visualizing movements, imagining related sensations, and mentally simulating the timing and sequencing of actions [41,50]. Integrating mental practice into rehabilitation protocols as an independent technique or in combination with physical practice has demonstrated improvements in motor function, muscle strength, and coordination [34,35,48].

7.2. Virtual Reality

VR offers an immersive and interactive platform for motor imagery training, enabling individuals to participate in realistic and engaging simulations of movements and activities [14]. VR-based motor imagery training employs virtual environments, avatars, and interactive tasks to augment visualization and cognitive rehearsal of movements. This technology provides real-time visual and auditory feedback, enhancing presence and embodiment, and has exhibited promising outcomes in stroke rehabilitation, spinal cord injury, as well as other neurological conditions by ameliorating motor function, coordination, and quality of life [14,29].

7.3. Biofeedback and Neurofeedback

These techniques deliver real-time data on physiological processes associated with motor control that can be incorporated with motor imagery to boost self-awareness, refine motor performance, and foster neuroplastic changes [34,35]. Biofeedback monitors physiological signals such as heart rate, muscle activity, or skin conductance; whereas neurofeedback evaluates brain activity utilizing electroencephalography (EEG). Merging biofeedback or neurofeedback with motor imagery allows individuals to obtain instant feedback on their cognitive practice, guiding them to modify their motor imagery strategies. These techniques have been effectively implemented in stroke rehabilitation, Parkinson's disease, and other motor disorders, resulting in enhanced motor control and functional outcomes Figure 6 [1,51–53].

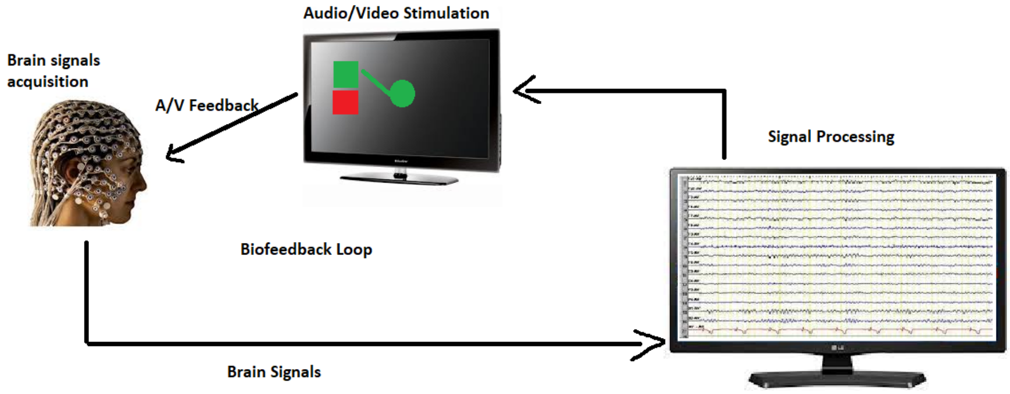

Figure 6. Biofeedback loop Therapy.

7.4. Electromyography

EMG evaluates muscle activity and can be integrated with motor imagery to offer feedback on the activation of specific muscles during cognitive rehearsal. EMG-assisted motor imagery training empowers individuals to supervise and modulate muscle activity, facilitating motor learning and control. By converging EMG with motor imagery, individuals can augment muscle activation, refine coordination, and optimize motor performance [52,54–56].

7.5. Brain–Computer Interfaces

BCIs facilitate direct interactions between the cerebral cortex and external apparatuses and have been utilized for the detection and interpretation of neuronal signals correlated with motor imagery. These signals undergo a translation process to produce control commands for assistive technologies or virtual avatars, therefore enhancing neural pathways associated with motor control and fostering neuroplastic adaptations. BCIs demonstrate potential applicability in post-stroke rehabilitation, spinal cord injuries, and other medical conditions, offering novel opportunities for motor recovery and functional restoration [15,57,58].

Integrating multiple motor imagery methodologies and training regimens augments the advantages of motor imagery in rehabilitation efforts [54]. Comprehensive paradigms, such as the amalgamation of mental practice with virtual reality, biofeedback, and electromyography, yield extensive and interactive training programs that address diverse components of motor functionality and neuronal activation. These synergistic approaches afford a customizable and adjustable rehabilitation experience, fostering multisensory integration, engagement, and motivation—all crucial elements in motor learning and recuperation.

Motor imagery techniques and training protocols encompassing mental practice, VR, biofeedback, neurofeedback, EMG, and BCI offer distinct benefits in reinforcing motor function, accelerating neuroplasticity, and ameliorating overall rehabilitation outcomes. Incorporating these methodologies into individualized and tailored rehabilitation initiatives can enhance the efficacy of motor imagery interventions for disabled individuals. Further exploration and technological advancements are imperative to unleashing the full potential of these methods and expediting their widespread integration within clinical environments.

8. Challenges of MI Based Rehabilitation

The potential of motor imagery in rehabilitation is significant; however, numerous challenges and limitations must be acknowledged. This section examines the obstacles relating to variability in imagery ability, individual disparities and training responses, incorporation of motor imagery into clinical practice, and technological restrictions.

8.1. Variability in Imagery Proficiency

A primary challenge when employing motor imagery is the varying proficiency in individuals' ability to imagine movements. Some individuals possess a heightened capability to create vivid and detailed mental images of actions, while others encounter difficulties generating distinct mental representations. This variability may hinder the effectiveness of motor imagery interventions, as those with limited imagery proficiency may face challenges engaging in precise and immersive mental simulations.

To tackle this issue, customized strategies are necessary. Practitioners and researchers must assess and comprehend each person's imagery proficiency to design personalized motor imagery training programs. Techniques such as offering visual prompts, auditory guidance, or employing guided imagery can assist individuals with diminished imagery capabilities.

8.2. Individual Disparities and Training Response

Cognitive and neural process heterogeneity can impact an individual's reaction to motor imagery training. Elements like attentional capacity, cognitive adaptability, and baseline motor functioning can influence the efficacy of motor imagery interventions. Furthermore, psychological aspects, motivation levels, and emotional states may also sway an individual's engagement during motor imagery exercises.

Recognizing and accommodating these individual disparities is crucial for maximizing motor imagery intervention outcomes. Tailored training initiatives that take into account cognitive, emotional, and motivational traits can boost engagement and elicit improved responses to training. Additionally, continuous evaluation and modification of training protocols based on individual progress can guarantee the effectiveness of motor imagery interventions.

8.3. Motor Imagery Implementation in Clinical Practice

Incorporating motor imagery into clinical practice presents challenges due to multiple factors. One predominant obstacle involves insufficient awareness and knowledge regarding motor imagery among healthcare professionals. Educating healthcare providers on motor imagery principles and applications is vital for its successful integration into rehabilitation programs.

Another hurdle is the constraints related to time and resources in clinical environments. Integrating motor imagery into existing rehabilitation protocols may necessitate supplementary time and specialized training for therapists. Moreover, the accessibility of suitable technology and equipment for motor imagery training can pose limitations in certain clinical settings. To surmount the aforementioned obstacles, it is imperative to introduce educational programs aimed at increasing awareness and offering specialized training on motor imagery for healthcare practitioners. The creation of cost-effective and accessible technologies tailored for motor imagery instruction will further streamline its incorporation into clinical procedures.

8.4. Technological Constraints

The implementation of motor imagery interventions can be hindered by various technological constraints. For instance, the acquisition of virtual reality systems demands substantial investments, specialized knowledge, and physical space. Therefore, it is essential to develop economical and intuitive virtual reality platforms to render them more readily available in clinical environments.

Moreover, the precision and dependability of measurements and feedback during motor imagery training may be restricted due to technical factors. Electroencephalography (EEG) signals are prone to noise interference and artifacts, which compromise the quality of neurofeedback-centric training. Likewise, electromyography readings may exhibit limitations in discerning minor alterations in muscular activity occurring during motor imagery.

Progression in technology, including enhancements in EEG and EMG apparatuses, signal processing methodologies, and real-time feedback systems, is vital to combat these constraints. Sturdy and dependable technologies delivering precise feedback and objective evaluations of motor imagery performance have the potential to augment the efficacy and overall efficiency of motor imagery interventions.

Despite the considerable promise of motor imagery in the realm of rehabilitation, several challenges remain to be confronted. The fluctuation in imagery aptitude, individual distinctions, integration into clinical practice, and technological barriers contribute to hindrances against broader adoption. By tackling these issues through customized approaches, pedagogical initiatives, and technological advancements, motor imagery can be effectively employed to enhance rehabilitation outcomes for persons with disabilities. Persistent research efforts and interdisciplinary collaboration between scholars, clinical professionals, and technologists are indispensable for overcoming these obstacles and fully exploiting the capabilities of motor imagery within the sphere of rehabilitation.

9. Future Directions

Motor imagery in rehabilitation is an ever-evolving domain, with multiple promising avenues for future exploration and enhancement. This section delves into the crucial areas poised to advance motor imagery interventions, including the creation of individualized training curricula, refining neurofeedback methodologies, breakthroughs in virtual reality and brain–computer interface (BCI) technology, long-standing follow-ups and maintenance strategies, as well as cross-disciplinary collaborations.

9.1. Development of Personalized Training Programs

Developing customized training programs catering to specific individual requirements and traits is imperative for augmenting the efficacy of motor imagery interventions. Upcoming research must emphasize the formulation of assessment instruments and models that allow precise evaluation of an individual's cognitive, emotional, and motor aspects to steer the development of specialized motor imagery protocols. It is vital to consider components such as imagery competence, attention capacity, foundational motor functionality, and motivational influences to certify maximum involvement and effective training outcomes.

Moreover, advancements in machine learning and artificial intelligence may expedite the establishment of intelligent systems that adapt based on individual progress and instantaneous feedback. These systems can dynamically modify difficulty levels, material content, and evaluation modalities to optimize training experiences and facilitate improved results.

9.2. Optimization of Neurofeedback Techniques

Therein lies immense potential in employing neurofeedback methodologies to boost the efficacy of motor imagery interventions. Future research directions should concentrate on enhancing neurofeedback paradigms by ensuring accurate and dependable real-time brain activity feedback. Improvements in signal processing algorithms, feature extraction techniques, and machine learning methodologies will facilitate more robust detection and interpretation of neural markers associated with motor imagery.

Furthermore, investigating innovative neurofeedback modalities beyond conventional EEG applications (e.g., functional near-infrared spectroscopy (fNIRS) or magnetoencephalography (MEG)) can furnish supplementary data and increase neurofeedback training specificity. The incorporation of numerous modalities coupled with advanced data analytics can significantly improve the precision and efficacy of neurofeedback-centered motor imagery interventions.

9.3. Advancements in Virtual Reality and BCI Technologies

With rapid progression in the fields of virtual reality and brain–computer interface technology, immense potential exists for motor imagery. Future research should concentrate on aspects such as the enhancement of virtual reality platform fidelity, usability, and accessibility for motor imagery training purposes. Essential elements include improvement in virtual environmental realism, development of user-centric interfaces, and minimizing expenses and technical intricacies associated with VR systems. Consequently, progressive developments in BCI technology have the potential to profoundly impact the incorporation of motor imagery into rehabilitative practices. Enhancements in the precision and dependability of BCI systems, investigation of non-invasive and wearable alternatives, and refinement of neural signal translation into motor instructions can pave the way for novel opportunities in motor recuperation and assistive technologies. Merging BCI advancements with virtual reality platforms can generate immersive, interactive training environments that bolster user engagement and encourage neuroplasticity.

9.4. Prolonged Monitoring and Sustained Progress

Extensive monitoring and sustained progress in motor imagery interventions are vital for evaluating long-lasting effects and ensuring ongoing improvement. Future studies ought to scrutinize the enduring advantages and maintenance of motor function enhancements attained via motor imagery exercises. This encompasses determining the ideal dosage, scheduling, and duration of training sessions to achieve durable outcomes.

Additionally, advocating for self-management and home-based motor imagery programs may augment the durability and availability of these interventions. Mobile applications, wearable technology, and telerehabilitation platforms can support remote supervision, direction, and feedback—allowing individuals to maintain their motor imagery practice beyond clinical environments.

9.5. Synergy and Comprehensive Methodologies

Synergistic endeavors and all-encompassing methodologies are essential to advance the realm of motor imagery within rehabilitation contexts. Researchers, healthcare professionals, technologists, and individuals with disabilities should collaborate to stimulate innovation, share expertise, and bridge divides between research findings and clinical applications. Collective efforts can result in the creation of comprehensive, versatile motor imagery interventions tailored to address the wide-ranging needs and obstacles confronted by those living with disabilities.

Furthermore, comprehensive collaborations can facilitate the integration of motor imagery with additional rehabilitative strategies such as physical therapy, occupational therapy, and cognitive training sessions. Combined interventions designed to synergistically target motor skills alongside cognitive capacity and psychological factors could potentially augment overall rehabilitative outcomes—fostering an enhanced quality of life for individuals with disabilities. Persistent research, innovation, and collaboration are indispensable in propelling the field forward and ameliorating the lives of individuals utilizing motor imagery in rehabilitation.

10. Conclusions

In this review, we delved into the concepts, mechanisms, applications, benefits, techniques, challenges, and prospective directions of motor imagery within the framework of disability rehabilitation. Motor imagery encompasses the mental rehearsal of movements without physical execution and stimulates comparable brain regions to those activated during physical movement. This process can augment motor learning and performance via neuroplasticity mechanisms. Motor imagery boasts a broad spectrum of applications across various disabilities—from stroke rehabilitation and spinal cord injury to traumatic brain injury, Parkinson's disease, cerebral palsy, and musculoskeletal disorders. The technique harbors the potential for enhancing motor functionality, coordination, and overall quality of life for affected populations.

Motor imagery offers several advantages in rehabilitation efforts by improving motor function, cognitive capabilities, and psychological well-being while fostering neuroplasticity and motor recovery in disabled individuals [59–61]. A myriad of techniques and training protocols can be employed to support motor imagery interventions—including mental practice, virtual reality applications, biofeedback- and neurofeedback-based technologies, electromyography, brain–computer interfaces (BCI), and integrated methods customizable to individual needs. Each approach presents distinctive benefits that can amplify motor function while optimizing rehabilitative outcomes. Nonetheless, several challenges accompany motor imagery interventions—such as variability in imagery ability, individual differences and responsiveness to the training protocols, incorporation into standard clinical practice, and technological limitations. Addressing these challenges through tailored methodologies, targeted education, and advancements in relevant technologies is paramount in overcoming constraints and promoting comprehensive implementation. The prospects of motor imagery in rehabilitation are contingent on the evolution of personalized training paradigms, fine-tuning of neurofeedback techniques, progress in virtual reality- and BCI-based systems, sustained follow-up measures, alongside teamwork and multidisciplinary cooperation. These domains exhibit potential for augmenting the efficacy and accessibility of motor imagery interventions. The article delivered an exhaustive analysis of motor imagery in disability rehabilitation, emphasizing its potential influence on enhancing motor function, cognitive function, psychological well-being, and overall quality of life for individuals with disabilities. The findings propose that motor imagery interventions can be incorporated into clinical practice to supplement traditional rehabilitation methodologies and improve treatment outcomes. The prospects for motor imagery in rehabilitation appear promising. The formulation of personalized training schemes, refinement of neurofeedback methods, progress in virtual reality and BCI technologies, and long-term follow-up may contribute to more efficient and sustainable interventions. Collaborative efforts and multidisciplinary approaches are crucial for fostering innovation, connecting research and clinical practice, and tackling the challenges encountered in implementing motor imagery interventions. The potential ramifications of motor imagery surpass rehabilitation settings; it can enhance the lives of individuals with disabilities by equipping them with self-management techniques, boosting their autonomy, and promoting community integration. In summation, motor imagery serves as a valuable instrument in disability rehabilitation with an extensive array of applications and advantages. Through further exploration of its potential, addressing impediments, and capitalizing on technological advancements and interdisciplinary collaborations, the full potential of motor imagery interventions can be harnessed to revolutionize the realm of rehabilitation for disabled individuals.

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healthcare

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Review

Artificial Intelligence Models in Health Information Exchange: A Systematic Review of Clinical Implications

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Abstract: Electronic health record (EHR) systems collate patient data, and the integration and standardization of documents through Health Information Exchange (HIE) play a pivotal role in refining patient management. Although the clinical implications of AI in EHR systems have been extensively analyzed, its application in HIE as a crucial source of patient data is less explored. Addressing this gap, our systematic review delves into utilizing AI models in HIE, gauging their predictive prowess and potential limitations. Employing databases such as Scopus, CINAHL, Google Scholar, PubMed/Medline, and Web of Science and adhering to the PRISMA guidelines, we unearthed 1021 publications. Of these, 11 were shortlisted for the final analysis. A noticeable preference for machine learning models in prognosticating clinical results, notably in oncology and cardiac failures, was evident. The metrics displayed AUC values ranging between 61% and 99.91%. Sensitivity metrics spanned from 12% to 96.50%, specificity from 76.30% to 98.80%, positive predictive values varied from 83.70% to 94.10%, and negative predictive values between 94.10% and 99.10%. Despite variations in specific metrics, AI models drawing on HIE data unfailingly showcased commendable predictive proficiency in clinical verdicts, emphasizing the transformative potential of melding AI with HIE. However, variations in sensitivity highlight underlying challenges. As healthcare's path becomes more enmeshed with AI, a well-rounded, enlightened approach is pivotal to guarantee the delivery of trustworthy and effective AI-augmented healthcare solutions.

Keywords: artificial intelligence; electronic health record; health information exchange; machine learning

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1. Introduction

1.1. Background

Thanks to the accessibility of electronic patient data, precision in medicine has seen rapid advancements. The Electronic Health Record (EHR) systems not only store patient biographical data but also amass all information gathered from institutions, encompassing radiographic imaging, blood tests, and other diagnostic tests. Consequently, the sheer volume of data, which originates from diverse patient details across various clinics, hospitals, and private care, along with modalities such as imaging, prescriptions, and procedures obtained at disparate times, forms a vast dataset that is notable in its scope and complexity [1–4].

EHRs are being rapidly adopted by healthcare groups worldwide to improve efficiency and efficacy and reduce care costs [5,6]—47% of nations now use national EHRs [7,8].

The Institute of Electrical and Electronics Engineers (IEEE) defines interoperability as the "ability of two or more systems or components to exchange information and to use the information that has been exchanged" [9]. However, since EHR data is often captured in multiple formats, achieving interoperability becomes a significant challenge, given the multitude of unique EHR formats to contend with. Health Information Exchanges (HIEs) can be an answer for fragmented healthcare systems by gathering EHR data from different provider groups and networks into a single, interoperable repository [7,10].

HIE is a valuable tool for disease monitoring due to its extensive regional and demographic spread [7,11]. However, merging data from various sources into an HIE could result in possible quality problems, such as dropout, or aggravate the problems present in each EHR system, such as low data integrity [11–14].

For the interchange, integration, and access of electronic health information, Health Level 7 (HL7) standards such as HL7 v2, HL7 v3, and Fast Healthcare Interoperability Resources (FHIR) specify the vocabulary, structure, and data formats necessary for interaction between systems. These guidelines support professional practice and viewpoints on administering, providing, and assessing healthcare services [5,15,16]. In healthcare, data analytics is segmented into three tiers: predictive, prescriptive, and descriptive. These analytics are crucial in guiding decision-making and enhancing patient outcomes [17].

The healthcare industry is transforming, with advances in Artificial Intelligence (AI), Machine Learning (ML), Natural Language Processing (NLP), and Deep Learning Neural Networks (DNN) reshaping everything from diagnosis to treatments [15,18]. Using FHIR-based algorithms for data analytics can improve health outcomes for acute and chronic conditions while reducing the skill demands within the healthcare system [17,19,20]. However, adopting AI models could change the landscape by potentially increasing healthcare productivity, reducing costs, and minimizing energy consumption [21–24].

1.2. Problem Statement and Research Questions

Given the increasing relevance of HIE in the healthcare landscape and the transformative potential of AI, understanding its current applications and limitations within HIE is crucial. Although there has been significant research on the application of AI algorithms with EHRs for different levels of data analytics and decision-making [25,26], a noticeable gap exists in the literature—a comprehensive, systematic review and analysis of AI models specifically within HIE contexts. Our systematic review aimed to answer the following questions:

1. What are the implementations of AI models in the HIE?
2. What is the effectiveness of different AI models in improving clinical outcomes based on HIE data?
3. What are the barriers to the implementation of AI in HIE?
4. What limitations have been identified in current studies, and what potential future research directions are suggested?

1.3. Objectives

To answer these questions, we will identify and compile the most recent research on the application of AI in HIE settings. First, we assess the effectiveness of AI applications in monitoring and predicting various pathologies and determine the obstacles in this way. Then, we suggest possible solutions and provide topics for additional study in this field.

2. Methods

2.1. Search Strategy

A search strategy was implemented aiming to maximize precision and accuracy of yield.

Research Units	Keywords/Terms
Health Information Systems/Standards	"Health Information Exchange", "Health Level Seven", "HL7", "HIE", "FHIR", "HIO", "Fast Healthcare Interoperability Resource"
Artificial Intelligence & Data Analytics Methods	"Machine Learning", "Natural Language Processing", "Artificial Intelligence", "Logistic Models"

Keywords/terms from each research unit were combined using Boolean operators (AND, OR).

The final search string used was: ("Health Information Exchange" OR "Health Level Seven" OR "HL7" OR "HIE" OR "FHIR" OR "HIO" OR "Fast Healthcare Interoperability Resource") AND ("Machine Learning" OR "Natural Language Processing" OR "Artificial Intelligence" OR "Logistic Models").

This search string was formulated based on similar reviews and was utilized to execute the literature search.

2.2. Data Sources and Databases Searched

Two independent investigators searched five large digital bibliographic database sources: Scopus, Cumulative Index of Nursing and Allied Health Literature (CINAHL), Google Scholar, MEDLINE (PubMed), and Web of Science to cover the relevant studies adequately. In Scopus, we used the 'Article Title, Abstract, Keywords' search field option. Filters were applied to retrieve peer-reviewed journal articles.

In CINAHL, the search was executed in the 'TX All Text' field. Filters for 'Peer-Reviewed' and 'Journal Article' were applied. Google Scholar was searched using the basic search bar. Given the vast number of results from Google Scholar, only the first 100 papers of the search yield were evaluated. In MEDLINE (PubMed), the search was applied to the 'Title/Abstract' fields. We used the 'Journal Article' filter to refine our results.

The 'Topic' field was used to conduct the search at Web of Science, and the 'Articles' filter was applied to refine our results.

Our search commenced on 20 March 2023; notably, we did not restrict the search period. The specific features or nuances of each database (e.g., using MeSH terms in PubMed) were considered while formulating the search strings. Any adjustments made to the search strings for each database due to database-specific functionalities were noted.

2.3. Study Eligibility and Selection Process

Inclusion criteria: original research articles describing the use of any form of AI in healthcare management situations with clinically based approaches on the HIE or EHR + HIE dataset. Exclusion criteria: articles that were published in non-peer-reviewed journals, articles in languages other than English, meta-analyses, systematic reviews, literature reviews, preprint studies, commentaries, opinion pieces, pilot studies, prototypes, technical designs, and secondary data analyses, and articles focused solely on data transfer security, HER data, dental/pharmacological procedures, or articles without full-text access.

We used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement as the basis of our organization [27] (Figure 1).

After performing the search, papers from each database mentioned above were selected based on the given search string. Next, each report was carefully reviewed chronologically, covering the title, abstract, keywords, introduction, background, methodologies, findings, discussion, and conclusion to ensure thoroughness. Finally, articles were retrieved from the databases if the search phrase or a substring met any article components.

Afterward, we eliminated duplicate articles obtained from different databases and filtered the collected papers using Endnote software (Version 20.4.1.).

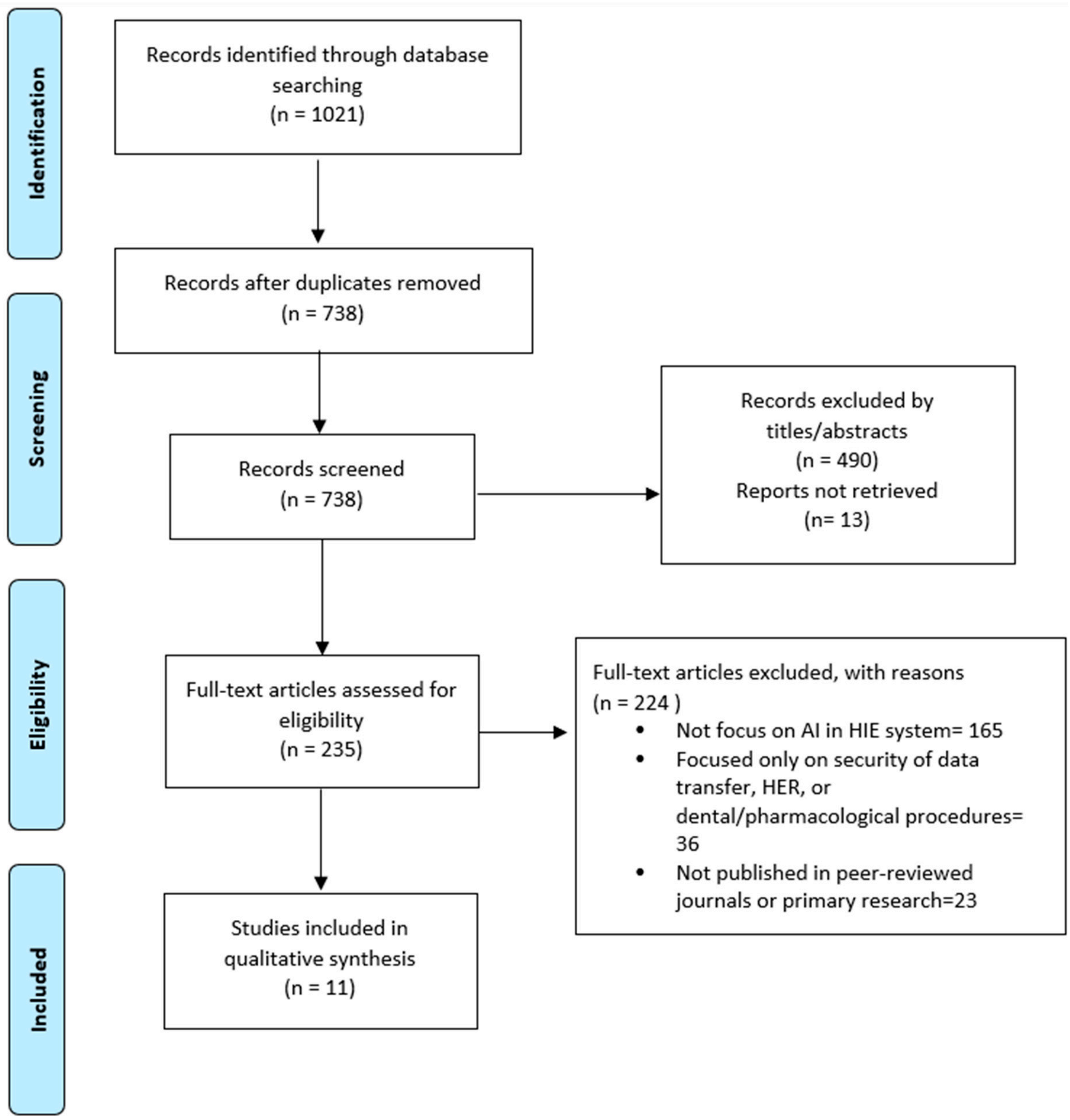

Figure 1. PRISMA flow diagram—study selection process.

2.4. Data Quality and Risk of Bias Assessment

We used a three-step method to assess the quality of the chosen articles. First, we carefully considered each article's title and abstract to ascertain its applicability to our research concerns. Second, we rapidly skimmed the complete piece to ensure it had all the pertinent information. Finally, we reviewed the full paper from start to finish to ensure it was valuable and could answer our research questions.

The first two authors independently evaluated each study for bias using the QUADAS-2 tool from the Cochrane Library for the quality assessment of diagnostic accuracy studies [28]. Subsequently, a summary and a graph were created using RevMan 5.4 (Cochrane Collaboration), enabling the stratification of bias in diverse areas. Any conflicts among the first two authors were solved by the decision of the third author independently.

2.5. Data Synthesis and Analysis

We collected various data types from each article, including author names, publication years, and study design. We also recorded the answers to our research questions from these articles for further descriptive analysis.

3. Results

3.1. Characteristics of Included Studies

3.1.1. Number of Included Studies

Our original search yielded 1021 articles for this systematic evaluation. After the application of eligibility criteria, the result was 11 papers that discussed the application of artificial intelligence models and algorithms in health information exchange and the interoperability of electronic health records. Table 1 shows a bias assessment summary, and a graph of included studies can be seen in Figures 2 and 3.

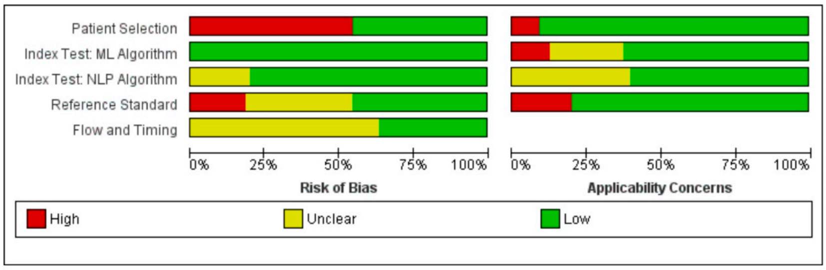

Figure 2. Risk of bias and applicability concerns graph: review authors' judgments about each domain presented as percentages across included studies. Red stands for high risk of bias, yellow stands for unclear risk, and green stands for low risk of bias.

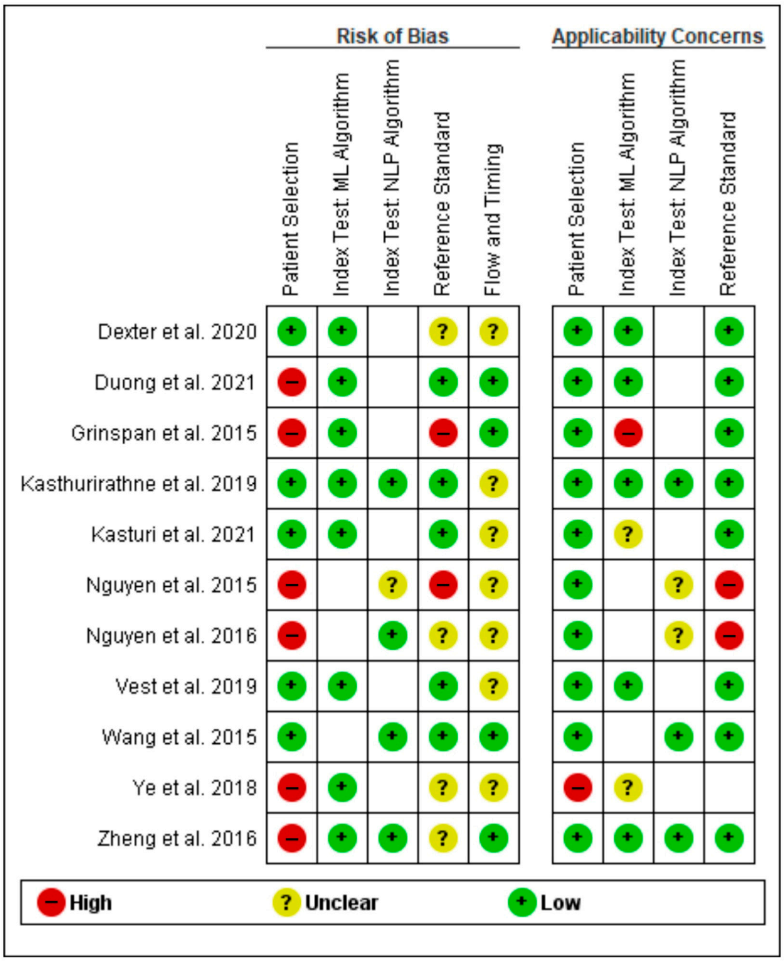

Figure 3. Risk of bias and applicability concerns summary: review authors' judgments about each domain for each included study. Red stands for high risk of bias, yellow stands for unclear risk, and green stands for low risk of bias [29–39].

Table 1. Characteristics of the included studies.

Author and Year	Study Design	Subjects	Outcome	HIE Network	FHIR Coding System	AI Model/Algorithms	Level of Implementation	Validation Method	Metric Score
Grinspan et al., 2015 [29]	Retrospective Cohort	8041 Patients	Epilepsy	NYCLIX, Manhattan, US	ICD-9	ML: LR, Lasso elastic LR, DT, RF, AdaBoost, CART, SVM	Prediction	Holdout	AUC: 78–88% Sensitivity: 12–30% PPV: 60–81% Calibration: 5–15%
Wang et al., 2015 [30]	Cohort	18,295 Patients	CHF	HealthInfoNet, Maine, US	ICD-9-CM SNOMED CT	NLP: RF	Data Extraction Case Finding	Prospective Cohort Manual Review Mann–Whitney Test Cross-Validation	RC: Sensitivity: 69%, Specificity: 98.80%, PPV: 92%, NPV: 94.10%, F1: 78.90% PC: Sensitivity: 64%, Specificity: 98.80%, PPV: 91.40%, NPV: 93.20%, F1: 75.30%
Nguyen et al., 2015 [31]	Development and Evaluation	500 Pathology Reports (201 notifiable cancer)	Notifiable Cancer	QCCAT, Queensland, Australia	SNOMED CT ICD-O	NLP: Medtex	Data Extraction	Manual Review	Recall: 78% Precision: 83% F-measure: 80%
Nguyen et al., 2016 [32]	Retrospective Observational	45.3 M Pathology Reports (119,581 histology and cytology)	Notifiable Cancer	QCCAT, Queensland, Australia	SNOMED CT	NLP: Medtex	Data Extraction	Manual Review	Sensitivity: 96.50% Specificity: 96.50% PPV: 83.70% F1: 89.60%
Zheng et al., 2016 [33]	Cohort	1.12 M patients (retrospective) 935,891 patients (prospective)	DM	HealthInfoNet, Maine, US	ICD-9-CM SNOMED CT	ML: RF NLP: DT	Data Extraction Case Finding	Manual Review Prospective Cohort	RC: Sensitivity 62%, Specificity 99.40%, PPV 95.40%, NPV 92.90% PC: Sensitivity 68%, Specificity 98.50%, PPV 90.10%, NPV 93.90%
Ye et al., 2018 [34]	Cohort	823,627 Patients (retrospective) 680,810 Patients (prospective)	HTN	HealthInfoNet, Maine, US	ICD-9-CM ICD-10-CM	ML: XGBoost	Prediction	Prospective Cohort	RC: AUC 91.70% PC: AUC 87%
Vest et al., 2019 [35]	Retrospective Observational	279,611 Patients	ED Visits	INPC, Indiana, US	N/A	ML: DT	Prediction	Holdout Cross-Validation	Travel SDOH: AUC 61% EHR with current visit data: AUC 69.60% EHR with Prior visit data: AUC of 70.70% HIE data: AUC of 71.30% All data: AUC 73.20%
Kasthurirathne et al., 2019 [36]	Retrospective Cohort	84,317 Patients	Depression Advanced Care	INPC, Indiana, US	ICD-9 ICD-10	ML: RF NLP	Data Extraction Prediction	Holdout	High-risk patients AUC: 86.31–94.43% Overall patient AUC: 78.87% Sensitivity: 68.79–83.91% Specificity:76.03–92.18%
Dexter et al., 2020 [37]	Retrospective Observational	1.7 M Laboratory Reports	Syphilis Salmonella Histoplasmosis	INPC, Indiana, US	LOINC	ML: RF	Data Extraction Prediction	Holdout Laboratory-Level Holdout	Syphilis: AUC: 99.22%, Recall: 91%, Precision: 89%, F1: 90% Salmonella: AUC: 99.91%, Recall: 95%, Precision: 97%, F1: 96% Histoplasmosis: AUC: 99.18%, Recall: 96%, Precision: 88%, F1: 92%

Table 1. *Cont.*

Author and Year	Study Design	Subjects	Outcome	HIE Network	FHIR Coding System	AI Model/Algorithms	Level of Implementation	Validation Method	Metric Score
Duong et al., 2021 [38]	Cohort	497,470 Patients (retrospective) 521,347 Patients (prospective)	HF	HealthInfoNet, Maine, US	ICD9 ICD-10-CM	ML: XGBoost	Prediction	Prospective Cohort Cross-Validation	AUC: 82.40% (81.80–83%) Sensitivity: 29.20% Specificity: 97.10% PPV 10% NPV 99.20%
Kasturi et al., 2021 [39]	Retrospective Cohort	96,026 Patients	Health Care Resource Utilization (COVID-19)	CoRDaCo, INPC, Indiana, US	N/A	ML: XGBoost	Prediction	Holdout	1 Week: AUC: 88.74%, Sensitivity: 52.50%, Specificity: 95.78% 6 Weeks: AUC: 86.21%, Sensitivity: 52.57%, Specificity: 94.26%

Abbreviations: CART: Classification and Regression Trees, CHF: Congestive Heart Failure, CPT: Current Procedural Terminology, DM: Diabetes Mellitus, DT: Decision Tree, HTN: Hypertension, ICD: International Classification of Diseases, ICD-9-CM: International Classification of Diseases-9th Revision-Clinical Modification, ICD-10-CM: International Classification of Diseases-10th Revision-Clinical Modification, IHCA: In-Hospital Cardiac Arrest, INPC: Indiana Network for Patient Care, LR: Logistic Regression, LOINC: Logical Observation Identifiers Names and Codes, NLP: Natural Language Processing, NYCLIX: New York Clinical Information Exchange, PC: Prospective Cohort, QCCAT: Queensland Cancer Control Analysis Team, RC: Retrospective Cohort, RF: Random Forest, SDOH: Social Determinants Of Health, SNOMED CT: Systematized Nomenclature of Medicine—Clinical Terms, SVM: Support Vector Machines, XGBoost: eXtreme Gradient Boosting.

3.1.2. Type of Studies

Overall, eleven articles were reviewed, encompassing various designs. Specifically, there were seven cohort studies [29,30,33,34,36,38,39], of which three were retrospective [29,36,39]. In addition, there were three retrospective observational studies [32,35,37] and one study that focused on developing and evaluating a model [31].

3.1.3. Parameters Obtained

Type of parameters obtained from the patient's records were demographics [29,34–36,39], risk factors [30,33–35], radiology encounters [29,34], histology and cytology reports [31,32], laboratory test results [34,37,38], visit history (ED, outpatient and, inpatient) [29,30,35,36,39], medications [33–35,38,39], comorbidities [29,30,35,39], and social determinants of health [35,38,39].

3.2. Types of HIE Standard, FHIR Medical Coding Systems, and Application Programming Interface (API)

The type of HIE used in the studies was Health Level 7 (HL7) [31,32,37,38]. Other studies used the specific HIE resources without mentioning the standard, such as the NYCLIX HIE network [29], Indiana Network for Patient Care (INPC) [35,36,39], and Maine Health Information Exchange (HealthInfoNet, HIN, Mount Lawley, WA, USA) [30,33,34].

The HIE medical coding systems used for data extraction were International Classification of Diseases (ICD)-9 codes [29,36,38], ICD-9-CM codes [30,33,34], ICD-10 codes [36], ICD-10-CM codes [34,38], Systematized Nomenclature of Medicine—Clinical Terms (SNOMED CT) [30–33], Logical Observation Identifiers Names and Codes (LOINC) codes [37] and ICD-O. Additionally, two studies did not mention the coding system they used [35,39].

Application Programming Interface (API), such as Java Messaging Service (JMS) API, was implemented in one of the included studies [31].

3.3. Types of AI Models, Applicability, and Validation

Most of the studies used ML models as the basis of their work (N = 8) [29,33–39], out of which two studies used both ML and NLP algorithms [33,36]. Three studies used NLP as their only prediction model [30–32]. At the same time, the most used NLP model was Medtex [31,32].

Meanwhile, five studies applied the Random Forest algorithm to train their AI model; however, three studies used different types of decision trees other than random forest [29,33,35].

The AI models included in this review were applied for different purposes—seven authors used the models as a prediction tool [29,34–39]; however, five used them to help with data extraction [30–33,36,39], and two for case finding [30,33]. Of these studies, cancer [31,32] and heart failure [30,38] were the most studied outcomes.

Several methods were implemented to validate and evaluate the effectiveness of the AI model applicability, including the holdout validation method (N = 4) [29,36,37,39], cross-validation method (N = 2) [30,35], prospective cohort (N = 4) [30,33,34,38], manual chart-review (N = 4) [30–33], and statistical methods (N = 1) [30].

3.4. Models Metric Scores

Overall, the studies were able to predict the frequency of emergency department (ED) visits. At the same time, some of them focused on people with epilepsy [29] with AUCs ranging from 0.78 to 0.88, indicating very good predictability, fair to good PPV (60–81%), and calibration (5–15%). However, sensitivity was uniformly poor (12–30%). Vest et al. [35] studied revisit rates over set periods and developed ML and NLP models from five distinct datasets. One model, based on census travel social determinants, had a 61% AUC. Another using patient-level EHR data from the current visit had 69.6% AUC. A third model, using historical patient EHR data, achieved 70.7% AUC. They also developed a model from

HIE data with 71.3% AUC and one combining current and past visits, which reached 73.2% AUC.

Reference [36] utilized random forest and NLP to identify depression patients and predict their advanced care needs, achieving AUC scores of 86.31–94.43% for high-risk groups and 78.87% overall. Meanwhile, 8.29% needed advanced care.

An automated system for cancer registry alerts from Medtex showed promising results: F1 scores ranged from 89.6% to 96.5%, and it categorized cancer traits with a recall of 0.78 and a precision of 0.83 [31,32].

Free-text laboratory data were used to train AI algorithms to identify three notifiable diseases: salmonella, histoplasmosis, and syphilis [37]. The ROC-AUC was 99.22%, 99.91%, and 99.18% for syphilis, salmonella, and histoplasmosis, respectively.

Duong et al. [38] evaluated a predictive model to detect heart failure. The model showed an AUC of 82.4%, while the Wang et al. [30] case-finding algorithm achieved 69% sensitivity, 98.8% specificity, and 78.9% F-measure. However, [39] utilized an ML model to predict healthcare resource use among COVID-19 patient subgroups. The AUC-ROC for the first week was 88.71% and 86.21% for the initial six weeks. Corresponding F1 scores were 61.81% and 61.36%, respectively.

On the other hand, Zheng et al. [33] looked into creating a decision tree-based model to detect the presence of diabetes mellitus in patients. In retrospective blind testing using an NLP-based algorithm, the model obtained 62% sensitivity and 99.4% specificity, while prospective verification yielded 68% sensitivity and 98.5% specificity.

Using prior-year medical data, Chengyin Ye et al. devised an algorithm predicting hypertension risk for the next year. Their XGBoost model achieved AUCs of 91.7% retrospectively and 87% prospectively. [34]

4. Discussion

4.1. Implications and Key Findings

According to this systematic review, using AI models in HIE may have potential benefits. First, it may enhance the precision and effectiveness of patient management based on HIE. These AI models and algorithms may accomplish various tasks, such as data extraction, clinical decision assistance, and prognosis prediction. In addition, AI may forecast multiple health-related results, such as cancer, sepsis, heart failure, in-hospital cardiac arrest, and COVID-19-related resource utilization [30,32,40–43]. Several measures, including area under the curve (AUC), precision score, positive predictive value (PPV), negative predictive value (NPV), sensitivity, specificity, calibration, and F-measure, were used to evaluate the performance of algorithms. In a clinical context, a higher AUC indicates better reliability in distinguishing between patients with and without the condition. The study's AUC of 90% (ranging from 61% to 99.91% across studies) demonstrates the model's strong ability to differentiate between these patient groups. Sensitivities nearing 96.5% (range: 12% to 96.5%) and a recall of 78% both highlight effective detection of true positives—critical for accurate diagnosis. Meanwhile, a specificity of 98.80% (range: 76.30% to 98.80%) limits false positives, reducing unneeded interventions. The model's positive and negative predictive values, 83.70% and 94.10%, respectively, underscore their accuracy in both confirming and ruling out the condition. A precision rate of up to 88% guarantees most positive detections are correct, refining treatment approaches. The harmony between the model's precision and recall is further shown by an F-measure that reaches 96%, and the limited classification error range (5.17% to 5.67%) supports the algorithm's consistent accuracy in clinical applications.

4.1.1. Health Information Exchange, Fast Healthcare Interoperability Resources, and Application Programming Interface

The "digital health" area is expanding quickly and uses digital tools to enhance population health, patient outcomes, and healthcare administration [44–48].

Although access to patient information for clinical treatment is the primary purpose of HIEs, data gathered by HIEs may also serve a secondary purpose in public health by helping to track disease and estimate its burden at the community level [7,10,49,50].

Efforts at uniformity in the HIE area include using coding systems and medical thesauruses. These are employed to categorize medical data and avoid repetition and misunderstanding in medical terminology [51–54]. FHIR is the most current HL7 system standard [54]. It was first introduced in March 2014, and multiple technical design studies conducted between 2018 and 2022 favored FHIR as their preferred standard [40–43]. HL7 messaging systems were used by [31,32,37,38] to gather their input information, and some authors tried to improve their data collection quality using HL7 version 2. Nevertheless, adopting the most recent standard, FHIR can increase the study's reliability due to its modern design, integrated data exchange, standardized resources, and enhanced support for current healthcare use cases, such as patient portals [41,55–57]. However, other studies conducted during different time frames did not specify the standard used [29,30,33–36,39].

Web services are created using a collection of architectural concepts called REST (Representational State Transfer). Using pre-existing web standards such as RESTful Application Programming Interfaces (API) and XML or JSON data exchange formats, which are lightweight and easy for individuals and machines to understand, has helped FHIR gain preference [5,58]. For HIEs, using Restful API offers many advantages, including scalability, speed, and adaptability, as demonstrated by Amrollahi et al. [42], Tseng et al. [41], and Henry et al. [43]. Still, it is also necessary to handle their complexities and security risks. Java Messaging Service (JMS) API is another reliable and scalable messaging system [59] interface that was used by Nguyen et al. [31].

The research emphasizes how crucial standardization is to health HIE networks. In particular, HL7 was widely utilized in the studies examined, which implies that policymakers and healthcare organizations should prioritize the adoption and implementation of this system, specifically FHIR, to ensure effective and efficient data sharing across various healthcare systems.

4.1.2. FHIR Medical Coding System

Globally, disorders and health conditions are categorized using the International Classification of Diseases (ICD) for medical documents and mortality certificates [5,60,61]. FHIR also makes use of a variety of system identifiers. For example, the Logical Observation Identifiers Names and Codes (LOINC) system distinguishes clinical and laboratory data such as blood tests, vital signs, and medical histories. Henry et al. [43] and Dexter et al. [37] used LOINC to obtain observation data from the FHIR server and handle their automated laboratory reports, respectively.

Systematized Nomenclature of Medicine—Clinical Terms (SNOMED CT), a specific and international clinical terminology used to define clinical concepts such as illnesses, treatments, and medications, is a different coding system [5,58,61,62]. Out of 11, 7 studies used various versions of ICD coding systems, such as ICD-9, ICD-10, and ICD-O [29–31,33,34,36,38]. Based on the population and nature of the research, each of these versions can be used depending on its unique characteristics.

ICD primarily focuses on categorizing illnesses, accidents, and causes of death. However, SNOMED CT offers a more thorough representation of clinical concepts that can be utilized, for instance, to map spans in pathology reports to clinical concepts [31,32] or to develop a controlled set of medical terms related to CHF [30].

The significance of using a uniform classification system is vital. For example, using ICD to retrieve information from patient records to guarantee uniformity and precision in data retrieval for AI algorithms is crucial to healthcare systems and must be implemented.

4.1.3. AI Models in Healthcare Data Exchange

AI describes algorithms that can perform duties corresponding to human cognitive abilities such as logic [26]. Improved patient outcomes and increased productivity are the goals of applying ML to patient care [63–67], with some models even surpassing human decision-makers in some situations [68].

AI models have demonstrated enhanced capabilities in managing health-related big datasets. Not only can they process upwards of 250 million images cost-effectively [69], but they also excel in creating "digital twins" by constructing comprehensive data infrastructures that encompass patient treatment histories, outcomes, and physiological parameters [70,71].

The two most popular ML models in healthcare are explanatory and predictive, with explanatory frameworks used to evaluate causal theories and predictive models for predicting new data. Predictive models include decision trees and random forests, which employ rule or tree-based reasoning. Although logistic and linear regression models are mainly used for prediction, they can also serve as explanatory models. Conversely, neural networks can be used for prediction and explanation tasks [15,72–75]—Figure 4 [76].

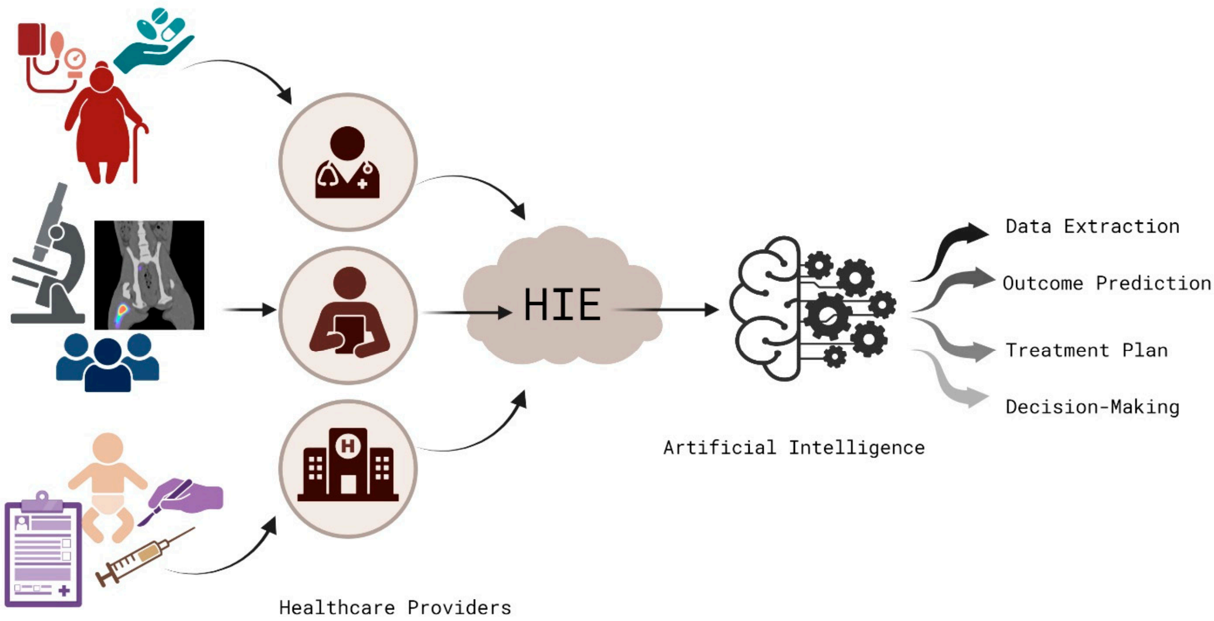

Figure 4. AI implication in Health Information Exchange System.

Despite the high degree of predictability and performance ratings that all AI models demonstrated, there are still some significant constraints. For example, to predict the incidence of emergency department visits by individuals who have epilepsy, Grinspan et al. [29] employed ML modeling, but they did not differentiate between visits for epilepsy and visits for other causes or between ED discharges and visits leading to inpatient stays. Inversely, Kasturi et al. addressed this problem by thoroughly examining the patient codes to only consider patients with COVID-19 diagnosis and not the admissions due to other causes such as accidents. Additionally, because the research was performed at four institutions in a single urban region, it may be less accurate to make general predictions using machine learning [29,31,32,34,37–39].

To overcome this limitation, Nguyen et al. [31] account for deviations frequently found in health data, such as missing data and skew distributions. They evaluated seven different predictive modeling methods in this regard. However, since their system has not been explicitly trained on some hidden categories, it may be more challenging to classify data correctly in this case. The restricted data categories utilized, especially those influencing prognostic capabilities such as insurance details and physician profiles, as highlighted in [29], might also impact the models' predictive accuracy.

Using a year of EMR data, researchers predicted a patient's likelihood of a first-time HF diagnosis using the XGBoost ML model. This model found a group with over nine times the HF risk compared to the baseline. However, it is important to mention that the study's omission of intervention effects on the predictive model could potentially misguide decision-makers [38]. Reference [30] also attempted to create a case-finding algorithm for detecting individuals with CHF employing only NLP analytics. The algorithm received outstanding results regarding sensitivity, specificity, and F-measure. However, the availability of CHF markers limited their contributions.

NLP, DNN, and ML models can categorize primary cancer types and forecast cancers of unclear origin [40]. NLP may be the best option for recognizing clinical notes that are not coded. Since clinical notes frequently use informal, unstructured language that may not adhere to a standardized vocabulary or style, it is challenging for conventional rule-based systems to recognize and retrieve information precisely. One of the possible drawbacks is the potential for missing diagnostic codes, which could restrict how broadly the NLP-based approach could be applied [33,77–81]. This is also applicable to [35] even though their ML-based HIE data model displayed a higher AUC in contrast to EHR patient-level data, as there is still a chance that the results will not be generalizable due to a potential lack of data availability in various HIE systems.

Nguyen et al. used the General Architecture For Text Engineering (GATE) platform-based Medtex medical text analysis system to obtain high levels of predictability with a sensitivity level of 96.50%. However, the increased frequency of false positives diminished the study's PPV [32]. In another study, they used the same Java-based NLP software (Medtex, version GATE 4.0 build 2752) platform to assess the service's ability to process a large volume of HL7 pathology messages. Again, the results were promising, with an F-measure of 0.80 [31].

As reported by [39], their decision tree-based ML model predicted healthcare resource utilization for COVID-19 patients but showed notable discrepancies between different demographic factors such as age, ethnicity, and gender. In addition, each model had lower-than-ideal recall results, suggesting that many individuals needing medical attention were neglected. This emphasizes how critical it is to conduct research with strict population confounding controls to analyze the effects of various factors across models. These discrepancies can have a significant impact, particularly on residents of underserved areas, and they can also contribute to healthcare disparities related to age [82–84].

The performed studies had the opportunity to work with a vast amount of data, but the time period for examining their models was generally limited. Most of the studies chose their patient data for a timeline of a year or two [29,30,32,33,37], while [34,38] extended the frame to three years, and only two studies chose their data for more than five years [35,36]. This issue may prevent the data from providing models with a full view of long-term risk, making it challenging to spot trends or forecast results and leading to ineffectual therapy or intervention.

The analyzed studies revealed confident outcomes in identifying diseases such as cancer, heart failure, and HTN. Therefore, to improve the accuracy and efficiency of diagnostics, healthcare organizations should consider incorporating AI models and algorithms into their diagnostic processes.

4.2. Strengths and Limitations of the Review

We discussed various AI uses in HIE data, such as data extraction, prediction, and clinical decision support. Additionally, to increase the validity and trustworthiness of our results, we used a strict, transparent approach for identifying, selecting, and evaluating relevant studies. There are some restrictions on the quality and variety of the included research. As a result, it may be challenging to come to a definitive conclusion about the utility and generalizability of the applied AI methods.

Studies with favorable or noteworthy findings may be more likely to be published and included in the review, making them susceptible to bias.

The AUC serves as a pertinent metric for evaluating model performance; however, its comparison across disparate studies demands caution due to variances in context and data intricacies. Notwithstanding the promise that high AUC values indicate in HIE, it remains imperative to rigorously evaluate each model in its intended context to ascertain its appropriateness and efficacy.

This study does not thoroughly examine the ethical, legal, and social aspects of using AI in HIE data, even though they are crucial factors in developing and applying AI systems in healthcare.

4.3. Future Directions and Recommendations

1. Future research should utilize diverse data sources (e.g., imaging records and lab findings) and explore alternative machine-learning methods to improve the model's ability to identify a broader range of disorders.
2. Include diverse patient populations and real-world settings to assess technical design effectiveness and conduct longer-term risk evaluations.
3. To ensure inclusivity, future research should implement strict population confounding controls, critically analyze effects across models, and prioritize addressing healthcare disparities, with a focus on underserved areas and age-related concerns.
4. To optimize model accuracy and predictive value, studies should account for intervention effects, balance sensitivity with positive predictive value, and try to integrate all pertinent predictive markers to enrich model contributions.
5. Further exploration of the ethical, legal, and societal implications of AI in HIE data can enhance our understanding of the significant challenges and issues in healthcare AI.

5. Conclusions

In our comprehensive review of 11 distinct research studies, several significant trends emerged regarding the integration of AI with HIE. A clear predilection for ML models was noted in forecasting clinical outcomes, particularly in the domains of cancer and heart failure, pointing to specific areas where AI can make substantial contributions. Additionally, while the HL7 standard has become the benchmark for HIE, the frequent adoption of ICD and SNOMED CT underscores their importance in data retrieval processes. The impressive predictive capacities of the models, as indicated by the AUC metrics spanning from 61% to 99.91%, are however juxtaposed with a wide-ranging sensitivity, highlighting both the potential and challenges of AI in this domain. As we delve into the intricacies of adopting AI in healthcare documentation, it is evident that a more holistic understanding is crucial. The findings underscore not just the complexity but the necessity for meticulous planning, understanding, and continuous exploration to navigate potential pitfalls such as prediction inaccuracies and biases. Only through rigorous analysis from diverse perspectives can we pave the way for practical and reliable AI-driven solutions in healthcare's future.

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Systematic Review

Efficacy and Safety of Respiratory Telerehabilitation in Patients with Long COVID-19: A Systematic Review and Meta-Analysis

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Abstract: The aim of this review was to identify, map, and synthesize the extent and nature of research activity on the use of telerehabilitation to support Long COVID-19 rehabilitation and examine the efficacy and safety of respiratory telerehabilitation in patients with Long COVID-19. A systematic review and meta-analysis of randomized controlled trials were performed. We included controlled trials that tested the effect of respiratory telerehabilitation interventions in patients with Long COVID-19 versus no intervention, usual care, placebo, or face-to-face intervention. The data were pooled, and a meta-analysis was completed for quality of life, dyspnea, lung function, anxiety and depression, respiratory muscle strength, functional capacity, and lower limb strength. Finally, 10 studies were included. The meta-analysis results show significant differences in favor of respiratory telerehabilitation in quality of life ($p = 0.02$), dyspnea ($p < 0.00001$), respiratory muscle strength ($p < 0.001$), functional capacity ($p < 0.0001$), and lower limb strength ($p = 0.01$) but not in lung function ($p = 0.28$) and anxiety and depression ($p = 0.55$). In addition, there were no statistically significant differences in adverse effects ($p = 0.06$) between the telerehabilitation and comparator groups. The results suggest that these interventions can improve quality of life, reduce dyspnea, and increase respiratory and lower extremity muscle strength as well as functional capacity in patients with Long COVID-19.

Keywords: Long COVID-19; telerehabilitation; quality of life; dyspnea; adverse effects; functional capacity

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1. Introduction

Long COVID-19, defined by the WHO as the onset of COVID-19 with symptoms that last after infection for at least 2 months and cannot be explained by an alternative diagnosis [1–3], affects between 5.4 and 17.9 million people worldwide and is one of the leading causes of disability [4].

The estimated prevalence of Long COVID-19 is approximately 23% of people with at least one post-COVID condition, specifically 35% in patients treated for COVID-19 on an outpatient basis but approximately 87% among cohorts of hospitalized patients [5,6]. In this line, these symptoms are leading contributors to the rapid increase in the demand for health services worldwide over the last few years [7,8] with most of the expenditure increase occurring in pain, respiratory difficulties, hyperlipidemia, malaise and fatigue, and hypertension [9–11]. Given their significant and growing financial burden [7,8], potential efficiencies in the model of care for patients with Long COVID-19 are a matter of considerable policy interest.

Traditionally, rehabilitation services form a core component of the care pathway for any disabled patient as a means of facilitating the recovery of functional independence in rehabilitation centers or hospitals. Additionally, the increased life expectancy and the limited resources in public health highlight the importance of reaching effective and sustainable rehabilitation services to cope with the needs of the population [12].

Recent advances in digital and telecommunication technologies, such as e-Health, telemedicine, wearable devices, virtual reality, and online educational tools, have made healthcare services more affordable and convenient for consumers [13]. The pandemic and the situation generated by COVID-19 have intensified the use of telerehabilitation in the healthcare sector. There is an increasing number of studies that have proven the efficacy of telerehabilitation in other pathologies, although on occasions, it has been difficult to establish generalizations due to the heterogeneity of the interventions [14]. This has created an unprecedented opportunity for the rehabilitation of patients with Long COVID-19 to adapt to new approaches to care by using innovations in digital technology.

Telerehabilitation is emerging as a viable substitute for in-person rehabilitation, particularly in the realm of cardiac and pulmonary rehabilitation, among other areas [15]. Both physical and cognitive virtual reality exercises administered through telerehabilitation have demonstrated their effectiveness and safety in addressing post-COVID-19 conditions in patients [16]. Patient satisfaction, as reported in various studies conducted during and after periods of confinement, underscores the significance of incorporating telerehabilitation into the comprehensive rehabilitation of individuals in the acute phase and those experiencing COVID-19-related sequelae [17].

A growing body of literature supports the use of telerehabilitation to improve patient satisfaction and health outcomes for a diverse range of clinical conditions, such as neurological diseases [18,19], stroke [20], cancer [21], and cardiac and pulmonary rehabilitation [22]. The British Society of Rehabilitation Medicine [23], Chartered Society of Physiotherapy [24], and the British Thoracic Society [25] have each issued policy documents regarding COVID-19 rehabilitation. Nonetheless, there is still a scarcity of concrete evidence regarding the most effective approach to deliver rehabilitation in this particular context. While the ideal rehabilitation strategy for COVID-19 remains uncertain, three fundamental components are relevant to the rehabilitation of nearly all conditions: (1) exercise training; (2) education, which includes self-management; and (3) psychosocial support [26].

However, it has not yet been demonstrated for Long COVID-19. Furthermore, it cannot be assumed that all patients with Long COVID-19 can safely be involved in telerehabilitation, considering the heterogeneity of prognostic outcomes. Nevertheless, the up-to-date evidence base about the use of telerehabilitation for Long COVID-19 rehabilitation has not been reviewed and mapped. Therefore, the aim of this review was to identify, map, and synthesize the extent and nature of research activity on the use of telerehabilitation to support Long COVID-19 rehabilitation. Additionally, the literature surrounding the safety of telerehabilitation interventions in patients with Long COVID-19 has not been specifically reviewed.

2. Methods

2.1. Protocol and Registration

A systematic review and meta-analysis were performed in accordance with the principles outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement guidelines [27] and the Cochrane Collaboration guidelines for evaluating interventions [28]. The protocol for this systematic review was duly registered on PROSPERO (registration number: CRD42022373781, registration date: 7 November 2022).

2.2. Search Strategy

We conducted a systematic search of articles indexed on MEDLINE (via PubMed), Scopus, and PEDro that covered the period from the inception of the databases until July 2023. The screening and analysis of the studies took place between November 2022 and

July 2023. We developed a search strategy in MEDLINE using the following steps: (1) the development of keywords by examining relevant key terms used in the existing systematic reviews, (2) examination of the MeSH database, and (3) expert guidance and review by a specialist.

The search strategy was rigorously tested and refined to ensure its effectiveness for this review. Subsequently, the strategy was adapted to accommodate the differences in indexing across the other databases (Appendix A). To supplement our search, we manually checked the reference lists of the included studies and relevant review articles to identify any additional articles not captured in the systematic review of the databases.

To formulate the research question, we applied the PICOS model (Participants, Interventions, Comparisons, Outcome, and Study Design).

P (Participants): adults with Long COVID-19 syndrome without restrictions on gender, ethnicity, and setting.

I (Intervention): respiratory telerehabilitation interventions.

C (Comparison): the respiratory telerehabilitation had to be compared to no intervention, usual care, placebo, or face-to-face intervention.

O (Outcomes): quality of life, symptoms, physical capacity, function, and psychological well-being.

S (Study Design): randomized clinical trials were included.

Only full-text, randomized controlled trials written in English, Spanish, and French were included in the systematic review. Systematic reviews and meta-analyses, observational studies, clinical practice guidelines, letters, abstracts, editorials, conference papers, theses, and dissertations were excluded.

In this line, respiratory telerehabilitation interventions were considered as any intervention with the ability to provide distance support, evaluation, and intervention to persons who are disabled via telecommunication [29,30].

Once the records were retrieved from the various databases, duplicate entries were removed to ensure data accuracy. Subsequently, two reviewers (A.C and C.V) conducted separate evaluations of the titles and abstracts of all the articles to assess their relevance for potential inclusion. The studies that met the eligibility criteria were further scrutinized in detail. In case of any discrepancies or disagreements between the two reviewers, a third reviewer (G.R) was asked to resolve the differences and arrive at a consensus on the final selection of studies.

After the article's selection and the data extraction, we performed a methodological quality assessment with the Downs and Black quality assessment method [31]. This method has 27 items that comprise five subscales (study quality, external validity, study bias, confounding and selection bias, and study power), classifying methodological quality as "excellent" if studies have a 26 or higher score, between 20 and 25 "good", between 15 and 19 "fair", and 14 or lower "poor". This scale is ranked as one of the six highest-quality assessment scales suitable for use in systematic reviews due to the high validity and reliability presented [32,33].

The risk of bias for the included randomized controlled trials was assessed with the Cochrane Risk-of-Bias tool version 2.0 (RoB-2) [34]. This tool consists of five domains that focus on the randomization process, deviations from the intended interventions, missing outcome data, measurement of the outcome, and the selection of the reported result. The studies were interpreted as having a high, low, or unclear risk of bias.

2.3. Meta-Analysis

The study results with respect to quality of life, dyspnea, lung function, anxiety and depression, respiratory muscular strength, functional capacity, lower limb strength, and adverse events were pooled, and a meta-analysis was undertaken using Review Manager software (Rev-Man version 5.1, updated March 2011) and the Cochrane Collaboration guidelines for reviewing interventions [35].

Post-intervention means and standard deviations were utilized as the primary data for pooling the results. In cases where the data were insufficient for the meta-analysis (e.g., missing means or standard deviations), efforts were made to contact the authors of the respective trials to obtain the required information. In instances where standard deviations were not provided but *p*-values or 95% confidence intervals were available, these were used to calculate the missing standard deviations using the embedded Review Manager calculator. Additionally, if a trial compared multiple intervention arms, each arm was treated as a separate entity in the meta-analysis, allowing for a comprehensive and accurate analysis of the data. These procedures helped ensure that the meta-analysis was conducted with the most complete and accurate data available, maximizing the reliability and validity of the findings.

Continuous outcomes were analyzed using weighted mean differences when all studies measured outcomes on the same scale. Standardized mean differences were used when all scales were assumed to measure the same underlying symptom or condition, but some studies measured the outcomes on different scales. The 95% confidence intervals were computed for all outcomes.

Finally, a meta-analysis of the adverse effects that may be generated with respiratory telerehabilitation using OR (odds ratio) was performed. When performing the meta-analysis of adverse effects using OR, since some of the treatment or comparator groups had no adverse effects, the continuity correction technique was used [36]. The continuity correction is a strategy applied to avoid mathematical or statistical problems when the cells of a contingency table (used to calculate the OR) have small or null values. In these cases, a constant value (e.g., 1) is usually added to all the cells of the table to ensure that there are no null values and that the calculations are valid.

The overall mean effect sizes were estimated using random-effect models or fixed-effect models according to the statistical heterogeneity I^2 tests. $I^2 > 50\%$ is considered to be a heterogeneous meta-analysis, and a random-effects model was used. A visual inspection of the forest plots for outlier studies was also undertaken. Sources of heterogeneity were explored, and sensitivity analyses were conducted by excluding trials that were at a high risk of detection or attrition bias.

A sensitivity analysis was conducted to investigate potential sources of heterogeneity and to determine how sensitive the conclusions of the study are to the particular method or study design feature that was used. If the effect and confidence intervals in the sensitivity analysis lead to the same conclusion as the primary meta-analysis value, the results are deemed robust.

3. Results

3.1. Study Selection

A comprehensive search was conducted in the selected databases that found a total of 9539 records. After removing duplicates, 5507 records remained, which were screened based on their title and abstract. Only 35 articles were selected for full-text evaluation. After reviewing the inclusion and exclusion criteria, 10 studies were deemed eligible for inclusion in the qualitative and quantitative syntheses [37–46] (Figure 1).

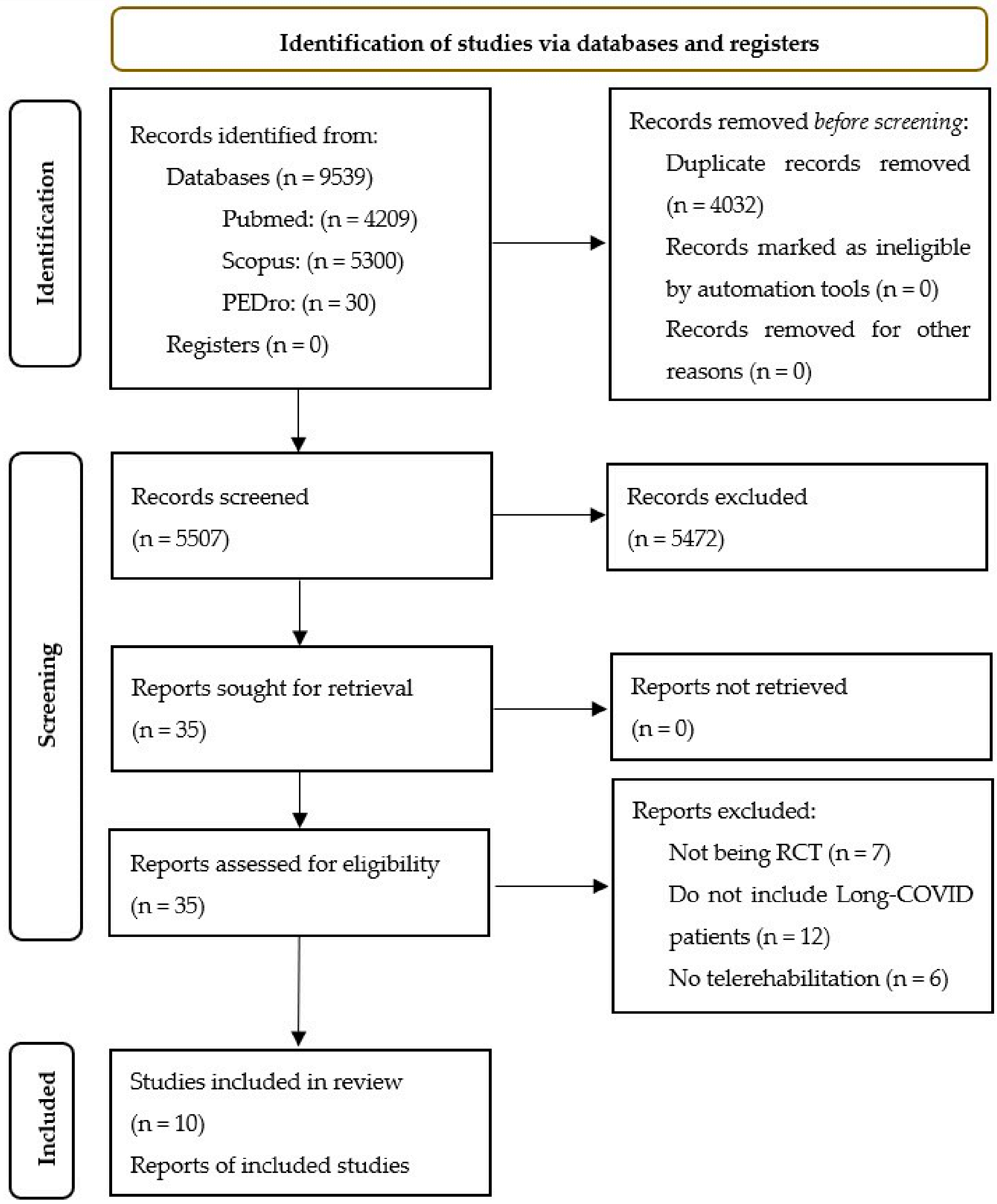

Figure 1. Flow diagram of the included articles.

3.2. Study Characteristics

The characteristics of the sample and the methodological evaluation of the included studies are shown in Table 1. A total of 866 patients with Long COVID-19 were included in the systematic review with a female predominance (73%) and an age range from 40 to 55 years.

Table 1. Characteristics of the included studies.

Study (Year)	Sample Size (n (% Female)) and Age (Mean)	Time since Acute Infection (Days)	Hospital Admission (%)	Length of Hospital Stay (Days)	Severity of Acute Infection	Quality Assessment Downs and Black (Risk of Bias)
Li et al. (2021) [37]	119 (66), 51	103.7	100	26.2	Severe and critical	25 (low risk)
Del Corral et al. (2022) [38]	88 (71), 46	350.8	31.8	NR	Mild, moderate, severe, and critical	27 (low risk)
McNarry et al. (2022) [39]	148 (90), 47	270	NR	NR	Mild, moderate, severe, and critical	23 (low risk)
Okan et al. (2022) [40]	52 (48), 51	86.9	100	9.5	Severe and critical	25 (low risk)
Philip et al. (2022) [41]	150 (80), 50	320	17.3	NR	Mild, moderate, and severe	24 (low risk)
Sharma et al. (2022) [42]	30 (NR), NR	NR	NR	NR	Mild	14 (high risk)
Vallier et al. (2022) [43]	17 (29), 55	140.9	76.5	11.3	Mild, moderate, severe, and critical	19 (high risk)
Kuut et al. (2023) [44]	114 (72.8), 46	187.5	11.4	NR	Mild, moderate, severe, and critical	22 (some concerns)
Rodríguez-Blanco et al. (2023) [45]	48 (54), 41	NR	0	Not applicable	Mild	21 (low risk)
Samper-Pardo et al. (2023) [46]	100 (80), 48	483.6	NR	NR	Mild, moderate, severe, and critical	22 (low risk)

Notes: NR, not reported.

Among the included articles, four studies [38,39,41,46] featured patients who had experienced acute COVID-19 infection more than 9 months prior, while four articles [37,40,43,44] focused on patients who had been infected 3 months prior. Two of the articles did not report the time elapsed since acute infection [42,45].

This systematic review examined the hospitalization status of patients across the included studies. Two articles exclusively studied patients who had been hospitalized [37,40], indicating severe or critical acute infection severity, while two other articles only included patients with mild acute infection severity who did not require hospitalization [42,45]. The remaining studies encompassed patients with a spectrum of severities [38,39,41,43,46] from mild to critical with a lower percentage of patients requiring hospitalization compared to the hospitalized groups [38,41,44]. Three articles did not report on the hospitalization status of patients [39,42,46]. Regarding the duration of hospitalization, only the articles that exclusively studied hospitalized patients [37,40] reported on the days of hospitalization, which ranged from 9.5 to 26.18 days.

This systematic review evaluated the methodological quality of the studies using the Downs and Black quality assessment method. Of the studies included, one was classified as excellent [38], while seven were classified as good [37,39–41,44–46], one was classified as fair [43], and one was classified as poor [42]. Additionally, the risk of bias of all ten studies [37–46] was assessed using the RoB-2 tool (Figure 2), which concluded that five of the articles had a low risk of bias [38–41,45], three of them had some concerns [37,44,46], and two others had a high risk of bias [42,43]. These findings suggest that most of the studies included in this review were conducted with rigorous methodology.

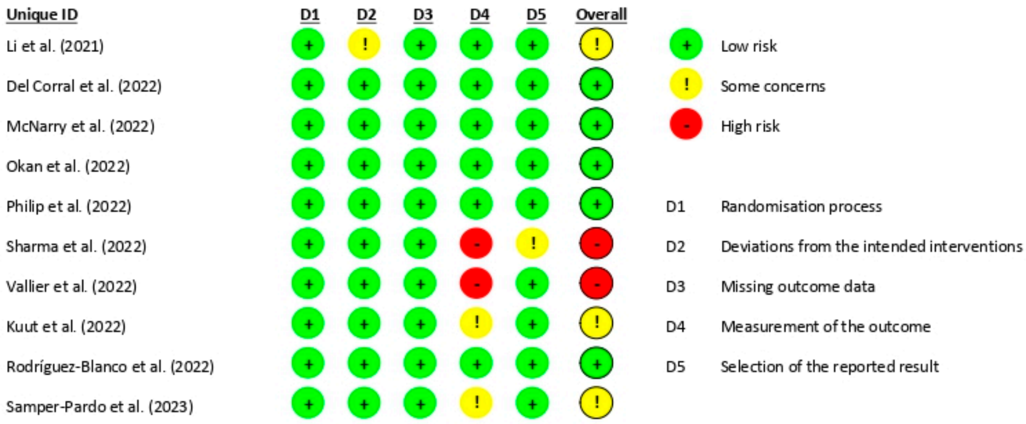

Figure 2. Risk of bias [37–46].

The details of the interventions performed and the results obtained are shown in Table 2. The modality of the respiratory telerehabilitation performed varied among the different studies included. Therefore, eight of the included studies performed respiratory training or breathing exercises [37–42,45,46]. Four of them combined it with aerobic exercise or strength training [37,42,45,46]. Philip et al. [41] combined breathing exercises with anxiety self-management exercises, and the rest performed the breathing exercises or respiratory training in isolation [38–40]. Kuut et al. [44] conducted a multidisciplinary telerehabilitation program based on cognitive behavioral therapy. Vallier et al. [43] conducted a telerehabilitation program that combined aerobic exercises, strength exercises, and relaxation exercises and compared it with the same rehabilitation program but applied in a face-to-face setting. For this reason, it was included in the qualitative analysis but not in the quantitative analysis.

With respect to the different components of the telerehabilitation programs, the most repeated were tele-education in self-management, symptom and mood telemonitoring, physical activity telemonitoring with personalized feedback, and teleconsultation with healthcare professionals that were included in up to eight of the ten studies. Remote decision-support systems and telecommunication with other patients were included in four of the ten studies.

The duration of the respiratory telerehabilitation programs ranged from 4 weeks to 17 weeks with the most repeated duration being 6 weeks of treatment. The duration in minutes of the different respiratory telerehabilitation sessions ranged between 20 and 60, and they were performed 3 to 7 days a week, repeating two times a day in the study of Del Corral et al. [38] and three times a day in the study of Okan et al. [40]. All the articles included in this review adjusted the volume of the interventions with continuous reevaluations.

Table 2. Characteristics of included interventions.

Study (Year)	Intervention and Comparator Group	Telerehabilitation Components	Duration, Frequency, Volume, and Intensity	Intervention Technology and Intervention Monitoring	Outcome Measures
Li et al. (2021) [37]	**IG:** Breathing exercises + Aerobic exercise + Strength exercises **CG:** Educational instructions	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals • Remote decision-support systems	• 6 weeks • 3–4 days/week • 40–60 min • Divided into three levels of volume • Tailored to each participant through continuous feedback	• Video conference • Weekly monitoring in individual sessions	**Quality of life (SF-12):** IG ** > CG ($p < 0.05$) **Dyspnea (mMRC):** IG ** > CG ($p < 0.001$) **Lung function (FVC):** IG * vs. CG * (NSD) **Functional capacity (6MWT):** IG ** > CG ($p < 0.001$) **Adverse events:** IG (0) vs. CG (0)
Del Corral et al. (2022) [38]	**IG1:** Respiratory training (inspiratory musculature) **IG2:** Respiratory training (inspiratory/expiratory musculature) **CG1:** Sham respiratory training **CG2:** Sham respiratory training	• Tele-education in self-management • Teleconsultation with healthcare professionals • Telecommunication with other patients	• 8 weeks • 6 days/week • 2 times/day • 20 min • 6 set × 10 rep • 50% of MIP	• Video conference • Daily monitoring in group session	**Quality of life (EQ-5D):** IG1 * vs. CG1 * (NSD) IG2 * > CG2 ($p < 0.001$) **Lung function (FVC):** IG1 vs. CG1 (NSD) IG2 vs. CG2 (NSD) **Anxiety and depression (HADS):** IG1 * vs. CG1 * (NSD) IG2 * vs. CG2 (NSD) **MIP:** IG1 * > CG1 * ($p < 0.05$) IG2 * > CG2 * ($p < 0.05$) **Functional capacity (RT):** IG1 vs. CG1 (NSD) IG2 * vs. CG2 (NSD) **Lower limb strength (1STS):** IG1 * > CG1 ($p < 0.05$) IG2 * > CG2 ($p < 0.05$) **Adverse events:** IG1 (0) vs. CG1 (1) IG2 (0) vs. CG2 (0)
McNarry et al. (2022) [39]	**IG:** Respiratory training **CG:** Usual care	• Tele-education in self-management • Symptom and mood telemonitoring	• 8 weeks • 3 days/week • 20 min • 6 set × 6 rep • 80% of SMIP	• Video conference • Not monitoring	**Quality of life (K-BILD):** IG ** vs. CG (NSD) **Dyspnea (TDI):** IG > CG ($p < 0.05$) **Adverse events:** NR

Table 2. *Cont.*

Study (Year)	Intervention and Comparator Group	Telerehabilitation Components	Duration, Frequency, Volume, and Intensity	Intervention Technology and Intervention Monitoring	Outcome Measures
Okan et al. (2022) [40]	**IG:** Breathing exercises **CG:** Education brochure	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals	• 5 weeks • 7 days/week • 3 times/day • 1 set × 10 rep • NR	• Mobile app • Weekly monitoring in individual sessions	**Quality of life (SGRQ):** IG ** > CG ** ($p < 0.001$) **Dyspnea (mMRC):** IG ** > CG * ($p < 0.001$) **Lung function (FVC):** IG ** vs. CG ($p < 0.001$) **Functional capacity (6MWT):** IG ** > CG ($p < 0.001$) **Adverse events:** IG (0) vs. CG (0)
Philip et al. (2022) [41]	**IG:** Breathing control and anxiety self-management exercises **CG:** Usual care	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals • Telecommunication with other patients • Remote decision-support systems	• 6 weeks • On-demand and adapted to each participant through continuous feedback	• Video conference • Weekly monitoring in group sessions	**Quality of life (SF-36):** IG > CG ($p < 0.05$) **Dyspnea (MD-12):** IG vs. CG (NSD) **Anxiety and depression (GAD-7):** IG vs. CG (NSD) **Adverse events:** IG (1) vs. CG (0)
Sharma et al. (2022) [42]	**IG:** Breathing exercises + Aerobic exercise + Strength exercises **CG:** Usual care	• PA telemonitoring with personalized feedback	• 6 weeks • 4 days/week • NR	• Mobile app • Not monitoring	**Dyspnea (mMRC):** IG * > CG ($p < 0.05$) **Fatigue (VAS):** IG * > CG ($p < 0.05$) **Adverse events:** IG (0) vs. CG (0)
Vallier et al. (2022) [43]	**IG:** Aerobic exercise + Strength exercises + Relaxation exercises **CG:** Face-to-face physiotherapy	• Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals	• 4 weeks • 4 days/week • 40–60 min • 90–100% HR	• Video conference • Weekly monitoring in individual session	**Quality of life (VQ11):** IG * vs. CG * (NSD) **Dyspnea (mMRC):** IG * vs. CG * (NSD) **Lung Function (FVC):** IG * vs. CG * (NSD) **Fatigue (MFI):** IG ** > CG ** ($p < 0.05$) **Functional capacity (6MWT):** IG ** vs. CG ** (NSD) **Lower limb strength (1STS):** IG ** vs. CG ** (NSD) **Adverse events:** NR

Table 2. *Cont.*

Study (Year)	Intervention and Comparator Group	Telerehabilitation Components	Duration, Frequency, Volume, and Intensity	Intervention Technology and Intervention Monitoring	Outcome Measures
Kuut et al. (2023) [44]	**IG:** Multidisciplinary telerehabilitation based on cognitive behavioral therapy **CG:** Usual care	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals • Telecommunication with other patients • Remote decision-support systems	• 17 weeks • On demand and tailored to each participant	• Video conference • On-demand monitoring in individual sessions	**Quality of life (SF-36):** IG > CG ($p < 0.001$) **Fatigue (CIS-F):** IG > CG ($p < 0.001$) **Adverse events:** IG (8) vs. CG (20)
Rodríguez-Blanco et al. (2023) [45]	**IG:** Breathing exercises + Strength exercises **CG:** No intervention	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals • Remote decision-support systems	• 2 weeks • 7 days/week • 30 min • 1 set × 12 rep • Tailored to each participant through continuous feedback	• Video conference • Daily monitoring in individual session	**Dyspnea (MD-12):** IG ** > CG ($p < 0.001$) **Fatigue (VAS):** IG ** > CG ($p < 0.001$) **Functional capacity (6MWT):** IG ** > CG ($p < 0.001$) **Lower limb strength (30STS):** IG ** > CG ($p < 0.001$) **Adverse events:** IG (0) vs. CG (0)
Samper-Pardo et al. (2023) [46]	**IG:** Breathing exercises + Aerobic exercise **CG:** Usual care	• Tele-education in self-management • Symptom and mood telemonitoring • PA telemonitoring with personalized feedback • Teleconsultation with healthcare professionals • Telecommunication with other patients	• 12 weeks • On demand and tailored to each participant	• Mobile app • Not monitoring	**Quality of life (SF-36):** IG vs. CG (NSD) **Anxiety and depression (HADS):** IG vs. CG (NSD) **Lower limb strength (30STS):** IG vs. CG (NSD) **Adverse events:** NR

Notes: * Difference with respect to the baseline $p < 0.05$. ** Difference with respect to the baseline $p < 0.001$. 1STS, 1 min Sit-to-Stand Test; 30STS, 30 s Sit-to-Stand Test; 6MWT, 6 Minutes Walking Test; CG, Control group; CIS-F, Fatigue severity subscale of the Checklist Individual Strength; EQ-5D, EuroQol 5-Dimension; FVC, Forced Vital Capacity; GAD-7, Generalized Anxiety Disorder 7; HADS, Hospital Anxiety and Depression Scale; HR, Heart rate; IG, Intervention group; K-BILD, Kansas City Pulmonary–Behavioral Inventory of Lung Disease; MD-12, Multidimensional Dyspnea-12; MFI, Multidimensional Fatigue Inventory; MIP, Maximal Inspiratory Pressure; mMRC, Modified Medical Research Council; NR, Not reported; NSD, Non-Significant Difference; PA, Physical activity; RT, Ruffier Test; SF-12, Short Form 12 Health Survey; SGRQ, St. George's Respiratory Questionnaire; SMIP, Sustained Maximal Inspiratory Pressure; TDI, Transition Dyspnea Index; VAS, Visual Analog Scale; VQ11, Short health-related quality of life questionnaire.

The intensity of the respiratory telerehabilitation was regulated according to the maximal inspiratory pressure (MIP) [38], sustained maximal inspiratory pressure (SMIP) [39], or heart rate (HR) [43] values in three of the articles; in five articles, it was adjusted to each participant based on continuous feedback [37,41,44–46]; and two articles [40,42] did not specify the way to regulate the intensity of the respiratory training.

The interventions included in this review were all home-based, and most were monitored. The most common form of monitoring was weekly, daily, or on-demand online sessions, which could be group or individual. Three articles did not monitor the interventions in any way [39,42,46]. The technology most commonly used by the different authors to conduct the telerehabilitation interventions was videoconferencing followed by mobile apps.

With respect to the comparison of interventions, five of the studies compared respiratory telerehabilitation with the usual care [39,41,42,44,46], and two other articles compared respiratory telerehabilitation against an educational brochure [37,40]. Del Corral et al. [38] compared their respiratory training with a sham respiratory training with the same treatment but performed with valveless devices that did not oppose resistance to the patient. Finally, Rodriguez-Blanco et al. [45] compared their intervention with no intervention, and Vallier et al. [43] compared their intervention with the same intervention carried out in person.

3.3. Results Obtained in Meta-Analysis

The results obtained in the meta-analysis with respect to quality of life were analyzed as shown in Figure 3. The pooled standardized mean difference (SMD) showed a significant overall effect of respiratory telerehabilitation compared to the comparator groups (SMD = 0.59; 95% CI = 0.09; 1.09; p = 0.02). The results showed heterogeneity, detecting a significant variability of I2 = 90%, not attributable to chance.

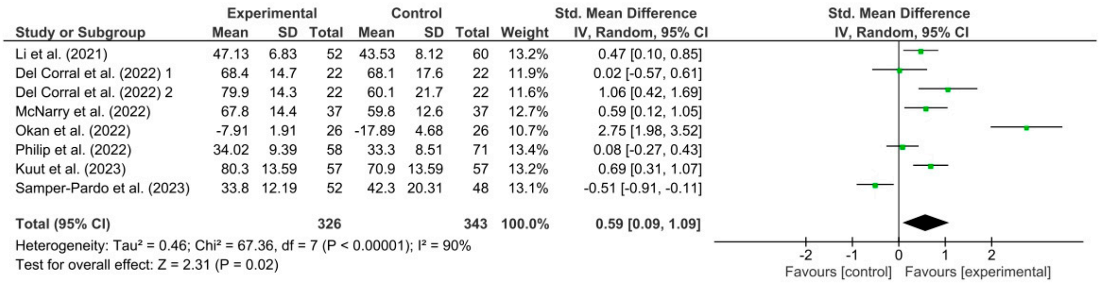

Figure 3. Results of the quality of life [37–41,44,46].

Figure 4 shows the results obtained in the meta-analysis for dyspnea. The pooled standardized mean difference (SMD) showed a significant overall effect of respiratory telerehabilitation compared to the comparator groups (SMD = 4.95; 95% CI = 2.81; 7.08; $p < 0.00001$). The results show heterogeneity, detecting a significant variability of I2 = 98%, not attributable to chance.

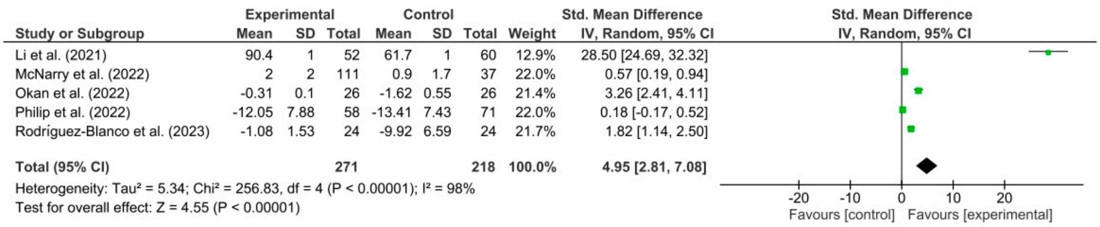

Figure 4. Results of dyspnea [37,39–41,45].

Figure 5 shows the results obtained in the meta-analysis for FVC. The pooled mean difference (MD) showed a non-significant overall effect of respiratory telerehabilitation compared to the comparator groups (MD = 0.21; 95% CI = −0.17; 0.60; p = 0.28). The results show heterogeneity, detecting a significant variability of I2 = 66%, not attributable to chance.

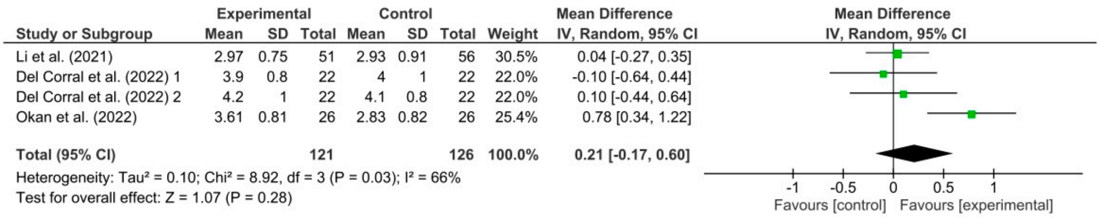

Figure 5. Results of FVC [37,38,40].

Figure 6 shows the results obtained in the meta-analysis for anxiety and depression. The pooled standardized mean difference (SMD) showed a non-significant overall effect of respiratory telerehabilitation compared to the comparator groups (SDM = −0.05; 95% CI = −0.23; 0.12; p = 0.55). The results do not show heterogeneity, detecting a significant variability of I2 = 0%.

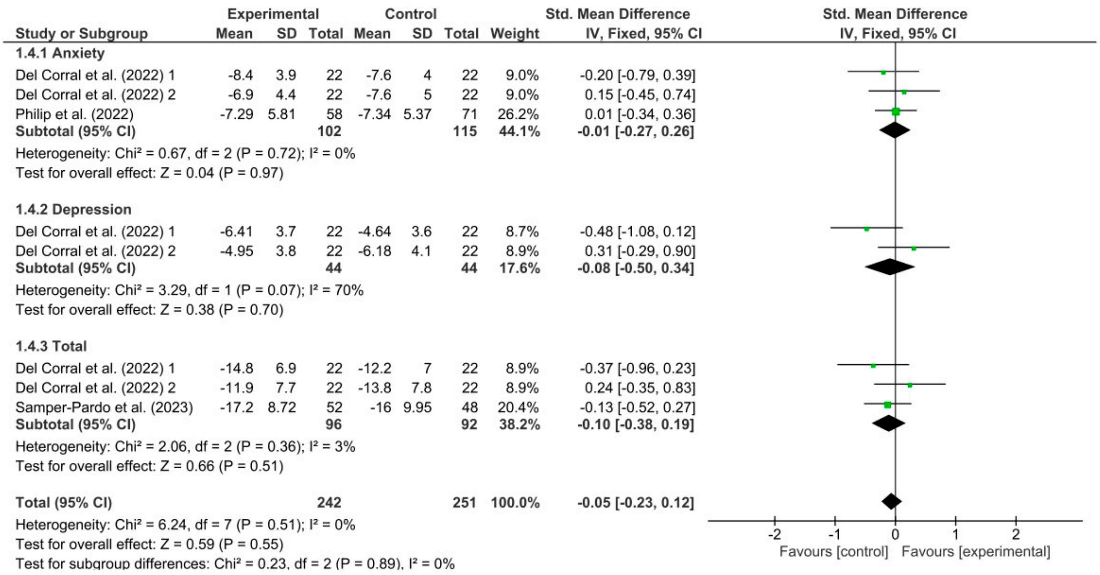

Figure 6. Results of anxiety and depression [38,41,46].

Figure 7 shows the results obtained in the meta-analysis for respiratory muscular strength. The pooled mean difference (MD) showed a significant overall effect of respiratory telerehabilitation compared to the comparator groups (MD = 13.71; 95% CI = 5.41; 22; $p < 0.001$). The results do not show heterogeneity, detecting a significant variability of I2 = 0%.

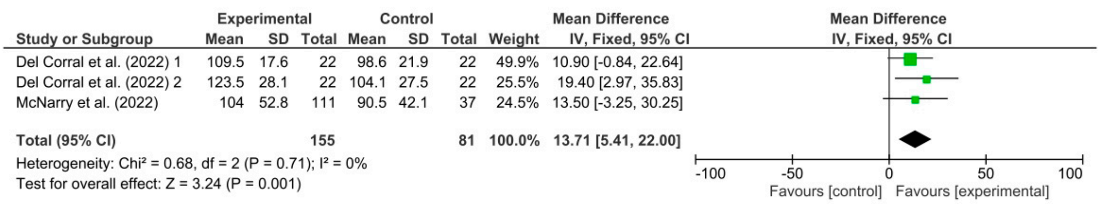

Figure 7. Results of MIP [38,39].

Figure 8 shows the results obtained in the meta-analysis for functional capacity. The pooled standardized mean difference (SMD) showed a significant overall effect of respiratory telerehabilitation compared to the comparator groups (SMD = 0.75; 95% CI = 0.39; 1.11; $p < 0.0001$). The results show heterogeneity, detecting a significant variability of I2 = 66%, not attributable to chance.

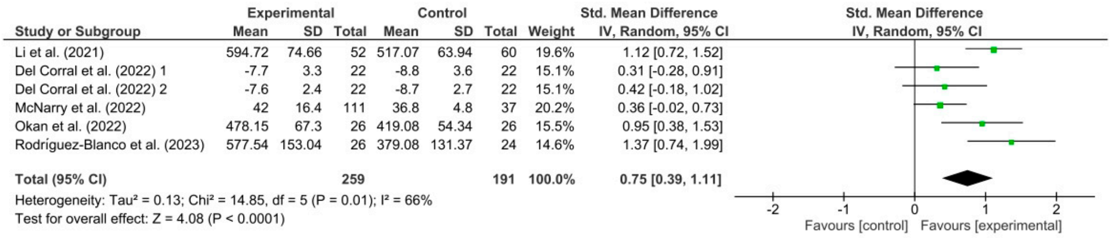

Figure 8. Results of functional capacity [37–40,45].

Figure 9 shows the results obtained in the meta-analysis for lower limb strength. The pooled standardized mean difference (SMD) showed a significant overall effect of respiratory telerehabilitation compared to the comparator groups (SMD = 0.67; 95% CI = 0.15; 1.18; $p = 0.01$). The results show heterogeneity, detecting a significant variability of I2 = 81%, not attributable to chance.

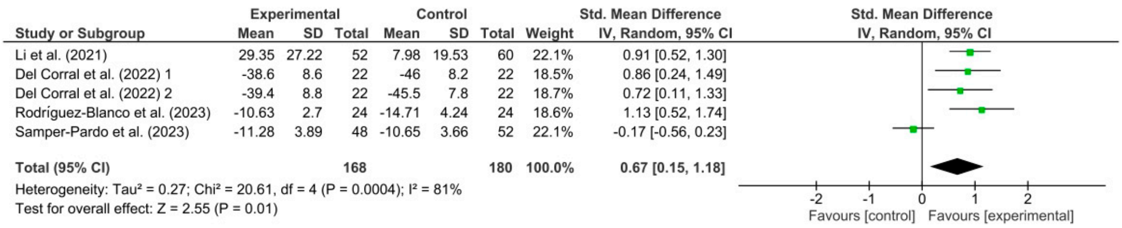

Figure 9. Results of lower limb strength [37,38,45,46].

Figure 10 shows the results obtained in the meta-analysis for adverse events. The result shown by this meta-analysis (OR = 0.53; 95% CI = 0.27; 1.02; $p = 0.06$) means that the difference between the groups exposed to telerehabilitation and the comparison groups is not statistically significant, implying that there is no strong evidence of an association between telerehabilitation and adverse effects.

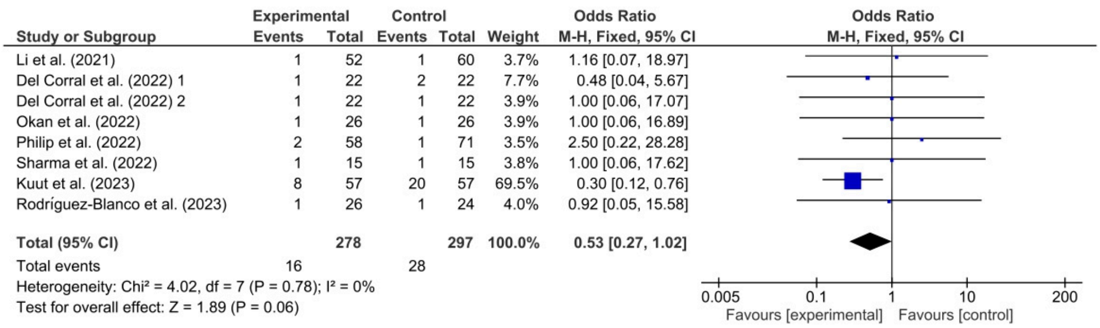

Figure 10. Results of adverse events [37,38,40–42,44,45].

4. Discussion

The COVID-19 pandemic has had a significant impact on the health and well-being of the worldwide population. One of the most worrying consequences of this disease is the syndrome known as Long COVID-19 where symptoms persist after acute infection and affect patients' quality of life. This systematic review and meta-analysis aimed to evaluate the efficacy and safety of respiratory telerehabilitation as a potential intervention for the management of persistent Long COVID-19 symptoms.

The sample of our systematic review shows the characteristics of the Long COVID-19 population. The articles analyzed included only patients with Long COVID-19; however, the severity of the patients' symptoms during the acute phase was variable. Of the 866 patients with Long COVID-19, 73.32% were women, and the age ranged from 40 to 55 years; the data are consistent with the characteristics of this population since it has been shown to be a disease more prevalent in women [47–49].

The respiratory telerehabilitation programs were heterogeneous among themselves with the most repeated parameters being 6 weeks of treatment at least three times a week with a duration of 20 to 60 min per session. These parameters are in line with the parameters of different pulmonary telerehabilitation programs presented in a review carried out in patients with COVID-19 [50]. Due to the pandemic situation in which the studies included in this review were carried out, all the interventions were performed at home [29–38], and most of them were monitored [37,38,40,41,43–45].

With respect to the components included within the telerehabilitation programs, the results found in this systematic review are in line with previous reviews in which it was shown that the most common and promising interventions are based on a combination of self-management tele-education, telemonitoring of symptoms and mood, telemonitoring of physical activity with personalized feedback, and teleconsultation with healthcare professionals [51,52].

The results of this review highlight the growing interest in the application of telerehabilitation in the management of patients with Long COVID-19. Ten studies were identified that met the inclusion criteria, suggesting that this area of research is of increasing interest. Most of the studies obtained a rating of good or excellent methodological quality, which increases the confidence in the results obtained.

The results of this review indicate that respiratory telerehabilitation may be an effective strategy to improve quality of life and reduce dyspnea in patients with Long COVID-19. The meta-analysis showed that respiratory telerehabilitation was associated with significant improvements in quality of life, decreased dyspnea, and increased respiratory and lower extremity muscle strength and functional capacity compared to the control groups receiving standard care or placebo interventions. These findings suggest that respiratory telerehabilitation may be a valuable tool for addressing persistent symptoms and improving functionality in patients with Long COVID-19.

The systematic reviews conducted to date that attempt to clarify whether telerehabilitation is an effective and safe tool for the therapeutic approach of patients with Long COVID-19 show results similar to those found in this systematic review. In general, the results demonstrate the effectiveness and safety of telerehabilitation as a therapeutic tool to improve functional capacity, quality of life, dyspnea, and lower limb strength. However, the reviews previously carried out have a low number of studies and include patients with short- and long-term sequelae. Thus, an updated review was needed of all randomized controlled studies performed to date that included only patients with Long COVID-19.

Moreover, our results are in line with the results obtained with systematic reviews performed in other chronic respiratory pathologies, such as chronic obstructive pulmonary disease [53,54]. These reviews demonstrate the effectiveness and safety of telerehabilitation in improving physical variables and patient reported outcomes.

The effectiveness of respiratory telerehabilitation can be explained by several factors. First, remote care allows patients to access rehabilitation services from the comfort of their homes, avoiding unnecessary travel and reducing the risk of exposure to other infections, especially for those with compromised immune systems [55,56]. In addition, flexible scheduling and session availability can improve adherence to rehabilitation as patients can schedule sessions at times that are convenient for them [15,57,58].

In addition, telerehabilitation offers the ability to customize interventions for each patient, which may be especially relevant given that the symptoms and needs of patients with Long COVID-19 can vary significantly. Telerehabilitation programs can be tailored to symptom severity, functional ability, and individual preferences, which can improve the effectiveness of rehabilitation [59,60].

It is important to mention that telerehabilitation for patients with Long COVID-19 comes with certain limitations and challenges. First, not all patients may be able to participate in this type of intervention due to the heterogeneity of Long COVID-19 outcomes [61,62]. Some patients may have medical conditions or disabilities that make safe participation in telerehabilitation programs difficult. Therefore, careful individualized assessment is required before implementing this approach.

The safety of respiratory telerehabilitation is also a critical factor to take into account. The findings from the meta-analysis of adverse events indicate that respiratory telerehabilitation is a safe approach with no significant difference in adverse event rates between the telerehabilitation and control groups. This is reassuring as it suggests that telerehabilitation could be a secure choice for managing patients with Long COVID-19. Nevertheless, it remains essential to consistently monitor and assess potential side effects and adverse reactions. From the ten articles included in the systematic review and meta-analysis, only six evaluated adverse events. Additionally, the adverse effects were recorded based on the patient's self-report, but in this way, a significant amount of information could be missing because many of the adverse effects require the observation of a professional (blood pressure, skin temperature, etc.).

Another challenge to consider is access and equity in the use of telerehabilitation. While these interventions can provide significant benefits, it is crucial to ensure that all patients have equal access to these technologies. This involves addressing economic and technological barriers that could hinder access to telerehabilitation, especially in disadvantaged or resource-limited communities.

In the context of health care and health policy, the results of this review have important implications. Telerehabilitation may be an effective solution to address the growing demand for Long COVID-19-related health services. By implementing telerehabilitation programs, health systems could optimize their resources and reduce the health care burden [63,64].

It is important to note that this review has some limitations that should be considered when interpreting the results. First, the limited number of included studies and the relatively small sample sizes may limit the generalizability of the results. In addition, although efforts were made to minimize bias and heterogeneity, some differences in study designs and intervention approaches may have contributed to the variability in the results. The heterogeneity of the different interventions makes it more difficult to standardize the results; however, the sensitivity analysis performed suggested that the effect of telerehabilitation interventions was consistent, regardless of the variability of the different interventions. However, further research with robust designs and standardized protocols is needed to confirm the findings of this review and provide a solid basis for the implementation of respiratory telerehabilitation in clinical practice.

Furthermore, this review highlights the need for further research in the field of Long COVID-19 telerehabilitation. Although the results are encouraging, further studies are needed to fully understand the long-term effects of telerehabilitation in this patient population. Future research could explore more targeted and personalized approaches as well as assess the sustainability and feasibility of implementing technology-assisted rehabilitation programs on a large scale.

5. Conclusions

In conclusion, this systematic review and meta-analysis provide promising evidence on the efficacy and safety of respiratory telerehabilitation in the management of persistent Long COVID-19 symptoms. The results suggest that telerehabilitation can improve quality of life, reduce dyspnea, and increase respiratory and lower extremity muscle strength and functional capacity in patients with Long COVID-19. However, caution is required when interpreting the results due to the observed heterogeneity and the limited number of included studies. Further research is needed to identify the subgroups of patients who may benefit most from telerehabilitation and to develop standardized protocols to ensure the effectiveness and safety of this intervention in Long COVID-19. Despite these limitations, respiratory telerehabilitation presents itself as a promising option for improving the care and management of patients with Long COVID-19 in the digital era.

Author Contributions: A.C.-M. had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis, especially including any adverse effects. A.H.-C. and L.L.-L. contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript. J.M.-N. had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. M.C.V. contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript. S.H.-H. contributed substantially to the study design, data analysis and interpretation, and the writing of the manuscript. A.H.-C. and G.R. had full access to all of the data in the study and take responsibility for the integrity. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors have no competing interest to declare.

Appendix A. Search Strategy

Medline (via Pubmed): ("post-acute COVID-19 syndrome" OR "post-acute COVID syndrome" OR "long-COVID" OR "long COVID" OR "long-haul COVID" OR "long haul COVID" OR "persistent COVID-19" OR "long hauler COVID" OR "post-acute sequelae of SARS-CoV-2 infection" OR "chronic COVID syndrome" OR "post-COVID" OR "post COVID" OR "long-term COVID-19" OR "post-COVID syndrome" OR "post-COVID-19 syndrome" OR "post COVID-19 condition" OR "post-COVID-19 condition" OR "post-COVID-19 conditions" OR "post-COVID conditions" OR "post-COVID condition" OR "COVID-19 persistent symptoms" OR "COVID-19 consequences" OR "Ongoing symptomatic COVID-19") AND ("Physical Therapy Modalities" OR "modalities, Physical Therapy" OR "modality, Physical Therapy" OR "physical Therapy Modality" OR "physiotherapy (Techniques)" OR "physiotherapies (Techniques)" OR "physiotherapy" OR "physical" OR "therapy" OR "therapies" OR "physical Therapy Techniques" OR "physical Therapy Technique" OR "techniques, Physical Therapy" OR "group Physiotherapy" OR "group Physiotherapies" OR "physiotherapies, Group" OR "physiotherapy, Group" OR "physical Therapy" OR "physical Therapies" OR "therapy, Physical" OR "neurological Physiotherapy" OR "physiotherapy, Neurological" OR "neurophysiotherapy" OR "Physical Therapy Specialty" OR "Specialty, Physical Therapy" OR "Therapy Specialty, Physical" OR "Physiotherapy Specialty" OR "Specialty, Physiotherapy" OR "Rehabilitation" OR "Habilitation" OR "Exercise Therapy" OR "Remedial Exercise" OR "Exercise, Remedial" OR "Exercises, Remedial" OR "Remedial Exercises" OR "Therapy, Exercise" OR "Exercise Therapies" OR "Therapies, Exercise" OR "Rehabilitation Exercise" OR "Exercise, Rehabilitation" OR "Exercises, Rehabilitation" OR "Rehabilitation Exercises" OR "activity" OR "activities" OR "exercise" OR "training" OR "Exercise Movement Techniques" OR "Movement Techniques, Exercise" OR "Exercise Movement Technics" OR "Pilates-Based Exercises" OR "Exercises, Pilates-Based" OR "Pilates Based Exercises" OR "Pilates Training" OR "Training, Pilates" OR "Telerehabilitations" OR "Tele-rehabilitation" OR "Tele rehabilitation" OR "Tele-rehabilitations" OR "Remote Rehabilitation" OR "Rehabilitation, Remote" OR "Rehabilitations, Remote" OR "Remote Rehabilitations" OR "Virtual Rehabilitation" OR "Rehabilitation, Virtual" OR "Rehabilitations, Virtual" OR "Virtual Rehabilitations")

Scopus: TITLE-ABS-KEY (("post-acute COVID-19 syndrome" OR "post-acute COVID syndrome" OR "long-COVID" OR "long COVID" OR "long-haul COVID" OR "long haul COVID" OR "persistent COVID-19" OR "long hauler COVID" OR "post-acute sequelae of SARS-CoV-2 infection" OR "chronic COVID syndrome" OR "post-COVID" OR "post COVID" OR "long-term COVID-19" OR "post-COVID syndrome" OR "post-COVID-19 syndrome" OR "post COVID-19 condition" OR "post-COVID-19 condition" OR "post-COVID-19 conditions" OR "post-COVID conditions" OR "post-COVID condition" OR "COVID-19 persistent symptoms" OR "COVID-19 consequences" OR "Ongoing symptomatic COVID-19") AND ("Physical Therapy Modalities" OR "modalities, Physical Therapy" OR "modality, Physical Therapy" OR "physical Therapy Modality" OR "physiotherapy (Techniques)" OR "physiotherapies (Techniques)" OR "physiotherapy" OR "physical" OR "therapy" OR "therapies" OR "physical Therapy Techniques" OR "physical Therapy Technique" OR "techniques, Physical Therapy" OR "group Physiotherapy" OR "group Physiotherapies" OR "physiotherapies, Group" OR "physiotherapy, Group" OR "physical Therapy" OR "physical Therapies" OR "therapy, Physical" OR "neurological Physiotherapy" OR "physiotherapy, Neurological" OR "neurophysiotherapy" OR "Physical Therapy Specialty" OR "Specialty, Physical Therapy" OR "Therapy Specialty, Physical" OR "Physiotherapy Specialty" OR "Specialty, Physiotherapy" OR "Rehabilitation" OR "Habilitation" OR "Exercise Therapy" OR "Remedial Exercise" OR "Exercise, Remedial" OR "Exercises, Remedial" OR "Remedial Exercises" OR "Therapy, Exercise" OR "Exercise Therapies" OR "Therapies, Exercise" OR "Rehabilitation Exercise" OR "Exercise, Rehabilitation" OR "Exercises, Rehabilitation" OR "Rehabilitation Exercises" OR "activity" OR "activities" OR "exercise" OR "training" OR "Exercise Movement Techniques" OR "Movement Techniques, Exercise" OR "Exercise Movement Technics" OR "Pilates-Based Exercises" OR "Exercises, Pilates-Based" OR "Pilates Based Exercises" OR "Pilates Training" OR "Training, Pilates" OR "Telerehabilitations" OR "Tele-rehabilitation" OR "Tele rehabilitation" OR "Tele-rehabilitations" OR "Remote Rehabilitation" OR "Rehabilitation, Remote" OR "Rehabilitations, Remote" OR "Remote Rehabilitations" OR "Virtual Rehabilitation" OR "Rehabilitation, Virtual" OR "Rehabilitations, Virtual" OR "Virtual Rehabilitations"))

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Article

Machine Learning Applications in Sarcopenia Detection and Management: A Comprehensive Survey

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Abstract: This extensive review examines sarcopenia, a condition characterized by a loss of muscle mass, stamina, and physical performance, with a particular emphasis on its detection and management using contemporary technologies. It highlights the lack of global agreement or standardization regarding the definition of sarcopenia and the various techniques used to measure muscle mass, stamina, and physical performance. The distinctive criteria employed by the European Working Group on Sarcopenia in Older People (EWGSOP) and the Asian Working Group for Sarcopenia (AWGSOP) for diagnosing sarcopenia are examined, emphasizing potential obstacles in comparing research results across studies. The paper delves into the use of machine learning techniques in sarcopenia detection and diagnosis, noting challenges such as data accessibility, data imbalance, and feature selection. It suggests that wearable devices, like activity trackers and smartwatches, could offer valuable insights into sarcopenia progression and aid individuals in monitoring and managing their condition. Additionally, the paper investigates the potential of blockchain technology and edge computing in healthcare data storage, discussing models and systems that leverage these technologies to secure patient data privacy and enhance personal health information management. However, it acknowledges the limitations of these models and systems, including inefficiencies in handling large volumes of medical data and the lack of dynamic selection capability. In conclusion, the paper provides a comprehensive summary of current sarcopenia research, emphasizing the potential of modern technologies in enhancing the detection and management of the condition while also highlighting the need for further research to address challenges in standardization, data management, and effective technology use.

Keywords: sarcopenia; AWGSOP; EWGSOP; physical performance; ML algorithms

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1. Introduction

Sarcopenia, a condition characterized by the loss of muscle mass, strength, and physical performance, is a significant health concern, particularly in older populations. As the global population ages, the prevalence of sarcopenia is expected to rise, leading to increased healthcare costs and degradation in the quality of life (QoL) for affected individuals. Accordingly, the prediction and management of sarcopenia disease become critical for public health all over the world. In this survey paper, we first explore sarcopenia in depth and propose a healthcare platform with applicable technologies for its detection and management.

There is no unified criterion globally for sarcopenia diagnosis. This lack of consensus in sarcopenia's definition and diagnostic criteria can be a hurdle to developing effective interventions and treatments. Instead, several methodologies exist, such as muscle mass or strength measurement and physical performance tests. For this, the European Working Group on Sarcopenia in Older People (EWGSOP) and the Asian Working Group for Sarcopenia (AWGSOP) each define criteria for diagnosing sarcopenia.

The measurement of muscle mass is crucial for the diagnosis of sarcopenia. Instruments including Dual-energy X-ray absorptiometry (DEXA), computed tomography (CT), and magnetic resonance imaging (MRI) are popularly used to measure muscle mass. However, the diagnostic outcomes can vary by each instrument with disparate sensitivity and intrinsic specificity, and the threshold values for diagnosing sarcopenia via these imaging modalities are absent of unique standards. Furthermore, diagnostic equipment may not be readily available in primary care settings, which can obstruct the early detection of individuals at risk of developing sarcopenia and following therapeutic management.

The early detection of sarcopenia is crucial as it allows for the implementation of interventions that can slow the progression of the condition, improve the quality of life for affected individuals, and reduce healthcare costs.

Recent literature demonstrates considerable interest in evaluating determinants of sarcopenia and devising methodologies to precisely quantify these determinants [1]. Key determinants include the degree of physical exertion, prolonged sedentary behavior, cardiopulmonary endurance, and muscular fortitude. However, accurately measuring these determinants presents challenges. Self-reported data are commonly utilized to assess physical exertion but may be subjective and biased. Moreover, while fitness examinations provide objective data, they may not be feasible across all settings. Therefore, developing valid and reliable metrics to evaluate physical activity and fitness levels is critical for identifying and intervening in sarcopenia.

Machine learning techniques show promise for predicting sarcopenia, as demonstrated through Support Vector Machines (SVM), Random Forests (RF), and Gradient Boosting Machines (GBM) models. These algorithms can analyze large datasets and detect patterns predictive of sarcopenia onset and progression. However, applying machine learning for sarcopenia detection faces obstacles like data accessibility, imbalance, and feature selection. High-quality, representative training and testing data are needed but scarce [2]. Imbalanced class distributions can skew predictions. Identifying predictive features while avoiding overfitting remains challenging. Thus, effective data collection, balancing, and feature selection strategies are vital when utilizing machine learning to detect sarcopenia.

Wearable devices offer the potential for tracking sarcopenia by continuously monitoring physical activity and health indicators. The resulting data could reveal muscle mass, strength, and function changes to identify and manage sarcopenia. However, wearables also present data accuracy, interpretation, and user adherence limitations that warrant consideration before deployment.

Various models employ blockchain technology and edge computing to enhance privacy protection and data sharing for personal health records, promoting security, confidentiality, and interoperability. Nonetheless, current frameworks have shortcomings in handling large medical datasets and dynamically selecting resources that require improvement.

Despite extensive research, major gaps remain in sarcopenia prevention, diagnosis, and management. There is no consensus on its operational definition or cut-off values for key parameters like muscle mass and strength. Multiple assessment techniques like imaging, physical performance tests, and questionnaire tools are employed, but their integration into diagnostic and monitoring frameworks needs optimization. Rapid advancements in technologies like wearable sensors, machine learning, and mobile health apps offer tremendous potential to enhance sarcopenia detection and care but also present analysis, validation, and implementation challenges.

This comprehensive survey aims to synthesize insights from recent studies to elucidate the current state of sarcopenia research. It explores promising technical approaches for assessment and diagnosis but also critiques their limitations to shed light on areas needing further investigation. The survey delves into sophisticated machine learning techniques but grounds their utility through a careful examination of challenges related to data accessibility, feature selection, and model optimization. It highlights innovative sensor-based tools while weighing factors influencing their accuracy, adoption, and integration into platforms or interventions.

In consolidating evidence regarding sarcopenia, this survey identifies remaining knowledge gaps, technology limitations, and standardization needs. It provides a launch point to motivate key next steps in strengthening definition consensus, assembling predictive datasets, advancing analytics, and translating technologies into patient care. Most importantly, it aims to guide future sarcopenia research toward targeted efforts that move from conceptual frameworks toward pragmatic clinical solutions. This paper seeks to inspire tangible progress in screening, diagnosis, and management to reduce the encroaching public health burden of this complex geriatric condition.

This survey synthesizes current evidence on the topic of interest. The literature search used Google Scholar, Web of Science, and ScienceDirect databases. Peer-reviewed papers published in English within the last three years were prioritized for inclusion, see Table 1. Both original research studies and review articles were eligible for inclusion if they provided relevant insights on the topic. Key data and findings were extracted from the selected papers using a standardized form to collate and compare results. Information was synthesized by grouping papers into themes and chronologically analyzing research trends. The main limitation of this approach is that the literature search may not be as comprehensive without predefined search strategies across multiple databases. However, this survey still provides a qualitative synthesis of existing evidence on the topic.

Table 1. Literature review methodology.

Review Methodology	Details
Literature Search	• Google Scholar • Web of Science • ScienceDirect
Inclusion Criteria	• Peer-reviewed papers • Published in the last 3 years • English language • Original research and review articles
Information Extraction	• Key data extracted into a standardized form • Results collated and compared
Synthesis Approach	• Grouped by themes • Chronological analysis of research trends

Compared to the survey paper by Pawan and Praveen [3], the current review provides a more comprehensive overview of sarcopenia detection and management leveraging modern technologies. While [3] focused predominantly on diagnostic criteria and physical performance assessments, the current paper delves deeper into technological innovations like machine learning, wearable devices, blockchain, and edge computing for sarcopenia. It highlights advancements in applying techniques like SVM, random forests, and gradient boosting for prediction. The discussion on wearables, mobile apps, insoles, and IMUs for continuous monitoring and assessment is more detailed.

Moreover, the current review uniquely covers emerging topics like blockchain for secure health data exchange and edge computing for localized processing absent in [3]. However, the machine learning section in [3] explores supervised learning algorithms more extensively. Overall, the current paper provides better insights into technology-enabled sarcopenia management with a broader scope.

The structure of this paper is as follows. Section 2 delves into the intricacies of physical performance with respect to sarcopenia, while Section 3 explores the criteria for diagnosing this condition. Digital health technologies and IoT devices specifically crafted for sarcopenia are the subject of Section 4. A thorough examination of the healthcare platform underpinning these IoT frameworks is given in Section 5, while Section 6 offers an overview of the machine learning algorithms applicable in the context of sarcopenia.

Section 7 uncovers the challenges associated with applying these technologies in the management of sarcopenia. Finally, the paper draws to a close with Section 8, summarizing the key points and offering concluding thoughts.

2. Physical Performance Test for Sarcopenia

Sarcopenia, a progressive and generalized skeletal muscle disorder, leads to adverse outcomes such as falls, disability, cognitive decline, and mortality and a significant threat to the maintenance of independence [4], which can be estimated by a decrease in muscle mass and strength, and physical performance.

2.1. Grip Strength

Hand grip strength (HGS), as a surrogate for muscle strength, is often assessed to indicate muscle functions in the context of sarcopenia [5]. HGS is useful for identifying individuals with low muscle strength as an initial step in diagnosing sarcopenia according to universal cut-off points for grip strength recommended by the European Working Group on Sarcopenia in Older People (EWGSOP2) [4].

Conventionally, HGS has been measured by a dynamometer and measurement protocols. Recently, innovative approaches have been proposed indirectly to measure grip strength. Jeong et al. [6] adopted joint angles of fingers from finger tracking to measure hand grip strength, which could potentially be developed into a mobile application, showing a low error rate of less than 15% in measuring grip strength. Also, Barrios et al. [7] introduced a simple mobile application measuring finger tapping speed, which is related to grip strength.

However, grip strength measured by those methods can vary and cause a wide range of cut-off points in the screening for sarcopenia [8,9]. Furthermore, grip strength can be different across countries, which is expected to impact the prevalence of sarcopenia. Accordingly, the choice of HGS criterion (average vs. maximum) significantly impacted the prevalence of low HGS and sarcopenia, and their predictive validity for physical performance [10]. Similarly, De et al. [11] argued that HGS as an independent predictor of sarcopenia should only be used as a screening tool to stratify the need for confirmatory CT-based assessment of sarcopenia.

For understanding differences in grip strength by country, age, and sex, standardization of HGS measurements and criteria are needed for sarcopenia diagnosis. Therefore, several studies have attempted to standardize the measurement of grip strength and determine cut-off points. For instance, the "Southampton protocol" proposed by Roberts et al. [12] and a systematic review by Schaap et al. [13] were introduced to standardize the measurement of grip strength [5]. Despite these efforts, various factors such as racial diversity, body size, lifestyle differences, and socioeconomic status can still influence grip strength and thus the cut-off points for diagnosing sarcopenia [9].

Alternatively, other bio evidence can be used to indirectly estimate lower grip strength and muscle power. For instance, an increment in plasma asymmetric dimethylarginine (ADMA) level can be measured and is significantly associated with low grip strength and sarcopenia [14]. In [15], serum proteomics analysis was used to identify novel biomarkers for the diagnosis of sarcopenia, which found a total of 114 deferentially expressed proteins (DEPs) between the patients and healthy older adults, including 48 upregulated proteins and 66 downregulated proteins, and identified cholesterol ester transfer protein and Apolipoprotein A2 as potential biomarkers that are related to low muscle power.

2.2. Short Physical Performance Battery (SPPB)

The Short Physical Performance Battery (SPPB) is a widely utilized and validated tool for evaluating physical performance in older adults and has been extensively applied in the diagnosis and assessment of sarcopenia [16,17]. Multiple studies have utilized the SPPB to elucidate the relationships between sarcopenia, physical performance, and health outcomes, providing valuable insights into the significance of this condition.

Population-specific investigations of the SPPB in Asian communities have established normative values that can potentially improve the precision of sarcopenia diagnoses. A meticulous assessment of SPPB parameters—balance, repeated chair sit-to-stand, and gait speed—resulted in average scores of 11.6 for men and 11.5 for women, which decreased with advancing age [16]. Other studies have validated the SPPB as an objective measure of muscle strength and physical performance for diagnosing sarcopenia, with a cut-off point of 8 having high sensitivity but lower specificity for severe sarcopenia [17].

The association between SPPB, sarcopenia, and falls resulting in fractures appears to have gender-specific distinctions, with low handgrip strength and SPPB scores influencing falls in males, while only low muscle mass influenced falls in females [18]. Sarcopenia and sarcopenic obesity also have differential effects in cardiovascular disease patients, implying distinct implications for cardiovascular health [19].

Higher thyroid hormone levels within normal ranges have been associated with improved muscle mass and SPPB performance, suggesting a potential role in preserving muscle function [20]. However, other studies indicate a complex relationship between adiposity, obesity, and sarcopenia parameters like handgrip strength and SPPB, with obesity potentially conferring some protective effects against sarcopenia in women [21].

The SARC-F questionnaire is another sarcopenia screening tool that correlates with SPPB scores and outcomes but may be limited by a ceiling effect [22]. The SPPB is an extensively utilized and validated assessment tool that has provided critical insights into sarcopenia and its relationships with physical performance and health outcomes. However, it has some limitations, indicating that a combination of methodologies may be optimal for sarcopenia assessment.

2.3. Gait Speed

Multiple studies have demonstrated that reduced gait speed is associated with sarcopenia and correlated with disease severity and functional impairment in older adults. Gait speed has emerged as a key indicator and potential screening tool for sarcopenia-related disability. This subsection synthesizes evidence from recent research on gait alterations indicative of sarcopenia, the relationship between gait velocity and sarcopenia severity, and the utility of instrumented gait analysis for assessing and monitoring age-related mobility decline.

In a large cohort study of nearly 20,000 older Colombian adults, Perez et al. [23] found that slower gait speed mediated the relationship between sarcopenia and dependence on activities of daily living (ADLs). After adjusting for confounders, the researchers concluded that maintaining gait velocity may help mitigate sarcopenia's negative impact on functional status. Similarly, Liao et al. [24] reported delayed post-operative gait recovery in sarcopenic, obese, and sarcopenic obese patients following total knee replacement.

Several studies reveal specific quantitative gait changes associated with sarcopenia. Compared to healthy controls, sarcopenic individuals exhibit reduced step length, shortened stride length, slower walking velocity, shortened single limb support phase, and prolonged double support phase [25–27]. While cadence is often preserved, sarcopenic gait shows a shortened gait line, indicating reduced muscle mass [25]. Sarcopenic women had a significantly slower pace and shorter steps versus normal controls in one study [27].

Beyond simple speed, the variability and dual-task cost of gait may provide further insights into sarcopenia severity. Kang et al. [28] found sarcopenic elderly men walked significantly slower daily than non-sarcopenic peers. Dual-task assessments demonstrate greater slowing in individuals with sarcopenia versus single-task walking [29]. Greater dual-task costs are associated with increased fall risks and mobility impairment.

Wearable sensors enable continuous monitoring of gait parameters in real-world settings. Kang et al. [28] showed daily gait speed derived from wearables accurately reflected sarcopenia diagnosis. Machine learning models using combinations of gait features derived from wearables may enable sarcopenia detection and monitoring [29]. Compared to infrequent clinical gait tests, continuous monitoring could facilitate early identification of mobility decline.

While gait speed shows promise as an indicator of sarcopenia severity, optimal thresholds for screening remain unclear. Most diagnostic criteria define sarcopenia as gait speed below 0.8 m/s [30], but this cut-off may lack sensitivity. Machine learning applied to wearable gait data could potentially derive optimal speed thresholds and improve detection. Additional research should validate gait parameters and thresholds that best correlate with imaging-confirmed sarcopenia.

Though gait speed is consistently associated with sarcopenia, the underlying mechanisms remain incompletely understood. Reduced velocity may stem directly from the loss of muscle mass and strength. However, neurological and cognitive impairment also correlate with slowed gait in sarcopenic patients [31]. Disentangling the multiple interacting factors contributing to gait changes represents an area for further study.

Extensive evidence demonstrates reduced gait velocity and altered gait patterns across multiple clinical contexts in sarcopenic patients. Slower speed correlates with disease severity, risk of falls and fractures, and functional impairment. Instrumented gait analysis, especially using wearable sensors, provides a promising approach to screening for sarcopenia and monitoring age-related mobility decline. Future research should further validate optimal gait parameters and diagnostic thresholds. Preserving mobility through exercise interventions may help mitigate sarcopenia-related disability.

2.4. Timed Up and Go (TUG) Test

The Timed Up and Go (TUG) test is a commonly utilized assessment for evaluating physical functioning, sarcopenia, and frailty status in older adults and diverse clinical conditions [32,33]. This simple test measures the time required for an individual to rise from a chair, walk 3 m, turn around, walk back, and sit down.

Comparative studies have elucidated the relationships between TUG performance, gait speed, and sarcopenia indicators. TUG completion time demonstrates a nonlinear association with gait velocity and may be most useful for assessing individuals at the lower end of physical function, whereas gait speed assessments can evaluate performance across a wider spectrum [32]. For community-dwelling older adults, slower gait and poorer TUG performance are both associated with sarcopenic obesity [32].

In chronic obstructive pulmonary disease patients, poorer TUG test results are significantly associated with an increased likelihood of sarcopenia [33]. This highlights the test's utility for identifying sarcopenic individuals. Similarly, longer TUG completion times are linked to higher sarcopenia risk in the general older population [34].

However, other studies indicate that TUG performance may not correlate with all sarcopenia indicators. Probable sarcopenia based on muscle mass and strength criteria was associated with slower gait but not impaired TUG performance [35]. Low muscle power, measured by chair rise testing, had stronger associations with functionality than sarcopenia classification itself [35].

Overall, the TUG test is a simple and clinically useful assessment tool that provides insights into sarcopenia likelihood and associated impairments in physical functioning. However, its relationships with specific sarcopenia parameters are complex. Recent research has focused on enhancing TUG assessment through quantitative movement analysis using inertial sensors, enabling more objective and detailed performance characterization [36]. Such technological augmentation of TUG testing shows promise for improving sarcopenia screening and monitoring. Nevertheless, the TUG test alone has limitations in comprehensively evaluating this multifaceted condition. Using TUG alongside other validated sarcopenia assessments can provide the most accurate insights.

2.5. Five Times Sit-to-Stand Test

The early detection and diagnosis of sarcopenia through validated assessment tools are critical for implementing timely interventions to curb the progressive loss of muscle mass and function in the geriatric population [37,38]. In this context, the Five Times Sit-to-Stand Test (5TSTS) has emerged as a clinically useful and valid instrument for evaluating functional trajectories in older adults. A key advantage of the 5TSTS is its capacity to detect sarcopenia in individuals who may be missed by conventional handgrip dynamometry, highlighting the need for a more comprehensive battery of tests [37].

As a simple, quick, and easy-to-administer test with minimal space, equipment, and time requirements, the 5TSTS provides valuable functional performance data to track sarcopenia progression [38]. Beyond sarcopenia, 5TSTS performance can identify fall risk, with times exceeding 13.5 s suggesting poorer lower limb muscle quality and fall propensity [39]. Intriguingly, sarcopenia prevalence is substantially higher when defined using the 5TSTS rather than handgrip strength, confirming its superiority for detecting age-related strength decline in the lower limbs [40].

The 5TSTS encapsulates multiple facets of lower body function, including strength, power, and dynamic balance. Test parameters such as ground reaction force, rate of force development, and chair rise time provide insight into strength and locomotor capacity [41]. As a measure of power, the 5TSTS is proposed as a simple but valid screening tool for age-related muscle weakness [42]. Superior diagnostic accuracy stems from the high power output needed to complete multiple rapid stands. Shorter 5TSTS times indicate greater muscle strength and power.

In summary, extensive evidence endorses the 5TSTS as a clinically useful assessment tool for sarcopenia screening and monitoring. Key advantages, including simplicity, minimal equipment needs, and detection of lower limb weakness, cement its role within a comprehensive geriatric assessment battery. Continued research is needed to refine diagnostic cut-off points and further validate their utility across diverse populations.

2.6. Physical Performance Test: Challenges and Future Work

Grip strength is a key component of sarcopenia diagnosis and an important biomarker in older adults, predicting outcomes such as mortality [43]. However, grip strength measurement lacks standardization across studies, including standardized testing protocols and weakness cut-off points [43,44]. Similarly, gait speed strongly predicts adverse health outcomes but also suffers from variability in cut-off points for sarcopenia diagnosis [23,27]. Although gait speed shows promise in assessing sarcopenia impact, with one study finding it may positively influence sarcopenia-related disability after adjusting for confounders [23], additional research is needed to determine optimal cut-off points.

The SPPB, commonly used to assess physical performance, also has limitations like the lack of universal cut-off points and classification accuracy for diagnosing sarcopenia [17,45]. However, the SPPB exhibits potential for sarcopenia screening when other assessments are unavailable [17]. The TUG test is another physical performance measure with promise for assessing sarcopenia [46,47] but requires the establishment of standardized cut-off points and further evaluation of feasibility in varied clinical settings before wider adoption.

Overall, current tools for sarcopenia assessment require additional research to determine standardized protocols and cut-off points tailored to different populations. Focusing on muscle function rather than mass alone may provide a greater prediction of outcomes. Emerging techniques like blood flow restriction training show promise in counteracting sarcopenia but require more study. Early screening in healthy young adults could help mitigate future sarcopenia onset. In conclusion, current sarcopenia assessment tools have limitations but hold promise with further refinement and research on optimal implementation.

3. Cut-Offs for Diagnosing Sarcopenia

The Asian Working Group for Sarcopenia (AWGS) and the European Working Group for Sarcopenia (EWGS) are devoted to the diligent scientific scrutiny and elucidation of sarcopenia. Characterized as the age-associated systemic decline of skeletal muscle mass and strength, sarcopenia signifies a health condition that entails numerous detrimental outcomes. The primary aim of these working groups is to formulate, refine, and disseminate strategies pertaining to the prevention, diagnosis, and clinical handling of sarcopenia.

However, it is imperative to acknowledge the multifaceted nature of sarcopenia. Managing and intervening in these conditions are swayed by a wide array of factors. Factors such as age, gender, race, ethnicity, and even geographical location play substantial roles in the inception and intensification of sarcopenia, as affirmed by multiple studies. Given such complexity, it is abundantly clear that sustained, comprehensive research is vital for attaining an all-encompassing understanding of the condition. This acquired knowledge is then indispensable in formulating efficacious, evidence-supported strategies for the management and intervention of sarcopenia.

3.1. Cut-Offs of Asian Working Group of Sarcopenia

The complexity and nuances of diagnosing and treating sarcopenia, characterized by an age-related loss of muscle mass and declining physical performance, have prompted the formulation of various operational definitions and guidelines. Among the key contributors to this discourse is the Asian Working Group for Sarcopenia (AWGS). The seminal work of Chen et al. [48] provides an insightful overview of AWGS's updated approach, setting the group apart from its counterparts in a number of significant ways.

AWGS has been instrumental in introducing a series of influential updates in the sarcopenia landscape. These changes encompass a revised definition of sarcopenia, novel diagnostic criteria, and new guidelines for treating and managing the condition. Of particular importance is the recognition of low muscle mass as a fundamental indicator of sarcopenia, a shift that has significant implications for diagnosis. Moreover, the inclusion of gait speed as a functional parameter marks a pivotal step in the operationalization of the condition, taking into account the patient's physical functionality in addition to their muscular characteristics. Further, the endorsement of resistance training as a primary treatment option underscores the importance of strength conditioning in managing and reversing the condition's progression.

It is also noteworthy how AWGS's perspective on diagnosing and treating sarcopenia distinguishes itself from other organizations. For example, the AWGS 2014 consensus characterized sarcopenia with explicit criteria, including an age-related loss of muscle mass coupled with low muscle strength and/or diminished physical performance. The AWGS also provides specific cut-offs for each diagnostic component, contrasting with other organizations adopting different definitions and diagnostic criteria.

A crucial point of distinction lies in AWGS's emphasis on ethnic differences in muscle mass and function when diagnosing sarcopenia in Asian populations. This is an acknowledgment of the variability in physiological characteristics across different ethnic groups, a factor that plays a key role in the manifestation and progression of sarcopenia.

In summary, AWGS's approach, as highlighted by Chen et al. [48], exhibits a number of unique aspects, including an updated definition of sarcopenia, the inclusion of functional parameters, and consideration of ethnic differences. These contributions significantly enrich the ongoing discourse on the effective diagnosis and treatment of sarcopenia.

AWGS offers a range of practical recommendations for healthcare professionals working with sarcopenic patients. These include the following:

1. Screening older adults for sarcopenia using a combination of muscle mass, muscle strength, and physical performance measures.
2. Implementing lifestyle interventions and providing related health education for primary healthcare and preventive service users with potential sarcopenia.
3. Referring patients to a hospital for a confirmatory diagnosis if sarcopenia is suspected.
4. Investigating potential underlying causes of sarcopenia, particularly reversible ones, in hospital and research settings.
5. Developing appropriate personalized intervention programs for older adults with sarcopenia, including resistance training, nutritional support, and pharmacological interventions if necessary.

These guidelines aim to assist healthcare professionals in effectively diagnosing and managing sarcopenia in older adults. Cut-offs, as per the Asian Working Group for Sarcopenia, include the following, see Table 2:

Table 2. Cut-offs as per the Asian Working Group for Sarcopenia.

Criteria	Measurements
Low Muscle Mass	DXA: <7.0 kg/m^2 in men and <5.4 kg/m^2 in women BIA: <7.0 kg/m^2 in men and <5.7 kg/m^2 in women DXA (NIH criteria): <0.789 kg/BMI for men and <0.512 kg/BMI for women
Low Muscle Strength	Grip Strength: <28 kg in men and <18 kg in women
Low Physical Performance	Gait Speed: $\leq$0.8 m/s

These cut-offs can be employed to diagnose sarcopenia based on low muscle mass, low muscle strength, and/or low physical performance criteria, as specified by the AWGS 2019 consensus update on sarcopenia diagnosis and treatment.

3.2. Cut-Offs of European Working Group of Sarcopenia

A key aspect in the geriatric healthcare domain involves the evaluation of potential predictors of mortality risk, particularly in the context of sarcopenia, a condition associated with the aging process. Recent studies have focused on identifying the most accurate predictors, and in doing so, they have called into question the effectiveness of existing diagnostic criteria. The research conducted by Spexoto et al. [49] serves as a prime example of this emerging narrative.

The European Working Group on Sarcopenia in Older People (EWGSOP) has developed two diagnostic frameworks for sarcopenia, namely EWGSOP1 and EWGSOP2. Notable differences between the two criteria lie in the cut-off values for muscle mass, the inclusion of gait speed as a diagnostic parameter, and the severity classification. Specifically, the EWGSOP1 criteria define Low Muscle Mass (LMM) and Low Muscle Strength (LMS) with higher cut-off values and Low Physical Performance as a gait speed < 0.8 m/s [49]. On the other hand, the EWGSOP2 employs more stringent cut-off values for LMM and LMS but maintains the same threshold for Low Physical Performance [49].

In their study, Spexoto et al. [49] undertook an expansive analysis of 6182 individuals aged 60 years and above within the English Longitudinal Study of Ageing. The outcomes of this study indeed add a new dimension to our understanding of mortality predictors.

Contrary to the LMS definitions predominant in the literature, the study identified cut-off values of <36 kg for men and <23 kg for women, in conjunction with a Low Gait Speed (LGS) $\leq$ 0.8 m/s, to demonstrate the highest accuracy for predicting mortality. This discovery brings forth an intriguing possibility that existing diagnostic criteria might not optimally represent mortality risk in older adults, see Table 3.

Moreover, when applied, these adjusted thresholds resulted in a more accurate classification of sarcopenia severity. The revised classification delineated probable sarcopenia, sarcopenia, and severe sarcopenia as per the EWGSOP2, and these were superior predictors of mortality risk when compared to the classifications according to EWGSOP1. Interestingly, the study discovered that LGS $\leq$ 0.8 m/s was a superior mortality risk predictor exclusively in individuals with probable sarcopenia.

Table 3. Cut-offs as per the European Working Group for Sarcopenia.

Criteria	**Measurements**
LMM (Low Muscle Mass)	ASM (Appendicular Skeletal Muscle mass) divided by height squared: <7.0 kg/m^2 for men and <5.7 kg/m^2 for women
LMS (Low Muscle Strength)	Grip Strength: <27 kg for men and <16 kg for women
Low Physical Performance	Gait Speed: <0.8 m/s

In summary, the study accentuates the significance of LMS and LGS as potent predictors of mortality risk in older adults [49]. Furthermore, it suggests that the EWGSOP2 criteria might offer superior predictive accuracy for mortality risk compared to the earlier EWGSOP1 framework. These findings warrant a critical reevaluation of the existing diagnostic criteria and call for their refinement to enhance accuracy in mortality risk prediction.

4. Digital Health Technologies and IoT Devices for Sarcopenia Management

Recent advancements in Information and Communication Technology (ICT) have introduced novel methodologies for assessing and analyzing sarcopenia. This survey article delineates a technical framework for monitoring and evaluating sarcopenia, utilizing cutting-edge ICT solutions. In the subsequent subsections, each constituent of the Sarcopenia ICT system is delineated, as illustrated in Figure 1.

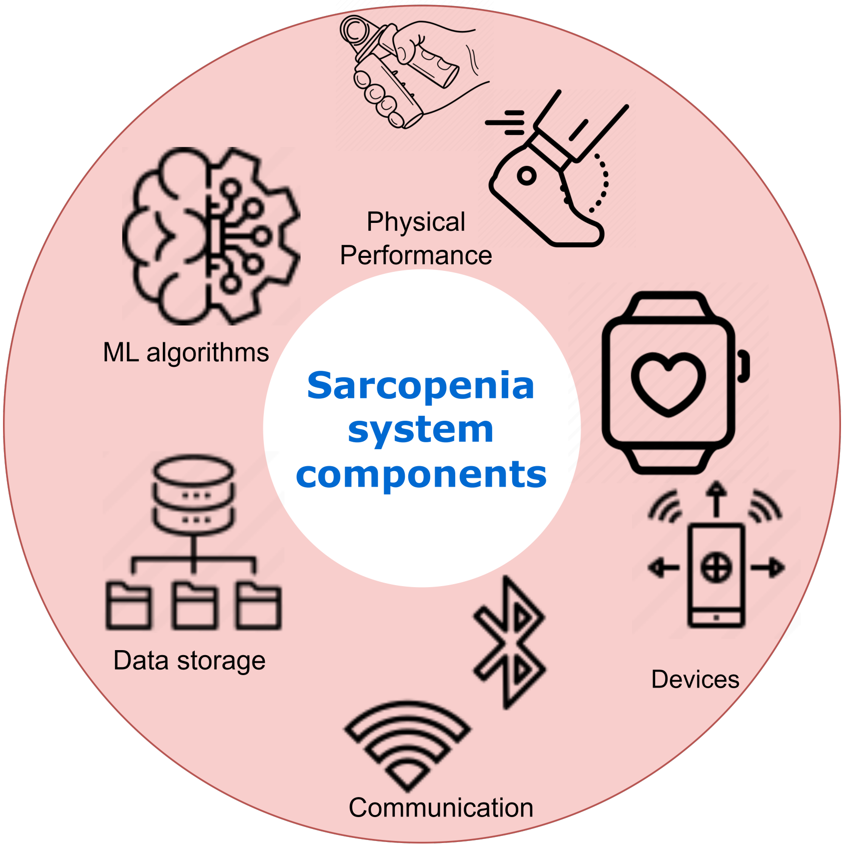

Figure 1. Sarcopenia system components. The sarcopenia monitoring system integrates wearable devices, edge computing, and AI to continuously collect multilayered health data, discern trends predictive of sarcopenia, and provide personalized recommendations to patients and clinicians.

4.1. Physical Activity Monitoring

This component involves using wearable devices like smartwatches and fitness trackers to continuously monitor physical activity levels, which are strongly associated with sarcopenia onset and progression. Key metrics tracked include step count, activity intensity, heart rate, etc. This allows longitudinal tracking of activity patterns predictive of sarcopenia.

4.2. IoT Integration

The system seamlessly integrates IoT-enabled devices like scales, blood pressure monitors, and pulse oximeters to regularly collect health parameters. Combined with activity data, these multilayered data provide insights into sarcopenia progression. The data are transmitted to a mobile app for aggregation and preprocessing.

4.3. Edge Computing Infrastructure

An edge computing infrastructure handles the continuous streams of monitored data. Edge computing allows real-time data processing to generate actionable insights and feedback for patients and clinicians. Machine learning models can discern trends predictive of sarcopenia.

4.4. AI and Machine Learning

AI and ML algorithms analyze heterogeneous datasets to recognize patterns in sarcopenia progression across patients. Patient-specific models can predict future changes and recommend interventions like exercise regimens and diet plans. The models improve continuously through retraining as more data are gathered.

4.5. User Interface and Clinical Feedback

A user-friendly interface provides patients and clinicians easy access to visualized data, detected trends, and AI-generated recommendations. Clinicians can validate insights and tweak intervention plans. Their feedback is used to retrain ML models.

4.6. Accelerometers

Accelerometers offer an objective approach to measuring physical activity and sedentary behavior, providing valuable insights into sarcopenia, a condition characterized by reduced muscle mass and function that commonly afflicts the elderly. Multiple studies utilizing accelerometers have uncovered intriguing connections between activity levels and sarcopenia, although some discrepancies exist regarding diagnostic methods and dose–response relationships (Figure 2).

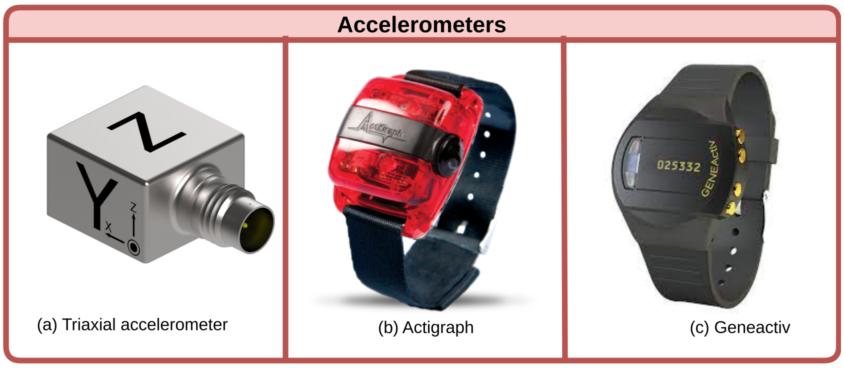

Figure 2. Accelerometer types. Triaxial accelerometers measure motion in three planes. Actigraphs specifically track metrics like step counts and activity intensities. Geneactivs provide raw acceleration data for sophisticated analysis.

Several investigations have demonstrated reduced moderate-to-vigorous physical activity (MVPA) in sarcopenic versus non-sarcopenic groups [50–54]. However, the relationship between sedentary time and sarcopenia remains unclear. While Scott et al. found a decreased likelihood of low appendicular lean mass (ALM) with more sedentary time [50], Johansson et al. showed MVPA modulates this association [51]. Nevertheless, consensus is lacking on accelerometer cut-off points and sarcopenia definitions [51,55].

Dose–response analyses reveal intriguing but preliminary findings. Iwasaka et al. observed a plateau in the relationship between steps and sarcopenia risk below 10,000 steps [52]. Additional research on step count recommendations is warranted.

Longitudinal and intervention studies underscore the importance of physical activity in counteracting sarcopenia. Increased activity correlated with reduced adiposity, higher muscle mass and strength, and lower sarcopenia likelihood [56]. Accelerometer-based activity monitoring could aid sarcopenia prevention and management in elderly adults [54,55].

Overall, accelerometers enable the quantification of activity patterns relevant to sarcopenia. While diagnostic consensus and dose–response relationships require further elucidation, accelerometers have proven utility in epidemiological studies on sarcopenia's complex etiology [57]. Standardizing methodology and accelerometer use will be key to developing effective interventions against this disabling condition.

4.7. Pedometers

Pedometers offer a practical means of objectively evaluating physical activity associated with sarcopenia, a condition of reduced muscle mass and function in the elderly. Multiple investigations demonstrate pedometer-measured step count as an insightful sarcopenia assessment and intervention metric [58].

Several studies reveal lower step counts in sarcopenic versus non-sarcopenic older adults. Using a validated accelerometer-based pedometer, Meier et al. found sarcopenic participants took fewer daily steps, spent more time sedentary, and showed worse physical function compared to active counterparts [59]. In a randomized controlled trial, Yuenyongchaiwat et al. implemented a pedometer-monitored walking regimen of 7500 steps per day to improve cardiopulmonary function in sarcopenic Thai adults successfully [58].

Additional research links reduced step count to heightened sarcopenia risk. In a year-long study, fewer steps and less moderate physical activity time correlated with lower muscle mass [60]. Yuenyongchaiwat and Akekawatchai demonstrated sarcopenia improvement in older adults instructed to walk $\geq$7500 steps daily [61].

While highlighting the utility of pedometers in sarcopenia assessment and activity monitoring, these studies establish associative rather than causal relationships. Further interventional research is required to delineate optimal step count recommendations and determine pedometer-based programs' efficacy for sarcopenia prevention and treatment. Nevertheless, existing research suggests pedometers could prove valuable tools alongside accelerometers and other devices in elucidating and managing sarcopenia's complex relationship with physical activity.

4.8. Inertial Measurement Units (IMUs)

Inertial measurement units (IMUs) offer a versatile option for evaluating physical functioning relevant to sarcopenia. These wearable sensors enable quantitative analysis of gait, balance, and mobility patterns by containing accelerometers, gyroscopes, and sometimes magnetometers. Multiple studies demonstrate IMUs' utility in sarcopenia assessment and monitoring.

Several investigations utilize IMUs to distinguish sarcopenic from healthy controls through gait analysis. Ortega-Bastidas et al. demonstrated an IMU's ability to assess fall risk during the Timed Up and Go test, highlighting the technology's portability and cost-effectiveness [62]. Employing various classification algorithms on IMU data, Kim et al. identified sarcopenic patients with 95% accuracy based on locomotion features [63]. In another study, Kim et al. uncovered associations between IMU-derived gait variables like stride length and gait speed with muscle mass, strength, and function [64].

Beyond gait analysis, IMUs enable the quantification of other relevant functional parameters. Kim et al. used IMUs to characterize diminished endurance, mobility impairments, and increased dependence in sarcopenic adults during daily living [65]. Byun et al.

developed an IMU algorithm to estimate walking speed in the elderly with high accuracy, demonstrating IMUs' potential for long-term monitoring [66].

These studies provide consistent evidence for IMUs' versatility in assessing muscle deterioration and functional limitations related to sarcopenia. While additional research is needed to optimize algorithms and standardize protocols, IMUs show promise as portable, cost-effective tools that complement existing sarcopenia evaluation and monitoring methods. Their capacity to measure gait, balance, endurance, and mobility deficits in real-world settings could prove invaluable in elucidating sarcopenia's impact on elderly patients' physical performance and independence.

4.9. Pressure-Sensitive Insoles

Instrumented insoles show considerable potential for assessing gait, balance, and fall risk in older adults. Several studies have explored pressure-sensitive insoles to analyze the center of pressure and plantar pressures during locomotion. Kraus et al. [67] and Anzai et al. [68] demonstrated that data from instrumented insoles can effectively identify physical frailty and sarcopenia risk through gait analysis. Compared to traditional assessments like SARC-F and Timed-Up-and-Go, machine learning models using insole data showed improved detection of frailty status.

Beyond frailty detection, pressure-sensitive insoles also enable an analysis of biomechanical factors that may predispose individuals to injury during physical activity. For instance, Draganich et al. [69] used insoles to examine changes in the center of pressure during the transition to minimalist running shoes as a way to identify runners at risk of stress fractures. Atreya et al. [70] assessed how kitchen task height impacted plantar pressures in older adults, suggesting the potential for using insoles to monitor age-related physical performance declines.

Several research groups have developed and tested insole-based sensors using different technological approaches. Martini et al. [71] created an optical plantar pressure sensor prototype for integration with wearable robotics. Silva et al. [72] built an instrumented insole with 10 pressure sensors for gait and balance analysis. Subramaniam et al. [73] reviewed various systems and their efficacy in assessing fall risk. In addition to sensing capabilities, the physical design of instrumented insoles may also contribute to fall prevention through improved balance and stability.

Pressure-sensitive insoles enable quantitative assessment of older adults' gait, balance, and fall risk. Continued technological development and research on analytic techniques point to the growing potential for instrumented insoles in the early detection of age-related physical performance decline and timely intervention to improve outcomes. Further validation of insole systems against gold-standard tools and prospective studies are still needed to translate this emerging technology into clinical practice.

4.10. Smartphone Applications

Smartphone applications (SAs) are emerging as innovative tools for sarcopenia management by providing nutritional support, fall prevention, social engagement, and exercise programs [74,75]. Smart appliances like refrigerators that monitor food contents could potentially enhance nutritional status, while mobile apps for fall detection and prevention address the high fall risk in sarcopenic populations [74]. Applications also mitigate social isolation associated with sarcopenia progression [74]. However, most nutrition apps are not validated and emphasize restriction over optimal protein and nutrient intakes for muscle health [75]. Further high-quality research is needed on virtual reality, wearables, robotics, and neuromuscular electrical stimulation to boost capacity for daily living activities and physical activity in sarcopenic adults [75].

Emerging work has focused on validating mobile apps for sarcopenia screening and detection. Montemurro et al. [76] validated an iPhone app measuring sit-to-stand power through video analysis plus muscle mass. Early detection of pre-sarcopenia enables timely interventions to prevent functional decline and adverse outcomes [76]. This handheld assessment of muscle power is as accurate as laboratory methods and allows rapid community-based screening [76]. Remote sensing devices like BandPass provide personalized feedback on resistance exercise compliance and progress by capturing quantitative muscle strength data [77]. HTSMayor software estimates appendicular muscle mass using anthropometry or DXA and demonstrates high diagnostic accuracy for sarcopenia versus DXA [78].

SAs represent promising tools for sarcopenia management. While early research has focused on screening and detection, further development and validation are needed for nutritional, social, fall prevention, and exercise apps tailored to sarcopenic populations. Wearables and remote monitoring devices also provide personalized feedback and progress-tracking opportunities. Overall, mobile health innovations may increase accessibility and optimize sarcopenia interventions.

4.11. Challenges and Future Work

Accelerometers provide objective measurements of physical activity levels and sedentary behavior valuable for diagnosing and monitoring sarcopenia [55]. However, the specific variables associated with sarcopenia can depend on the assessment tools and criteria used. Pedometers are limited by their indirect measurement of physical activity and muscle strength. However, combining pedometer data with other metrics like muscle quality could aid sarcopenia research [79].

Inertial measurement units (IMUs) can quantify mobility but are limited in their measurement of muscle strength and power. Improving IMU accuracy and affordability could enhance their utility for detecting changes in the range of motion and muscle function. Pressure-sensitive insoles provide insight into balance and gait but are limited in their direct assessment of muscle strength and power. Combining insoles with other tools like electromyography may allow a more comprehensive evaluation of muscle function [80].

Smartphone applications provide easy tracking of physical activity but rely on self-reporting and indirect strength measures. Integrating smartphone apps with wearable sensors or remote monitoring could improve measurement accuracy [81]. Overall, technology-based tools show significant potential for assessing sarcopenia but require ongoing research to refine accuracy, reliability, accessibility, and integration with other assessment techniques. Standardization of protocols and validation in diverse populations is also needed to fully realize their promise in sarcopenia diagnosis and management.

5. Healthcare Platform

5.1. Sarcopenia Datasets

Several studies have focused on identifying important variables associated with sarcopenia using datasets from specific populations. Zhang et al. [82] analyzed data from over 4000 older Chinese adults and found that a Wide and Deep neural network model incorporating 12 routine clinical variables (e.g., age, arm circumference, liver enzymes) could effectively predict sarcopenia status. Castillo-González et al. [83] followed 166 Mexican seniors over 6 months and applied machine learning to conclude that age, blood pressure, nutrition, comorbidities, and sodium levels were most indicative of sarcopenia level and progression. In an Italian cohort [84], albumin, C-reactive protein, vitamin D, and folate emerged as key biomarkers associated with sarcopenia, muscle mass, and strength, see Table 4 below.

Other studies have specifically examined whether analysis of pulse waveforms and spectral features using signal processing and machine learning methods could provide a simple approach to screen for possible sarcopenia. Wu et al. [85] found several differences in harmonic content and variability between 133 sarcopenic and robust seniors, and their models could discriminate based on 1-minute radial pulse measurements.

There has also been interest in developing prognostic models to identify those at risk of sarcopenia for early intervention. Cernea et al. [86] constructed a model for 200 older adults incorporating gait speed, BMI, fat-free mass, oxidative stress, depression, and medication use that could effectively predict sarcopenia status. Their results highlight the multifactorial nature of sarcopenia encompassing muscle mass, strength, function, and systemic factors.

Table 4. Sarcopenia datasets.

Study	Dataset Description	Population	Measurements	Key Findings
Zhang et al. [82]	West China Health and Aging Trend (WCHAT)	4057 people aged ≥ 50	Age, arm circumference, liver enzymes	12 routine clinical variables could effectively predict sarcopenia status
Castillo-Gonzalez et al. [83]	Baja California, Mexico	166 patients, mean age 77.24	Medical history, tests, comorbidities, functional capacity, nutrition status, biochemical data, and sociodemographics	The Decision Tree classifier on 5 key variables achieved high accuracy in assessing sarcopenia status and severity
Zupo et al. [84]	Clinical records and fluid markers, northern (Pavia) and southern (Apulia) Italy	1971 adults aged > 65	Low muscle mass, low muscle strength, and/or low physical performance according to EWGSOP2 guidelines.	Key variables identified include muscle mass, strength, sex, inflammation, and nutritional biomarkers
Wu et al. [85]	Tri-Service General Hospital (TSGHIRB 2-108-05-161)	133 subjects aged 71 years on average	Dynapenia, presarcopenia, and sarcopenia groups based on muscle strength, gait speed, and muscle mass measurements	Effectively discriminate possible sarcopenia subjects based on the noninvasive pulse measurements
Carnea et al. [86]	FRADEA (Frailty and Dependence in Albacete)	200 people aged ≥ 70	Fat-free mass, gait speed, body mass index, oxidative stress biomarkers, presence of depression, and use of proton pump inhibitors	The multifactorial nature of sarcopenia, with muscle mass, function, and quality as well as systemic factors like inflammation and oxidative stress contributing
Kim et al. [87]	Nationwide Korean Frailty and Aging Cohort Study (KFACS)	2123 community-dwelling older adults aged 70–84	Handgrip strength, usual gait speed, appendicular skeletal muscle mass	Higher prevalence of sarcopenia under AWGS 2019 definitions compared to AWGS 2014
Santos et al. [36]	Dataset on skeletal muscle mass index, body composition and strength in bariatric patients	46 bariatric surgery patients aged 18–60	Skeletal muscle mass index, body composition, strength	Provided a granular view of the impact of bariatric surgery and exercise on sarcopenia risk
Sun et al. [88]	2008 to 2011 Korean National Health and Nutrition Examination Survey	4937 adults aged 60 and older	Dual-energy X-ray absorptiometry scan	Prevalence of sarcopenia at 6.6%, with men more likely than women
Kang et al. [89]	Medical records of Korean postmenopausal women	4020 postmenopausal women	BMI, BUN, RBC count, dietary factors (water, fibre, protein intake)	Identified significant risk factors for sarcopenia using machine learning algorithms

Nationwide surveys of community-dwelling older adults in Korea have provided population-level insights, with sarcopenia prevalence estimates ranging from 6.6% to 13.3% using different diagnostic criteria [87,88]. These large datasets have elucidated shifting patterns in sarcopenia screening when using different muscle mass and physical performance measures [87]. Research has also leveraged datasets from specific clinical populations, including bariatric surgery patients, to elucidate sarcopenia risks and the impacts of interventions [36].

Beyond foundational prevalence data, datasets integrating detailed patient information have enabled predictive modeling of sarcopenia risk using machine learning. Models based on body composition, blood biomarkers, and dietary intake data can identify significant sarcopenia risk factors like low BMI, elevated BUN, and insufficient protein intake [89].

Longitudinal datasets have also provided insights into sarcopenia progression over time. Repeated measurements across treatment timelines for bariatric surgery patients reveal granular impacts of surgical interventions and exercise on body composition and strength [36]. Population-based surveys capturing health-related quality-of-life measures have characterized sarcopenia's effects on critical patient-centered outcomes [88].

Sarcopenia research has been strengthened by diverse datasets quantifying muscle mass, strength, physical function, patient-reported outcomes, and predictive risk factors in both cross-sectional and longitudinal formats [36,87–89]. These datasets underscore the multifaceted nature of sarcopenia and the need for regular, comprehensive assessments to elucidate prevalence, predictors, disease progression, and intervention efficacy across populations. Continued accrual of rich, heterogeneous datasets will further enhance sarcopenia characterization and support personalized risk stratification and care.

5.2. Cloud Computing in Healthcare

In recent years, cloud computing has emerged as a pivotal technology for enabling remote healthcare services and improving patient care. Several studies have investigated techniques for developing robust and secure cloud-based systems tailored to healthcare. Zhang et al. [90] proposed an isolation mechanism to ensure performance isolation between tenants in a multitenant IoT cloud platform for smart healthcare. Their scheduling algorithm provided effective feedback control of asynchronous data flows to achieve tenant isolation, reducing message delays. While this mechanism could enhance service quality for patients, future work on preserving privacy with isolation was noted.

Complementarily, Dang et al. [91] provided a comprehensive survey of the IoT framework for healthcare, reviewing the topology, structure, platform components, and key concepts, including fog computing, ambient assisted living, wearables, and blockchain. Trends and applications across patient monitoring, clinical operations, and fitness were summarized alongside security considerations and policies promoting IoT healthcare. However, issues like system development, resource management, and security/privacy remained.

Critically examining the security dimension, Masud et al. [92] proposed a robust and lightweight access scheme for cloud-based E-healthcare services to curb threats and prevent unauthorized access. Their scheme enabled end-to-end encryption and access control based on stakeholder identity to protect sensitive patient data in the cloud. While simplicity and robustness were strengths, further analysis of encryption mechanisms could be valuable. To boost the availability of quality healthcare services globally, Sahu et al. [93] designed an innovative remote patient monitoring system (RPMS) leveraging IoT for real-time health monitoring, abnormality detection, and alert notification. This system was positioned to potentially overcome challenges in delivering comprehensive healthcare for remote and underserved populations. Additional investigation into deploying such systems was recommended.

Providing a holistic perspective, Mohemmed Sha et al. [94] detailed how cloud computing has transformed healthcare data management, outlining a framework to harness relevant services from major providers to manage data flows. As a reference model, an architecture using Amazon cloud services was presented. While informative, further research into optimizing configurations for healthcare-specific needs could be useful.

Cloud computing presents a novel approach for enhancing remote healthcare delivery for sarcopenia through recent advances in multitenant platforms, comprehensive architectures, secure access schemes, real-time monitoring, and tailored data management.

5.3. Blockchain in Healthcare

Blockchain technology has emerged as a transformative solution to address longstanding challenges in healthcare information systems. As [95] discuss, blockchain implementation could enhance secure electronic medical record management, drug supply chain traceability, and interoperability across institutions. They propose a blockchain-based hospital system prototype where each patient's data reside in an interconnected block, enabling interaction with blockchain applications for decentralized data sharing.

Other studies have explored blockchain-based healthcare management systems leveraging smart contracts and decentralization for efficient, secure data handling. Research in [96] introduced a hybrid permission–permissionless blockchain model called Med-PPPHIS to manage personal health information through on-chain medical data tokens. However, they acknowledge limitations around inefficient chain queries, revocation of access permissions, and lack of dynamic public chain selection.

To facilitate ubiquitous-to-electronic health record conversion, in the study of Chelladurai and Pandian, Ref. [97] designed a blockchain system using smart contracts to regulate access to fragmented records across providers. It offers a distributed ledger for patients, guaranteeing security through cryptographic hashing while enabling seamless physician access. System performance was validated through metrics like resource use and transaction latency.

Similarly, Ref. [98] developed a multi-layered blockchain system for managing personal health information. It comprises blockchain, IoT, application, and adapter layers to address security, privacy, and interoperability challenges.

Blockchain solutions are transforming healthcare information systems by enhancing security, interoperability, and data sharing. While some limitations around scalability and flexibility exist, ongoing research aims to optimize blockchain-based approaches for managing electronic medical records. This technology promises to improve healthcare delivery by securing information exchange between patients and providers.

5.4. Edge in Healthcare

Edge computing is emerging as a promising technology for enhancing healthcare services through improved data collection, processing, and analytics. Recent studies have proposed innovative frameworks leveraging edge computing to enable more personalized, efficient, and secure healthcare systems.

For instance, Xie et al., (2022) presented a model that collects and stores digital healthcare data using a combination of soft computing and edge-driven multimodal systems. The model acts as a catalyst for personalizing healthcare by providing a comprehensive patient data perspective. Soft computing techniques address the complexities of healthcare data and improve the efficiency and effectiveness of services. The integrated file management system enables a feedback loop for deeper patient data insights.

Similarly, Jazaeri et al., (2023) introduced an edge computing approach to boost IoT healthcare quality, combining caching and classification techniques. Built on software-defined networking, it aims to provide timely, accurate information by improving efficiency and minimizing latency. A multi-criteria caching algorithm considers vital factors like data size, frequency, and significance. Spectral clustering groups patients based on medical records. These optimizations enhance performance, reduce latency, improve quality of experience, and lower costs.

Singh et al., (2023) designed an Edge of Things framework for secure, efficient health monitoring using edge computing. The tripartite architecture comprises edge, fog, and cloud layers performing data collection, processing, storage, and analysis. Security measures like encryption, authentication, and access control safeguard privacy. Key features include real-time monitoring, secure access, clustering, encryption, reduced overhead, and the three-layer model.

Liu et al., (2022) proposed integrating multimedia, multimodal sensing, and edge computing to optimize data in personalized healthcare supply chains. Multimedia and multimodal sensing gather diverse data, while edge computing enables real-time processing to improve supply chain efficiency. Benefits include interface optimization, efficient analysis, disease prevention, diagnosis, personalized care, social sensing, and ambient assisted living.

Edge computing shows great promise for advancing healthcare services through localized, real-time data processing. Key applications include personalization, security, efficiency, latency reduction, and improved analytics. Hybrid systems blending edge computing with IoT, soft computing, and multimodal data offer robust healthcare solutions. Further research can explore the optimization of these architectures.

6. Machine Learning Algorithms

This section will consider some aspects of machine learning algorithms in detecting sarcopenia. Logistic regression, a critical statistical technique, is used to predict the likelihood of sarcopenia by incorporating multiple predictor variables. While models like the ones proposed by Kaur et al., Agnes et al., and Yin et al. show their potential, the balance between statistical precision and practical implementation needs careful consideration. Moving on to machine learning algorithms, the Support Vector Machine (SVM) algorithm has demonstrated promise in sarcopenia prediction. However, it faces some limitations, like data dependency, feature selection sensitivity, and generalizability and interpretability issues. The Random Forest (RF) algorithm shows potential in managing extensive datasets and non-linear relationships, despite challenges with smaller datasets and overfitting. Gradient Boosting Machines (GBM) and K-nearest neighbors (KNN) have also been used for sarcopenia prediction, offering promising results. Despite the pros and cons of each method, these models provide crucial insights into sarcopenia risk prediction, significantly improving healthcare for older adults.

Furthermore, as illustrated in Figure 3, a comparative analysis was conducted on various machine learning-based predictive models for the detection of sarcopenia, specifically utilizing physical activity (PA), obesity measures, and the International Physical Activity Questionnaire (IPAQ) as the primary predictor variable [99]. Model performance was compared based on accuracy in predicting sarcopenia status. The gradient boosting machine (GBM), extreme gradient boosting (XGB), light gradient boosting machine (LGB), catboost (CAT), logistic regression (LR), k-nearest neighbors (KNN), support vector classifier (SVC), random forest (RF), multilayer perceptron (MLP), and deep neural network (DNN) models were trained and tested.

The DNN model achieved the highest accuracy of 89.2%, demonstrating the capability of deep learning methods for sarcopenia detection with multidimensional health data. The ensemble models GBM, XGB, LGB, and CAT performed well with accuracy scores above 83%, showing the utility of boosting techniques. The baseline LR model had an accuracy of 79.9%. In comparison, the KNN model performed relatively poorly with an accuracy of just 73.2%. Overall, the results highlight the feasibility of applying advanced machine learning approaches to leverage data from wearables, questionnaires, and health assessments for automated sarcopenia screening and diagnosis. Further research can build on these findings to develop more sophisticated and generalizable predictive models.

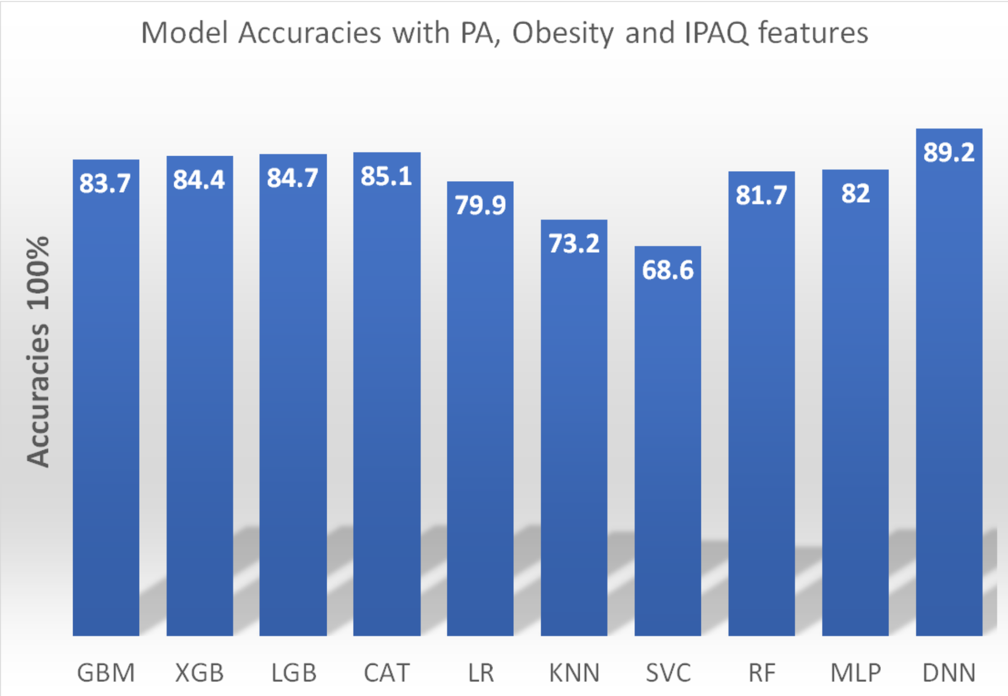

Figure 3. Accuracy of machine learning models for sarcopenia detection using physical activity, obesity, and IPAQ features. A deep neural network (DNN) model achieved the highest accuracy of 89.2%. Gradient boosting techniques (GBM, XGB, LGB, CAT) and random forest (RF) also performed well with accuracy above 81%. A multilayer perceptron (MLP) model scored 82% accuracy. Logistic regression (LR) and k-nearest neighbors (KNN) were weaker baseline models. The results demonstrate the feasibility of sarcopenia detection via machine learning applied to multidimensional health data [99].

6.1. Logistic Regression

Logistic regression has emerged as a powerful statistical technique for predicting sarcopenia risk and onset amongst aging populations. By incorporating multiple predictors like age, sex, body composition, and physical activity, logistic models can estimate the individual likelihood of developing sarcopenia [100–102]. These predictive models enable more targeted screening and early interventions.

A notable study by Kaur et al. [100] demonstrates the potential of logistic regression in evaluating sarcopenia and frailty. While specific variables were not defined, their model achieved a remarkable 97.69% accuracy in predicting outcomes. However, such high precision warrants further analysis of real-world applicability. In contrast, Agnes et al. [101] developed a multi-logistic model incorporating key predictors like BMI and calf circumference to predict sarcopenia. With 80% sensitivity and 70% specificity, this model shows promise as a practical screening tool. Expanding on this, Yin et al. [102] combined logistic regression and nomogram visualization to accurately predict individual sarcopenia risk, highlighting clinical utility.

Challenges in logistic regression modeling for sarcopenia may include issues related to data quality, sample size, and variable selection. For example, the use of computed tomography images to assess skeletal muscle index may be subject to measurement error. Additionally, small sample sizes may limit the ability to detect significant associations between sarcopenia and performance status. Finally, selecting the most relevant independent variables to include in the model can be challenging, as there may be many potential predictors of poor performance status in sarcopenia [103].

While forms and applications vary, logistic regression models consistently provide crucial insights and value in understanding, predicting, and combating sarcopenia. The capacity to distill risk factors and convert statistical findings into practical tools underscores the power of logistic regression in sarcopenia research and care. Synthesis of these studies suggests logistic modeling will continue to advance early detection and intervention efforts.

6.2. Support Vector Machine

The support vector machine (SVM) algorithm has demonstrated utility within sarcopenia prediction as an effective machine learning approach for classification and modeling. Studies leveraging SVM have generated predictive models with notable accuracy. For instance, Ko et al. [104] combined SVM analysis of data from inertial measurement units during walking to achieve 95% prediction accuracy. This highlights the potential of SVM-based kinematic analysis. Similarly, Kim [105] formulated predictive models for sarcopenia using public health data and multiple algorithms, including SVM. While the LightGBM algorithm performed best in this study with 85.2% accuracy, the SVM model also surpassed 80% accuracy. This comparison of SVM and LightGBM illuminates the need for further research into optimal algorithms. Nonetheless, SVM has exhibited considerable promise, as underscored by Seok and Kim [99].

Expanding the discussion towards the limitations of using SVM for sarcopenia prediction, certain impediments become evident:

- As underlined by Seok and Kim [99], one primary constraint lies in the data limitation. SVM is inherently dependent on ample datasets for effective model training. However, accumulating extensive data for sarcopenia prediction is daunting, as it necessitates specialized apparatus and expertise.
- Kang et al. [89] elaborate on the sensitivity of SVM towards feature selection. The careful selection of appropriate features becomes a pivotal aspect of achieving optimum accuracy in sarcopenia prediction.
- E Kim [105] raises a valid concern about the generalizability of SVM models. Due to the specific datasets used for model training, SVM models may lack the ability to generalize across new datasets or varied populations. This could potentially limit the model's capacity to encapsulate the complete variation of sarcopenia across disparate populations.
- A significant interpretability issue is raised by Castillo et al. [106]. They highlight that SVM models are frequently seen as "black box" models, which pose a challenge in interpreting the path leading to the model's predictions. This could hinder our understanding of the underpinning mechanisms of sarcopenia and the development of targeted interventions.

Although limitations remain, SVM has emerged as a valuable tool within multifaceted prediction frameworks for sarcopenia. The algorithm's classification prowess enables impactful modeling, particularly when combined collaboratively with other machine learning techniques. Ongoing optimizations to SVM and model integration will likely advance sarcopenia screening and care. While challenges persist, SVM's utility in this domain should not be discounted, and continued research is warranted.

6.3. Random Forest

The random forest (RF) algorithm has demonstrated increasing utility within sarcopenia prediction research. RF uses many decision trees, each trained on bootstrap samples with stochastic elements, to enable robust generalization [99]. This machine learning approach shows promise for sarcopenia modeling.

Specific applications include Kang et al. [89], who compared RF to other classifiers using 17 risk factors. Their 2000 tree RF model identified important predictors, though logistic regression performed best overall. Beyond this, Yoon et al. [107] applied RF to predict sarcopenia in cancer patients, while Seok and Kim [99] used physical activity data and RF to estimate sarcopenia likelihood in the elderly.

Generally, RF excels at managing extensive datasets and nonlinear relationships, making it well-suited for integrating diverse clinical and anthropometric sarcopenia predictors [99]. However, limitations exist, including poorer performance on small datasets, difficulty handling missing data, and overfitting risks. Cautious refinement is needed, but RF remains a powerful option for sarcopenia modeling.

Ongoing research should explore optimal RF configurations, predictor selection, missing data techniques, and model tuning to maximize predictive performance while minimizing overfitting. Though challenges remain, RF provides a flexible framework to leverage multiple data types for sarcopenia screening and risk stratification. Synthesis of existing research highlights the promising role of RF-based modeling in this domain.

6.4. Gradient Boosting Machines

Gradient boosting machines (GBMs) have emerged as versatile machine learning techniques for sarcopenia prediction. GBM uses an ensemble approach, integrating numerous weak decision tree models into a robust classifier [99]. The algorithm's unique boosting methodology has shown utility for sarcopenia modeling.

By repeatedly training models on diverse activity data and other attributes, GBM introduces randomness while optimizing based on error metrics [89,99,108]. Comparatively, GBM achieves prediction accuracy on par with logistic regression and random forest, with an AUC of 0.78–0.85 [99]. However, further validation of GBM sarcopenia models is needed.

Various informative features have been incorporated, including physical activity variables like gait speed, strength, and muscle mass [99], nutritional factors such as BMI and protein intake [108], and demographics like age and sex [89]. CT-derived radio mic muscle features also show promise [108]. These multifaceted data aid sarcopenia risk identification.

Specifically, activity-related parameters like BMI, walking speed, strength, muscle mass [99], and CT radiomic features [108] have been integrated into GBM models. Such data play a key role in developing predictive sarcopenia frameworks to identify risks in aging populations.

GBM is a versatile approach leveraging ensemble decision tree modeling for sarcopenia prediction. Despite needing further validation, GBM demonstrates comparable performance to other machine learning techniques. Ongoing research should refine feature selection and model optimization to maximize GBM predictive utility in sarcopenia screening.

6.5. K-Nearest Neighbors

The K-nearest neighbors (KNN) algorithm has emerged as a key machine learning approach for sarcopenia prediction. As a non-parametric method, KNN categorizes new data points based on the classification of their closest k neighbors in the training data [99,109]. This enables KNN to distinguish sarcopenic versus non-sarcopenic cases using activity and other predictor variables.

Moreover, KNN is often integrated into ensemble frameworks along with logistic regression, support vector machines, random forest, and gradient boosting machines to develop robust sarcopenia prediction models [89,99,108]. The synergistic use of KNN underscores its utility beyond a standalone tool.

Comparatively, KNN demonstrates prediction accuracy on par with leading machine learning algorithms for sarcopenia screening [89,99]. However, some methods like XGB have shown slightly better performance in select studies [89,110]. This highlights the nuanced nature of algorithm selection for optimal outcomes.

KNN is a versatile machine learning approach for sarcopenia prediction, especially when combined with other classifiers. Ongoing research should refine parameter selection and ensemble integration to maximize KNN's utility. Though performance varies across applications, KNN remains a valuable option for developing predictive sarcopenia frameworks.

6.6. Explainable AI

Explainable AI techniques are critical for building trustworthy AI systems, especially in sensitive domains like healthcare. For example, when developing algorithms to detect sarcopenia, a muscle loss condition in older adults, explainability enables physicians to understand and validate the algorithm's reasoning. This increases adoption, as doctors can trust the technology. Explainable sarcopenia detection systems could extract interpretable features from medical images and clinical data. They could also provide examples of similar cases and visual highlighting of affected regions. Overall, explainable AI provides transparency into how algorithms make decisions. This allows clinicians to feel confident leveraging AI for enhanced sarcopenia screening and treatment [111].

7. Research Challenges

Sarcopenia, a prevalent condition among the elderly, is typified by the age-related degradation of muscle mass and strength. It is a multifaceted condition arising from an intricate interplay of genetic, lifestyle, and environmental factors. Sarcopenia may precipitate numerous adverse health consequences, encompassing an elevated risk of falls, disability, and mortality. Therefore, the demand for efficacious strategies for managing and preventing sarcopenia is undeniable. Wearable technology, such as fitness trackers and smartwatches, offers the potential for invaluable insights into the progression of sarcopenia and may aid individuals in observing and controlling their condition. However, the use of wearable technology for sarcopenia research presents several challenges.

7.1. Machine Learning Challenges in Sarcopenia Detection

While machine learning techniques show promise for improving sarcopenia definition and diagnosis [2], several key challenges remain:

Data Accessibility: Limited data accessibility persists, as datasets are often small-scale and may contain incomplete entries due to inconsistent body measurement collection [2]. This can restrict model efficiency and generalizability.

Data Imbalance: Class imbalance is common, such as higher sarcopenia prevalence in females [2]. Although techniques like the Synthetic Minority Oversampling Technique (SMOTE) can balance classes, this risks over-generalization.

Feature Selection: Optimal feature selection is unclear, as excessive features reduce clinical utility while too few lower accuracy [2]. Moreover, feature combinations impact classifier performance differently, complicating comparisons.

Sarcopenia machine learning faces hurdles, including scarce quality data, class imbalance, and ambiguous feature selection. Moving forward, larger datasets, synthetic balancing methods, and feature optimization will be vital to maximizing model accuracy while retaining clinical applicability. Though challenges exist, machine learning presents exciting opportunities to advance sarcopenia assessment.

7.2. Challenges in Physical Performance Measurement

Several key challenges exist in the physical performance measurement of sarcopenia:

Absence of Consensus or Standardization: The absence of consensus on sarcopenia definition and diagnostic criteria hinders result comparison between studies, as groups like EWGSOP and AWGSOP use distinct measures [112,113].

Restricted Access to Reliable and Validated Diagnostic Equipment: Limited access to validated diagnostic equipment, especially in primary care, impedes early risk identification [114].

Measurement of Physical Activity, Sedentary Time, and Fitness: Accurately measuring physical activity, sedentary time, fitness, and strength is difficult. Self-reported physical activity can involve bias, while performance tests may not be universally feasible [59].

Patient Response to Potential Therapies: Evaluating diagnostic tools' ability to predict patient therapeutic response is challenging [113].

Key obstacles around standardization, imaging techniques, equipment availability, lifestyle factor measurement, and therapy prediction must be addressed to enhance sarcopenia assessment. Consensus-building and access expansion will be instrumental in overcoming these physical performance measurement challenges.

8. Conclusions

In conclusion, this survey provides a comprehensive overview of sarcopenia research, focusing on detection and management approaches leveraging modern technologies. However, several challenges remain in applying consensus definitions, standardized methodologies, and optimal technologies.

A key challenge is the lack of universal criteria for defining and diagnosing sarcopenia, as evidenced by distinct cut-off values and assessment protocols from EWGSOP and AWGSOP. This impedes comparative analyses and knowledge synthesis across studies. Standardizing sarcopenia assessment through collaborative initiatives could enable more robust insights.

Additionally, while machine learning shows promise for automating sarcopenia evaluation, limitations around data availability, labeling, and feature optimization must be addressed. Wearable sensors may help collect informative real-world mobility data to track sarcopenia progression and guide interventions. However, analytical techniques need advancement to glean clinically valuable insights from these data.

Emerging technologies like blockchain and edge computing may enhance privacy and decentralization for health data analytics. However, scalability and latency issues remain for processing high-volume medical datasets. More dynamic, optimized systems are needed to fully realize the potential of these technologies in sarcopenia management.

Future investigations into computational methods for sarcopenia diagnosis show promise. The application of fuzzy logic approaches may improve the accuracy of sarcopenia detection by accounting for the inherent imprecision in defining this syndrome. The fuzzy set theory provides mathematical formalism to handle such linguistic uncertainty [115]. Additionally, deep learning techniques like convolutional neural networks (CNNs) offer powerful pattern recognition capabilities that are well-suited for medical imaging applications. CNNs and other deep networks have achieved state-of-the-art performance in diverse computer vision tasks. Leveraging these advanced artificial intelligence methods could enable robust, automatic sarcopenia quantification and staging from routinely acquired CT, MRI, or ultrasound scans. This would facilitate large-scale screening, enhance reliability compared to manual evaluation, and reduce costs [116–120]. Further research should explore fuzzy logic and deep learning for sarcopenia diagnosis and validate these techniques on diverse, clinically relevant datasets.

This survey underscores key innovations and persisting challenges in sarcopenia detection and care. Opportunities exist for accelerating research through data sharing, advancing analytics, and strategically implementing technologies balanced with clinical needs. Additional coordinated efforts to standardize methodologies, collect representative data, and translate technical innovations into patient care will help address current gaps and drive future sarcopenia management.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Explanation
EWGSOP	European Working Group on Sarcopenia in Older People
AWGSOP	Asian Working Group for Sarcopenia
DEXA	Dual-energy X-ray absorptiometry
CT	Computed tomography
MRI	Magnetic resonance imaging
ADMA	Asymmetric dimethylarginine
SPPB	Short Physical Performance Battery
TUG	Timed up and go test
5TSTS	Five times sit-to-stand test
MVPA	Moderate-to-vigorous physical activity
ALM	Appendicular lean mass
SMOTE	Synthetic Minority Oversampling Technique
SVM	Support vector machine
RF	Random forest
GBM	Gradient boosting machines
KNN	K-nearest neighbors
IMU	Inertial measurement unit
IoT	Internet of Things
ICT	Information and communication technology
AI	Artificial intelligence
ML	Machine learning

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Article

Introducing Telemedicine in Italy: Citizens' Awareness of a New Healthcare Resource

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Abstract: In recent years, especially during the COVID-19 pandemic, new technologies have emerged as useful resources in healthcare. Telemedicine services may decrease opportunities for contagion by limiting direct medical contacts; they can lead to greater access to and better quality of care, especially for the elderly and chronically ill patients. However, there are still some difficulties in their widespread use, such as lack of knowledge about the effectiveness and safety of telemedicine; lack of awareness of its existence; privacy issues; and lack of computer literacy. The aim of this study is to assess the awareness of and attitude toward telemedicine in the Italian adult population, considering sociodemographic characteristics and territorial differences in telemedicine service implementation. A questionnaire was administered to Italian citizens from October 2022 to February 2023 using communication and social media in order to collect sociodemographic and health characteristics and data on awareness and use of telemedicine services. Less than half of the respondents (n = 1002) were aware of telemedicine services in their region; most of them did not use the available services due to a preference for in-person visits or lack of need. More than 90% of participants who used these services were satisfied with them. A negative attitude toward telemedicine was found in a higher proportion of older adults. This study demonstrated that, although telemedicine services are active in Italy, a large part of the population ignores its availability. Therefore, further efforts should be made to increase citizens' awareness and the use of telemedicine in our country.

Keywords: telemedicine; delivery of healthcare; information technology

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1. Introduction

In the last decade, especially in light of the COVID-19 pandemic, improvements in information technology have led to increased accessibility and quality of digitally delivered healthcare services [1–3].

In this context, the new terms telehealth and telemedicine have been adopted to indicate the application of the new technologies to healthcare services [2,3]. Telehealth refers to the use of telecommunications and information technology in healthcare delivery and patients' information and education. Within the wider concept of telehealth, telemedicine refers specifically to the use of new technologies for clinical services, such as video consultations, the transmission of clinical data, medical education, remote patient monitoring, and applications for wireless health devices [2,3]. The new technologies, especially via the Internet, allow both patients and providers to store and consult medical information in electronic medical records and to record and transmit data through cameras, digital measurement devices, and wearable biosensors; in addition, patients can meet physicians via live video in real time [2,3]. Therefore, telemedicine may increase access to care for remote places, especially for individuals living in rural areas, and decrease healthcare costs. Moreover, the new technologies can allow teleconsultation between doctors, which can lead to many benefits for patients' health, such as quick diagnoses and prompt access to adequate treatments [4,5].

Since telemedicine does not imply direct contact between healthcare personnel and other patients, its use has been reported as crucial during health emergencies related to infectious diseases, such as COVID-19 [6–8]. Even though telemedicine has known impressive growth in the course of the COVID-19 pandemic, several factors limit its spread. Among these, in addition to the difficulties of performing some types of remote physical examinations, which concern some medical specialties, the lack of knowledge about the efficacy and safety of telemedicine, about the availability of telemedicine services, or about how to access telemedicine visits, together with patients' preferences toward different providers, have been identified as barriers to telemedicine [9,10]. In the U.S., a study performed to assess telehealth satisfaction showed that nearly three-quarters of consumers were unaware of telemedicine services [11]. The most frequently reported patient barriers to telemedicine use were age, level of education, computer literacy, unawareness of services, and bandwidth [10]. In addition, it should be considered that those who were older, lived in rural areas, had less education, and had more chronic conditions were less likely to have access to the internet than their counterparts [12]. Furthermore, since sharing health information online poses privacy issues, patients who are not able to understand or mistrust privacy policies are often reluctant to use telemedicine services [2,10]. In Italy, the first national guidelines on telemedicine were approved by the General Assembly of the Superior Health Council in 2012 [13]. Since that year, several actions have been taken nationwide to promote the adoption of telemedicine, mainly in light of the COVID-19 pandemic. In 2015, a regulation on electronic health records was issued (Decree of the President of the Council of Ministers 29 September 2015, n. 178). Finally, the document "National guidelines for the provision of telemedicine services", approved in 2020, provided indications for the provision of some telemedicine services, such as televisits, medical health teleconsultations, teleassistance by health professionals, and telereporting [13].

Since 2012, all the Italian regions have progressively implemented the first national guidelines with their own resolutions, and many differences exist in telemedicine provision throughout the Italian territory. The national mapping performed in 2018 by the Telemedicine Working Group of the New Health Information System found notable discrepancies between regions, with the numbers of experienced telemedicine services ranging from 1 to 36 [14].

This study aims to assess the awareness and the attitude toward telemedicine in the Italian adult population, with regard to sociodemographic characteristics and territorial differences in telemedicine service provisioning.

2. Materials and Methods

This cross-sectional study was performed in Italy during the period of October 2022–February 2023 through the use of a Google form. Participants were asked to provide their informed consent before accessing the questionnaire. The Scientific and Ethical Board of the Inter-University Research Center "Population, environment and health" (CIRPAS) approved the study (approval n. 1810_2022).

2.1. Participants

The questionnaire was disseminated using communication media (i.e., mailing lists and instant messaging applications) and social networks (i.e., Facebook and Instagram), asking participants to further spread the questionnaire among their contacts. Inclusion criteria were being Italian and adult. Considering a response proportion of 50%, a 95% confidence level and a 5% margin error, it was calculated that a minimum sample size of at least 385 individuals was needed. In order to increase the representativeness of the sample, we accepted all questionnaires obtained within the stated period of the study.

2.2. Questionnaire

The electronic questionnaire included three sections (Supplementary Materials). The first aimed to collect the sociodemographic, behavioral, and health-related characteristics of participants. In particular, they were asked to report their sex, age, region of residence, educational level, occupational status (student/unemployed/worker/retired), sentimental/marital status (married/cohabiting or not with a partner/separated or divorced/widowed/single), residential status (living in their own home/other's home/nursing home), whether they had children, and current health chronic conditions. The second and third parts focused on the participants' knowledge and use of telemedicine services (e.g., televisits, medical video consultations, and telemonitoring) and electronic health data records.

The questionnaire was tested in a pilot study involving twenty people (data not published). Four experts in public health, epidemiology, and communication technologies designed the questionnaire based on the scientific literature, the aim of the study, and the current status of telemedicine in the country. Subsequently, an external panel of experts evaluated the tool to evaluate its content validity. Furthermore, the questionnaire's comprehensibility was evaluated in the pilot group. Participants were asked to rate each question on a 7-point scale, with 1 corresponding to "not meaningful" and 7 to "very meaningful"; a mean score of 5 per question was considered as the cut-off for acceptability. To this aim, 10 additional questions reporting grammatical and semantic errors were included in the original questionnaire to assess answer variability. The original questions showed a mean score >5 each, while the additional questions had a mean score <2, confirming the clarity of questionnaire content.

The reliability of the final version of the questionnaire was assessed using Cronbach's alpha as a coefficient of internal consistency reliability. The questionnaire achieved an alpha value of 0.75 during the pilot study and an alpha value of 0.74 during the larger study, demonstrating satisfactory internal consistency [15].

2.3. Statistical Analysis

A descriptive analysis was carried out on the sociodemographic and health characteristics of participants. Continuous variables were expressed as mean values ± standard deviations (SDs), while categorical variables were expressed as numbers and percentages (%) of respondents for each category. Respondents were then categorized into two groups based on their attitudes toward using telemedicine or electronic health data records (willing to use indicating positive attitude and unwilling to use indicating negative attitude). The sociodemographic and health characteristics of the participants were compared between the two groups using a chi-squared test with Yates correction. Those characteristics that significantly differed between the attitude groups were included in multinomial logistic regression models, which were performed considering negative attitude toward telemedicine and electronic health data records as dependent variables. Specifically, a value = 1 was assigned to a positive attitude toward telemedicine/health data records, while a value = 0 was assigned to a negative attitude. Age (expressed as 0 = lower or equal/1 = higher than the median value), sex (0 = male/1 = female), having a sentimental relationship (0 = non-engaged/1 = engaged), being a parent (0 = no/1 = yes), educational level (0 = non-graduated/1 = graduated), employment status (0 = unemployed/1 = employed), and having a concurrent health condition or disease (0 = no/1 = yes) were included in the regression analysis as independent variables. The results were expressed as odds ratios (ORs) and 95% confidence intervals (95% CIs). A p-value < 0.05 was considered statistically significant. Statistical analyses were conducted using SPSS (Statistical Package for Social Science; version 28.0; IMB SPSS; Armonk, NY, USA).

3. Results

A total of 1002 complete questionnaires were collected. Table 1 shows the sociodemographic characteristics of the sample.

Table 1. Sociodemographic characteristics of participants (n = 1002).

Variable	
Age	
mean ± SD	49.9 ± 14.8
range	18–90 years
median (IQR)	52 (20)
Sex	
n (%)	
female	481 (48.0)
male	520 (51.9)
other	1 (0.1)
Area of origin	
n (%)	
north	315 (31.4)
center	462 (46.1)
south	225 (22.5)
Sentimental relationship	
n (%)	
single	69 (6.9)
engaged, not cohabiting	133 (13.3)
engaged and cohabiting, not married	147 (14.7)
married	357 (35.6)
divorced/separated	204 (20.3)
widowed	92 (9.2)
Children	
n (%)	
no	478 (47.7)
yes	524 (52.3)
Educational level	
n (%)	
mandatory to high school	541 (54.0)
degree and post-degree	461 (46.0)
Occupational status	
student	123 (12.3)
unemployed	230 (23.0)
employed	573 (57.2)
retired	76 (7.6)
Place of residence	
n (%)	
own house	909 (90.7)
other's house (studying/working offsite)	35 (3.5)
other's house (as a guest)	37 (3.7)
nursing home	21 (2.1)
Chronic disease	
n (%)	
no	520 (51.9)
yes	482 (48.1)

The sample had a wide age range and showed quite equal distributions in the categories of sex, educational level, parent status, and chronic condition. The gender and age characteristics of the sample were quite similar to those of the general Italian population of the same age range (female gender: 51.6%; mean age: 51.9 years), as deduced by the data published by the Italian Institute of Statistics for the year 2023 (http://dati.istat.it/ (accessed on 30 June 2023). The majority of participants came from the center of Italy, were married, were employed, and lived in their own houses.

Tables 2 and 3 show the answers given by participants to the questions regarding telemedicine services and electronic health data records.

Table 2. Answers regarding participants' knowledge and attitude toward telemedicine services (n = 1002).

Question	**Respondents** *n* **(%)** †
Have telemedicine services been activated in your region?	
No	124 (12.4)
Yes	456 (45.5)
I don't know	422 (42.1)
If yes, how did you learn of them?	
My doctor	390 (92.4)
My work	5 (1.2)
Advertising	9 (2.1)
Friends or relatives	18 (4.3)
If yes, have you ever used them?	
No	267 (63.3)
Yes, for myself, autonomously	146 (34.6)
Yes, for myself, with someone's help	5 (1.2)
Yes, for a relative	4 (0.9)
If you have used these services, are you satisfied?	
No	8 (5.2)
Yes	147 (94.8)
If these services are available in your region, but you did not use them, why?	
It would be difficult for me to access	98 (36.7)
It would not be difficult for me, but I don't need them	25 (9.4)
It would not be difficult for me, but I prefer the traditional services	144 (53.9)
If it would not be difficult for you to use these services but you prefer the traditional ones, why?	
Privacy reasons	27 (18.7)
I prefer to meet doctors in person	9 (6.2)
I think that these services can be less effective	108 (75.0)
If these services are not yet available in your region, would you use them?	
No	52 (9.5)
Yes	494 (90.5)

† Percentages are calculated from the number of respondents to each question.

Less than half of the respondents were aware of telemedicine services in their region, while the majority of them were not sure about the activation of electronic health data records. Doctors were reported as the main source of information in both cases. The majority of the participants did not use the available services, mainly because of a preference for traditional visits or lack of need. Among those who preferred in-person services, the lack of trust in telemedicine effectiveness or functioning was the main reason reported. However, more than 90% of those who used the new services were satisfied with them, and a similar proportion of those who did not use telemedicine due to its unavailability were willing to use it.

As for the attitude toward telemedicine, Tables 4 and 5 show the results of the chi-squared tests performed comparing the sociodemographic characteristics of participants who were favorable and unfavorable toward the use of telemedicine services and electronic health data records.

Table 3. Answers regarding participants' knowledge and attitude toward electronic health data records (n = 1002).

Question	Respondents n (%) †
Have electronic health data records been activated in your region?	
No	169 (16.9)
Yes	166 (16.6)
I don't know	663 (66.4)
If yes, how did you learn of them?	
My doctor	133 (83.1)
My work	4 (2.5)
Advertising	5 (3.1)
Friends or relatives	18 (11.3)
If yes, have you ever used them?	
No	134 (80.7)
Yes, for myself, autonomously	23 (13.9)
Yes, for myself, with someone's help	9 (5.4)
If you have used this service, are you satisfied?	
No	2 (6.2)
Yes	30 (93.7)
If this service is available in your region but you did not use it, why?	
It would be difficult for me to access	3 (2.2)
It would not be difficult for me, but I don't need it to manage my data	127 (94.8)
It would not be difficult for me, but I prefer to keep my data	4 (3.0)
If it would not be difficult for you to use this service but you prefer to keep your data, why?	
Privacy reasons	0
I prefer to decide which data to share with a doctor	0
I am afraid that data can be lost/the service may be unavailable	4 (100.0)
If this service is not yet available in your region, would you use it?	
No	27 (3.2)
Yes	805 (96.8)

† Percentages are calculated from the number of respondents to each question.

Table 4. Comparisons of sociodemographic and health characteristics of participants with positive or negative attitudes toward telemedicine services with corresponding p-values from the chi-squared test (n = 1002).

Variable	Negative Attitude n (%)	Positive Attitude n (%)	p-Value
Age			
≤52 years	18 (34.6)	294 (55.1)	0.007
>52 years	34 (65.4)	240 (44.9)	
Sex			
female	27 (51.9)	246 (46.1)	0.693
male	25 (48.1)	287 (53.7)	
other	0 (0)	1 (0.2)	
Area of origin			
north	10 (19.2)	85 (15.9)	0.372
center	35 (67.3)	334 (62.5)	
south	7 (13.5)	115 (21.5)	
Sentimental relationship			
engaged	21 (40.4)	181 (33.9)	0.431
not engaged	31 (59.6)	353 (66.1)	
Children			
no	28 (53.8)	251 (47.0)	0.425
yes	24 (46.2)	283 (53.0)	
Educational level			
mandatory to high school	31 (59.6)	288 (53.9)	0.522
degree and post-degree	21 (40.4)	246 (46.1)	
Occupational status			
unemployed	25 (48.1)	234 (43.8)	0.657
employed	27 (51.9)	300 (56.2)	
Place of residence			
own house	49 (94.2)	491 (91.9)	0.753
other	3 (5.8)	43 (8.1)	
Chronic disease			
no	7 (25.9)	40 (14.0)	0.171
yes	20 (74.1)	245 (86.0)	

Table 5. Comparisons of sociodemographic and health characteristics of participants with positive or negative attitudes toward electronic health data records with corresponding *p*-values from the chi-squared test (n = 1002).

Variable	Negative Attitude *n* (%)	Positive Attitude *n* (%)	*p*-Value
Age			
≤52 years	13 (48.1)	401 (49.1)	0.920
>52 years	14 (51.9)	416 (50.9)	
Sex			
female	14 (51.9)	388 (47.5)	<0.001
male	12 (44.4)	429 (52.5)	
other	1 (3.7)	0 (0)	
Area of origin			
north	0 (0)	220 (26.9)	<0.001
center	13 (48.1)	422 (51.7)	
south	14 (51.9)	175 (21.4)	
Sentimental relationship			
engaged	14 (51.9)	291 (35.6)	0.127
not engaged	13 (48.1)	526 (64.4)	
Children			
no	7 (25.9)	377 (46.1)	0.060
yes	20 (74.1)	440 (53.9)	
Educational level			
mandatory to high school	10 (37.0)	424 (51.9)	0.186
degree and post-degree	17 (63.0)	393 (48.1)	
Occupational status			
unemployed	19 (70.4)	336 (41.1)	0.005
employed	8 (29.6)	481 (58.9)	
Place of residence			
own house	13 (48.1)	757 (92.7)	<0.001
other	14 (51.9)	60 (7.3)	
Chronic disease			
no	2 (8.3)	57 (12.5)	0.771
yes	22 (91.7)	398 (87.5)	

The group with a negative attitude toward telemedicine showed a significantly higher proportion of individuals with higher age than the other group.

The group with a negative attitude toward the use of electronic health data records showed significantly higher proportions of females, parents, individuals coming from the south of Italy, unemployed, and individuals not living in their own houses with respect to the group with a positive attitude.

In the regression analysis, age was found to be inversely related to a positive attitude toward telemedicine services (OR = 0.432, 95% CI: 0.238–0.784, p = 0.006); a positive attitude toward the use of electronic health data records was positively related with female gender (OR = 2.291, 95% CI: 1.759–2.985, $p < 0.001$).

4. Discussion

This study provides a picture of the current awareness and attitudes toward telemedicine among Italian citizens. The findings show that less than half of the sample was aware of the available telemedicine services, and less than 40% used them.

Although these findings are in line with the previous literature [11], it seems very surprising since the recent pandemic has determined an unprecedented recourse to new technologies for social and work activities, even among older adults [16–19].

Furthermore, among those who did not use the available services, the majority preferred traditional visits to televisits or declared their lack of need for electronic health data records. This appears to be in line with previous evidence from the same population, showing that Italian people preferred in-person relationships and sociocultural activities, even during the pandemic [20].

However, our results show that almost all the telemedicine users were satisfied with the accessed services. Furthermore, the majority of the respondents who were not aware of the telehealth services available in their region declared their willingness to use telemedicine.

Considering the possible benefits of telehealth services for patients, healthcare professionals, and the environment, this allows hope for a widespread diffusion and acceptance of telemedicine in the Italian territory.

In our sample, doctors emerged as the reference figures for information in this field. This is an encouraging result since a sample of Italian physicians involved in a pre-COVID-19 survey showed generally low levels of engagement in telemedicine and lower intention to use telemedicine among doctors of higher seniority, indicating a possible reluctance to change practicing habits [21]. Allowing a greater knowledge of patients and their needs, telemedicine and televisits may enable healthcare workers to better manage visiting and travel times and, consequently, enhance performance and thereby reduce work-related stress [2]. Considering the influence that doctors' indications may have on patients' choices [22], healthcare professionals should be aware of these potential benefits to increase confidence in telemedicine.

In our study, in accordance with current scientific evidence, a negative attitude toward telemedicine was associated with older age [10,23]. The elderly may experience greater difficulties in accessing and using digital health technologies. Many other barriers to technology use for older people include lower levels of digital literacy, lack of perceived usefulness, lack of access to and experience and skills with digital tools, and physical (especially visual impairments) and cognitive deficits that may hinder the use of these tools. This confirms previous findings regarding the use of digital resources to exercise during the pandemic in the Italian population [20].

With reference to this, it should be considered that elderly patients would be the most likely category to benefit from telemedicine and telehealth services. In particular, they could benefit from telemedicine thanks to the possibility of being visited through videoconferences, eliminating inconveniences related to travel costs and times, waiting times, and reduced autonomy. As a matter of fact, in a U.S. investigation, high proportions of unaware customers were found among participants living in rural or suburban areas, and those who indicated their health as "poor" had never used telemedicine, which shows that patients who may benefit the most from its services use it the least [11].

Furthermore, in our sample a positive attitude toward electronic health data records was related with female gender. This is in line with the higher adoption and satisfaction rates registered among female participants in other surveys [11,24,25].

Interestingly, in line with the previous literature [11], having a chronic condition, which may require periodical medical consultations and can benefit from telemedicine services, was not found to be related with the willingness to use them. Our previous study showed that having a chronic condition was inversely related with the use of web resources, as well as social and cultural activities and maintaining relationships [20], which may lead to social isolation in an emergency situation. At the same time, social isolation is associated with having more chronic diseases, generating a vicious circle [26].

On the other hand, the implementation of telemedicine services is not easy in terms of resources needed and patient acceptability. As for the resources, it should be considered that project costs are high: when a healthcare organization or a team of doctors and programmers decides to implement an effective telemedicine project (monitoring of elderly patients, remote evaluation of a disease, second opinion, etc.), it is necessary to deal with feasibility studies and technical economic evaluations. In every teleconsultation project, a very considerable organizational effort is required between doctors, computer scientists, and programmers to design the necessary software to start the pilot phase. A versatile technological infrastructure that is continuously updated by technical staff; the latest generation of secure servers certified with uninterruptible power supplies and back-ups so as not to lose data; easy and intuitive data and image entry and management procedures with automated control systems and alerts for inappropriate data entry; fast downloading and uploading of high-pixel-density images with zoom and image comparison software;

different access profiles for customized data visualizations; and applications for use of the procedures from mobile devices are required. Furthermore, efforts are needed to channel projects into services available for the whole population.

Finally, the market may not yet be ready to welcome the multiple and different telemedicine projects, and difficulties can be encountered when integrating telemedicine with existing care-delivering systems. Above all, the regulations are not yet unified, and government guidelines and sustainability guidelines have only recently been given in some countries, such as Italy. This leads also to the offering of different services throughout a country: currently, some Italian regions provide to citizens electronic data records, and others still do not; even in the same region, some healthcare institutions offer remote visits and consultations for some medical specialties, and others still do not. Furthermore, from the perspective of healthcare mobility, the use of shared software in medical informatics for teleconsultations is still difficult terrain, both for the usability of data software and for image transfer and sharing [27,28]. These aspects can also contribute to creating a negative patient attitude toward telemedicine. Security and privacy aspects are also important to increase acceptability and must comply with new regulations regarding data protection and encryption, especially for web-based platforms, such as with bureaucratic and legal procedures, informed consents, and codes of conduct for doctors [28].

Due to these multiple technical and human factors implicated, participation, responsibility, and desire for effective collaboration among all the stakeholders are the necessary requisites for success in telemedicine adoption. A suitable "network" culture with evaluation of accesses, acceptability, quality of the transmitted data, and medical efficacy should be created for this aim. Furthermore, in order to increase confidence in telemedicine, it would be useful if telemedicine were taught today in health degree courses [29,30].

This study has some limitations. First of all, the recruitment procedure did not allow us to obtain a nationwide representative sample; therefore, our results are not extendable to the whole Italian population. Moreover, the use of an electronic questionnaire and the recruitment procedure allowed us to involve in the study people who use social media and the Internet, who are probably more keen to use digital health than those who do not. Due to its nature, the study was based on subjective thoughts and beliefs, which may not reflect the attitudes of the whole Italian population toward telemedicine. Furthermore, the lack of an updated database of telemedicine services provided in the whole Italian territory prevented an in-depth analysis of the participants' awareness at a regional level. In addition, in order to avoid excessive length of the questionnaire, the study was not aimed at analyzing the specific types of telemedicine service used by participants, which hindered the detection of possible correlations with their characteristics or health conditions. This aspect can help to better characterize the satisfaction toward telemedicine and should be addressed in further studies.

However, to the best of authors' knowledge, this is the first study that analyzed the process of telemedicine implementation in Italy from the citizens' point of view. Since patient perspective is crucial for integrating new technologies into healthcare practice [31], these findings can be useful to address this process.

5. Conclusions

Our investigation demonstrated that, although many telemedicine services are already active in Italy, a large part of the population ignores its availability.

Considering that telemedicine can have a positive impact on quality of care, its use must be promoted among citizens [32], as well as in light of future restriction measures adopted to counteract possible emergencies. Moreover, the study highlighted the need for enhancing the awareness of and confidence in telemedicine of the Italian population. However, as underlined by our results, the creation of a national "network" culture of telemedicine should start from healthcare personnel, who had a fundamental role in promoting its adoption. Therefore, the integration of telemedicine in the core curriculum of health degree courses should be considered.

Although related to the Italian population, these findings may contribute to the characterization of the spread and acceptance of telemedicine worldwide.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare11152157/s1, Questionnaire used in the study.

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Communication

Primary Care of the (Near) Future: Exploring the Contribution of Digitalization and Remote Care Technologies through a Case Study

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Abstract: The Italian Government planned to invest €15 billion of European funds on National Health Service digitalization and primary care enhancement. The critical burden brought by the pandemic upon hospital care mean these investments could no longer be delayed, considering the extraordinary backlogs of many treatments and the ordinary gaps of fragmented long-term care, in Italy and abroad. National guidelines have been published to standardize interventions across the Italian regions, and telemedicine is frequently mentioned as a key innovation to achieve both goals. The professional resources needed to run the facilities introduced in primary care are defined with great precision, but no details are given on how digitalization and remote care technologies must be implemented in this context. Building on this policy case, this paper focuses on what contribution digitalization and telemedicine can offer to specific primary care innovations, drawing from implemented technology-driven policies which may support the effective stratification, prevention and management of chronic patient needs, including anticipatory healthcare, population health management, adjusted clinical groups, chronic care management, quality and outcomes frameworks, patient-reported outcomes and patient-reported experience. All these policies can benefit significantly from digitalization and remote care technology, provided that some risks and limitations are considered by design.

Keywords: algorithms; artificial intelligence; big data; informatics; NextGeneration EU; PNRR; primary care; telemedicine

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1. Introduction

Next Generation EU is the European Commission's €800 billion temporary recovery instrument to support the economic recovery from the coronavirus pandemic, and build a "greener, more digital and more resilient future" [1]. In April 2021, the Italian Government launched a National Recovery and Resilience Plan (in Italian: Piano Nazionale di Ripresa e Resilienza, PNRR) to invest about €190 billion of European funds in the six areas of digital innovation, ecological transition, mobility infrastructures, teaching and research, social cohesion and healthcare. Approximately €15 billion is dedicated to the latter (Mission 6), in particular to primary care enhancement (€7 billion) and the digitalization of the Italian National Health Service (NHS, approximately €8 billion). Telemedicine is frequently mentioned as a key innovation to achieve both goals [2].

The adoption of telemedicine, eHealth and information technology (IT) in support of primary care reform and chronic patient management has been recommended for a decade by the Ministry of Health [3,4] and by regional policy documents [5–8], although generally not described in detail, i.e., which technologies should be adopted to achieve which specific goals. Following the opportunity offered by NextGeneration EU and PNRR, the Ministry of Health published a Decree containing national guidelines on primary care modernization [9], binding on each Italian region and defining:

- the facilities that every region must adopt;
- the human resources needed to run each type of facility;
- the population that each facility is expected to cover;
- where telemedicine and digitalization should fit in.

However, (a) the stratification of patient needs on which primary care reform should be settled is based on algorithms and information systems described in previous policy documents that have not been implemented [10,11]; (b) no details are provided on how digitalization and telemedicine can support the "holistic evaluation of the health and social care needs of patients" [9] (p. 17) in terms of integrated care management.

The critical burden brought by the pandemic upon hospital care mean these investments can no longer be delayed [12], considering the extraordinary backlogs of many treatments and the ordinary gaps of fragmented long-term care, not only in Italy [13,14], but in all countries struggling to cover the needs of patients suffering from chronic morbidities [15–22] and social isolation [23]. For these patients, reducing distances is fundamental to maintain an acceptable quality of life, minimize life-threatening events and expensive preventable health complications, not to mention the direct burden on caregivers [24].

Building on this policy case, this communication paper focuses on what contribution telemedicine and remote care technology can offer to specific primary care innovations, synthesize and discuss them, both in terms of proactive governance of the healthcare demand (population health management) and integrated chronic patient management (planning, delivery, remuneration, evaluation).

The argument is structured by:

- Abstracting from national guidelines the key areas, functions and services in which digitalization (IT, integrated platforms, electronic clinical records, big data, artificial intelligence etc.) and remote care technologies (telemedicine, teleconsultation, televisit, telereferral, telemonitoring, telerehabilitation etc.) can make a contribution to primary care modernization;
- Describing some technology-driven policies which may support the effective stratification, prevention and management of chronic patient needs, integrating and/or filling the gaps of national guidelines, inspired by anticipatory healthcare, population health management, adjusted clinical groups, chronic care management, quality and outcomes frameworks, patient-reported outcome measurements (PROMs) and patient-reported experience measurements (PREMs);
- Pointing out some possible limitations, red flags and risks which are worth-considering by design.

We believe that this policy case can interest the multidisciplinary healthcare community (researchers, care professionals, policy makers, users) of all the systems called to handle the pressure of aging and chronic disease under limited financial resources, in order to share ideas, solutions, criticalities and ultimately help accelerate the reform of primary care.

2. Telemedicine and Primary Care Facilities

National guidelines have been published in Italy to standardize healthcare provision across public and private providers [25], hospital care [26] and ultimately primary care [9]. The latter are divided into 16 chapters among which No. 3 illustrates the stratification of patient needs on which the entire system should be based, No. 15 is entirely dedicated to telemedicine, and the eleven chapters in between introduce several interconnected primary and intermediate care facilities, all of which may benefit from telemedicine.

Telemedicine is defined as "A method of providing healthcare and long-term care remotely, enabled by information and communication technologies, and used by healthcare professionals to care for patients (professional—patient telemedicine), offer advice and support other professionals (professional—professional telemedicine)" [9] (p. 53). It consists of patient specialised televisit, teleassistance, telemonitoring, telerehabilitation, teleconsultation and telereporting, for the purpose of:

- Reducing physical distance between (a) healthcare professionals and patients, (b) healthcare professionals themselves;
- Connecting multiple healthcare professionals and providers, especially where integrated, multidisciplinary patient management is required (i.e., patients affected by chronic disease and/or social vulnerability, such as living alone, with limited autonomy and/or cognitive function);
- Performing early diagnoses and timely interventions in case of occasional acute events affecting chronic patients assisted at home;
- Providing efficient coverage and greater proximity to underserved areas, incrementing appropriate care and therapeutic compliance;
- Connecting primary and secondary care providers to promote de-hospitalization with safe patient discharge.

In this sense, telemedicine is considered a key driver to increase patient-oriented care and the responsive capacity of the NHS [9] (p. 54), reducing care gaps and inequalities caused by the social determinants of health (i.e., living place, distance from care facilities, family composition, income, health literacy, type of dwelling) which make certain population groups more or less consciously vulnerable (i.e., elderly chronic patients and/or patients with severe physical impairment and/or mental disability). That is why interconnected primary care facilities can benefit from telemedicine in several ways. In Table 1 these facilities are synthesized and divided per main function and services according to the guidelines provided by the Ministry, by the authors, in order to highlight how digital and remote care technologies can generate additional value in each area, according to the authors.

Table 1. Primary care facilities, main function and services which may benefit from digital and remote care technology.

Facility	Main Functions	Service	Technology
Casa di Comunità *. (Community Care Unit).	Outpatient clinic where General Practitioners (GPs) visit patients and perform basic diagnostics, multidimensional evaluation; connections with social care; maternity and childcare; ordinary specialistic visits are provided for high-prevalence chronic diseases; centralized administrative tasks (i.e., hospital reservations, drug and secondary care prescriptions, GP choice and revocation, medical certifications, payment exemptions are recognized).	Basic diagnostics.	Televisit, teleconsultation, teleremonitoring, telereferral related to ordinary chronic care conditions in patients at home. Teleprescription of ordinary drugs. Telereferral for driving licence renovation.
		Population screening.	IT can enable integrated platforms to inform patients on screening opportunities, where appropriate (i.e., age, previous relevant events). Integrated platforms can provide big data to enable population health management (see next paragraph). Artificial intelligence can work on big data to identify predictive factors, risks and unexpected disease determinants.
		Home care management.	Telemonitoring, telerehabilitation, informatics (see "Assistenza Domiciliare").
		Central reservation system.	IT can enable integrated platforms to remind patients/care givers/case managers (see next paragraph) about upcoming appointments, either by phone, emails or message texts (i.e., outpatient visits, planned admissions). Integrated platforms can provide big data to enable population health management. Artificial intelligence can work on big data provided by integrated platforms to identify correlations between medical procedures and complications or side-effects (i.e., surgical infections, incompatible drugs, medium- and long-term side-effects).

Table 1. *Cont.*

Facility	Main Functions	Service	Technology
Unità di Continuità Assistenziale. (Care Continuity Unit).	Mobile unit (i.e., doctor and nurse) ensuring the continuity of care in case of difficult contingencies (i.e., infectious outbreaks or logistical complications). Physically based in a Casa di Comunità.	Remote consultation with GP or specialist doctor.	Televisit, teleconsultation, telereporting disease parameters and patient outcomes.
		Telemonitoring in case of individual infection or local outbreak.	Televisit, teleconsultation, telereporting, telemonitoring.
		Home vaccinations.	IT can track patient compliance in support of collective immunization strategies, and trigger one-off information policies in case of non-compliance. IT can enable integrated platforms to support population health management (i.e., vaccine uptake). Integrated platforms can provide big data to identify correlations between patient characteristics (i.e., sex and age), comorbidities, vaccine effectiveness, safety or side-effects, even supported by artificial intelligence.
Centrale Operativa Territoriale. (Local operation center unit).	Nurse-led operating center ensuring links among primary care, hospital care, emergency care, connected to each individual providers' software.	Patient tracking between transitions.	IT can enable integrated platforms to notify whether the patient have successfully been admitted/discharged/moved to the appropriate care setting, even more when non-autonomous (i.e., cognitive dysfunction or social isolation), to activate eventual arrangements on time (i.e., care giver, home care, wearable devices).
		Logistical and informative support.	IT can record effective or ineffective transitions and provide evidence for policy arrangements.
		Clinical data collection including home care.	See "Assistenza domiciliare".
Assistenza domiciliare. (Formal home care).	Home-delivered care for non-autonomous patients waiting to stabilize clinical status, limit functional decline, improve quality of life, based on different levels of complexity evaluated by the GP and managed in a Casa di Comunità.	Activity records	Telemonitoring and telerehabilitation can help patients receive advice and stay safer at home. IT, big data, artificial intelligence can provide integrated platforms with health information collected at home, enhancing health policy, population health management and reducing the frequency of underreported health-related events such as side-effects or complications. Digital applications and wearable devices can track the health-related activity of patients at home, providing evidence-based information to evaluate compliance, performance variations and eventually alerting on time whether no physical activity or vital functions are registered. Similar devices can support decentralized clinical trials to increase trial retention while reducing travel to facility and eventually costs.

Table 1. *Cont.*

Facility	Main Functions	Service	Technology
Ospedale di Comunità. (Community hospital).	Intermediate inpatient care for patients temporary unable to stay home safely but still do not need resource-intensive hospitalization, or patients discharged from hospital in need of clinical stabilization. Closer to home than high-volume central hospitals. Maximum 20 beds and 30 days of stay.	Safe discharge	IT can enable integrated platforms support patient admission from home to intermediate hospital, from central hospital to intermediate hospital, and tracking. Integrated platforms can provide big data to identify correlations between disease and length of stay, acute care hospital treatment and post-acute hospital length of stay, intermediate care admissions/length of stay and reduced acute hospitalizations, complications and emergency care visits, proximity to admitted patients' home and relative effectiveness in reducing acutization. Artificial intelligence can find unexpected correlations between any of these factors (i.e., stability of internet connection and compliance to therapy, effectiveness and safety).
		Patient education (digital technology and self-care)	Digital education under a protected environment, in order to prepare patients to the eventual use of telemedicine and reduce the risks of the digital divide. Ensuring that the patient have stable internet connection at home should be considered.

* These facilities are divided in Hub and Spoke Units, based on the amount of population they are expected to cover. Some requirements compulsory for Hub Units are only recommended for Spoke Units. Distinctions are not reported here for simplification. Each facility is named in Italian according to the original version contained in the decree. The English translation is made by the authors to give the reader better understanding.

3. The Role of Technology in Population Health Management and Integrated Care Management

Not only can digital and remote care technologies fit in the intermediate and primary care facilities introduced by national guidelines. These technologies are likely to provide a substantial contribution to the proactive governance of healthcare demand and the integrated management of chronic patients.

3.1. Proactive Governance of Healthcare Demand

By proactive governance of healthcare demand, we refer to anticipatory approaches in which a specific patient population (i.e., national, regional, local) is stratified into homogeneous care clusters, associated by:

- Prevailing clinical needs (i.e., index disease and presence of comorbidities);
- Average care consumption (i.e., drugs, outpatient visits, hospital admissions and possibly social policies of healthcare significance, such as social prescribing, reablement, formal care giving or out-of-pocket payment exemptions) [27–30];
- Main area of intervention (i.e., hospital, primary, home or residential care facilities),

based on integrated administrative workflows provided by a common authority and shared by providers. The anticipatory approach lies in taking charge of patients before they develop or exacerbate certain disease conditions, or control them outside hospitals, both in terms of primary prevention (i.e., lifestyle education by GP advice), secondary prevention (i.e., screening programs and diagnoses) and tertiary prevention (minimizing acutization and complications through single-patient case management).

The result of stratification is a set of adjusted clinical groups meant to advice the best approach to assist an individual patient or group of patients (e.g., case management, disease management, self-care education), the appropriate organization of care (e.g., setting and integration), targeted policy interventions (e.g., dehospitalization, public health campaigns, integration with social care) and the subsequent allocation of resources. While the concept of adjusted clinical groups dates back to the work of Barbara Starfield and colleagues at The Johns Hopkins University in the late 1970s [31], population health management was systematically developed more recently by Kaiser Permanente, a non-profit organization covering almost 13 million American patients, in a different way from traditional insurance methods in the United States [32] (Figure 1).

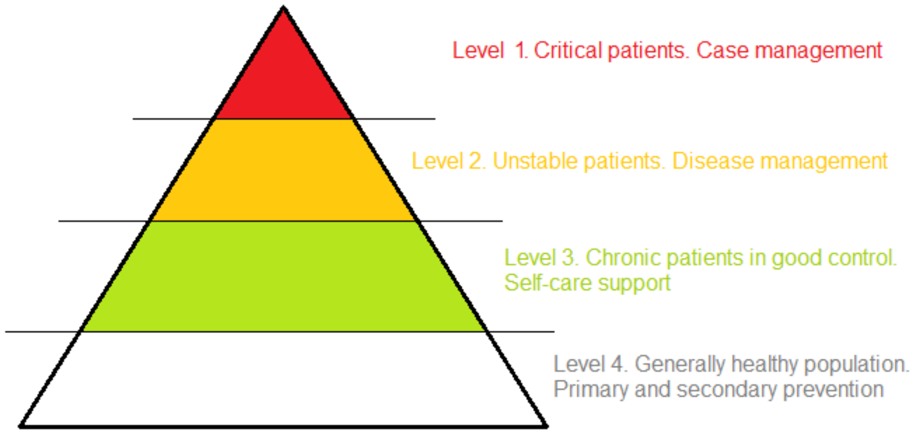

Figure 1. Population health management. Four-level model adopted by Kaiser Permanente, elaborated by the authors from [33] (p. 14).

Thanks to the continuous development of IT, these models gain greater impact today. Adjusted clinical groups are defined by algorithms that work on a large number of codified data, drawing information from different providers, integrating such information into single aggregated outputs and making possible the holistic assessment before mentioned (e.g., single patient visual history of care, average healthcare consumption, costs and current estimated need). Details on these algorithms and their applications are described by technical guidelines in support of the policy documents released by the Italian regions that invested in this approach [5] (pp. 58–61), [7] (p. 31), [34] (pp. 22–23).

Integrated information systems constantly update patient stratification on a common database, building on electronic health records shared on a regional [35], NHS [36] or public insurance base [37]. Electronic records enable patients to (a) check the progress of their medical history on an integrated dashboard, finding medical reports, diagnostic exams, lab tests, forthcoming appointments and certifications (e.g., vaccinations, sports); (b) add information directly from home, thanks to wearable devices, web applications, patient-reported outcomes, including participation to remote decentralized clinical trials [38].

The region of Lombardy adopted some of these technologies in a radical primary care reform effort, from 2015 onwards, interrupted by the violent outbreak of the COVID pandemic and then superseded by the national guidelines discussed here. The approach, broadly comparable to that proposed by the regions of Emilia Romagna, Sardinia, Tuscany and Veneto [5], offers important advice to support and complete the implementation of national guidelines on primary care modernization.

The region first introduced an integrated patient DataWareHouse, in 2002 (Banca Dati Assistito, BDA), including the health-related information useful to track the patient history of care across the providers where he or she was assisted, monitoring process and disease outcomes [34] (pp. 18–21). After a dedicated algorithm was developed and two pilot experimentations were run [39], a population health stratification similar to Kaiser Permanente's was adopted, in 2017, to define five levels of resource-intensive care need (Table 2), and drive the proactive recruitment of patients in dedicated care pathways of varying complexity.

Table 2. 5-Levels model, integrated information systems, patient-database driven population health management adopted by the region of Lombardy, elaborated by the authors from [40] (p. 12).

Need	Appropriate Setting(s) and Service Design	Number and Percentage of Patients over the Population of Lombardy *
Level 1. Complex, chronic patients at high risk of acutization, generally affected by comorbidities, functional limitations and social vulnerability.	Intensive integration between hospital and home care.	Approx. 150,000 (1.5%).
Level 2. Chronic patients characterized by comorbidities, predominantly outpatient clinical need and low-to-moderate social vulnerability.	Outpatient care, self-care education, tertiary prevention, intermediate or primary care facilities (i.e., aggregated GPs).	Approx. 1,300,000 (13%).
Level 3. Patients affected by a single and/or early-stage chronic disease, with low-to-moderate outpatient needs and no critical social vulnerability.	Outpatient care, self-care education, single GP and primary care facility.	Approx. 1,900,000 (19%).
Level 4. Non-chronic patients characterized by occasional healthcare consumption.	Not of this policy concern.	Approx. 3,000,000 (30%).
Level 5. Patients with negligible healthcare consumption.		Approx. 3,500,000 (35%).

* The population of Lombardy makes up 1/6 of the entire Italian population, namely 10,027,602 inhabitants at 31 December 2019 [41]. Today the population of Lombardy has dropped below 10,000,000 inhabitants after two years of the COVID pandemic, which affected old and fragile individuals most [12].

Then, each patient belonging to Level 1–3 was assigned an index pathology (e.g., diabetes) divided by three degrees of estimated complexity, based on eventual comorbidities (e.g., diabetes and heart failure), average healthcare consumption per year (e.g., outpatient drugs and visits), hospitalization (based on the Diagnosis Related Groups system, DRG), social need indicators (e.g., income, family composition, instruction) and patient-share exemptions, namely exemptions from outpatient treatment payment associated with specific chronic diseases. These data were provided by the integrated patient database and aggregated by algorithms. 65 index pathologies were run first, while social vulnerability indicators were being developed. An example reporting five index conditions is represented in Table 3.

Table 3. Algorithm-driven adjusted clinical groups, adopted by the region of Lombardy, elaborated by the authors from [40] (pp. 25–26).

Chronic Index Disease	Outpatient Level 3	Outpatient Level 2	Outpatient Level 1	Outpatient Drugs Level 3	Outpatient Drugs Level 2	Outpatient Drugs Level 1	Hospitalisation (Single DRG)
			Integrated provider and patient database				
Diabetes, type 1	€ 317	€ 419	€ 787	€ 883	€ 1001	€ 1565	€ 3000
Dementia	€ 302	€ 362	€ 450	€ 533	€ 718	€ 972	€ 7598
Multiple sclerosis	€ 1220	€ 1131	€ 1089	€ 96	€ 458	€ 1056	€ 13,689
Heart failure	€ 450	€ 587	€ 740	€ 593	€ 992	€ 1420	€ 9117
Active neoplasia	€ 1945	€ 1646	€ 1704	€ 375	€ 733	€ 1293	€ 9747

From the general patient stratification useful for epidemiological investigation and macro allocation of resources, each single patient affected by a chronic disease was proactively invited to contact the most appropriate care manager to meet their need, (a) evaluating the effective need in-person, (b) sharing a sustainable care plan (i.e., a plan that the patient is able and/or willing to comply with), (c) eventually taking charge of the patient.

3.2. Integrated Care Management

Each identified chronic patient was proactively contacted by the region with a paper letter and/or GP advice, and proposed a dedicated care manager able to provide (a) medical care for the index disease (i.e., with a general practitioner or specialist), (b) all the complementary treatments needed by the patient, either directly (in a single outpatient facility) or indirectly (by prescribing inpatient care or delegating services to connected third party suppliers). The idea was to evolve from a fragmented, disease-oriented, single "silos" approach, in which the patient is required to co-ordinate all the treatments, facilities and care professionals on their own (Figure 2), to an integrated, patient-oriented pathway digitally registered on a regional platform, clinically co-ordinated by a clinical manager, organizationally co-ordinated by a case manager and continuously updated with relevant information (e.g., test referrals, prescriptions, hospital clinical records, medical reports, exemptions) (Figure 3).

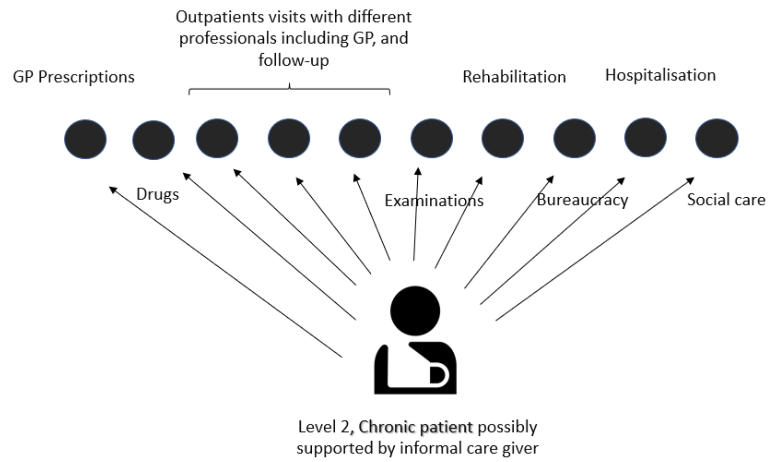

Figure 2. Fragmented care representation. Elaborated by the authors from [42].

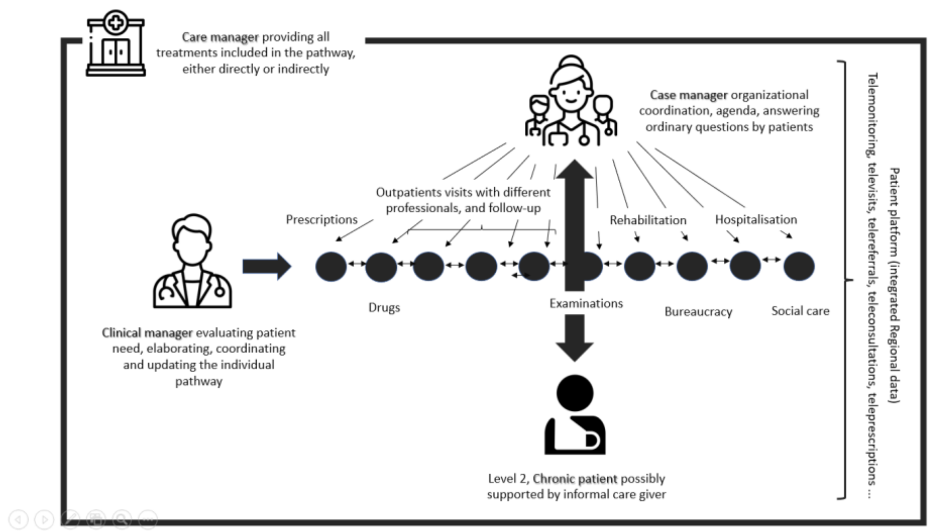

Figure 3. Digitally integrated patient management and remote care technology provision. Elaborated by the authors. See acknowledgements for graphic icons credit.

In this model, digitalization and remote care technology offer several opportunities (Table 4).

Table 4. Digitalization and remote care technology contribution to integrated chronic care management.

	Function	Facility or Professional	Technology
Care manager	Provision of all the treatments needed by the patient, either directly (single facility) or indirectly (delegated proximal service and hospitalization, when/where appropriate)	Single primary care facility, or network of primary care facilities, either public or private accredited, connected with hospital care (i.e., Azienda Socio-Sanitaria Territoriale, ASST in case of public care manager).	Integrated provider and patient platform software: • Input: access to health-related patient data available to the regional information system (national in perspective). • Output: recording the treatments provided on the regional information system (national in perspective).
Clinical manager	Patient assessment. Individual pathway design shared with patient and/or care-giver. Monitoring and updating. Prescribing treatments. Clinical co-ordination.	Medical doctor working in outpatient setting. GP in case of Level 3 chronic patient. GP in possible cooperation with a specialist of the index disease in Level 2 chronic patient. Specialist of the index disease in Level 3 chronic patient.	Televisits, telereferrals, telemonitoring, teleprescriptions in case of patients with limited mobility (either temporary, either permanent) or chronic ordinary needs (i.e., renewing prescriptions, monitoring parameters). Teleconsultations with colleagues (i.e., GP and specialist(s)).
Case manager	Monitoring chronic patients' ordinary parameters and providing support in case of need. Consultation with clinical manager when appropriate. Reminding patients about follow-up visits, diagnostic exams, therapy updates, certifications. Connecting providers (i.e., externalized or hospital) to ensure continuity of care and/or safe transitions.	Advanced nurse with co-ordination skills, working in outpatient setting.	Wearable and/or environmental devices to enable patient monitoring. Televisits with patients and teleconsultations with clinical manager. Where possible, automatic renovation of ordinary care prescriptions.

3.3. Compatibility and Scalability

Population health management is compatible with the stratification model proposed by the Ministry of Health [9] (p. 19),

(1) offering an already structured solution on which specific digital and remote care technologies can be implemented,
(2) based on policies largely shared by regions already working on primary care modernization,
(3) stressing the need to provide a unified information system on a national scale [9] (pp. 56,72),

to accelerate standardization and facilitate data exchange.

The sooner the data are unified and standardized, the greater scientific opportunities open up nationally and internationally, as big data science, artificial intelligence and machine learning will offer growing insights into epidemiology, policy, technology advancements and healthcare progress more in general (Figure 4), including outcome identification and systematic collection to express the best care value for patients (see next section).

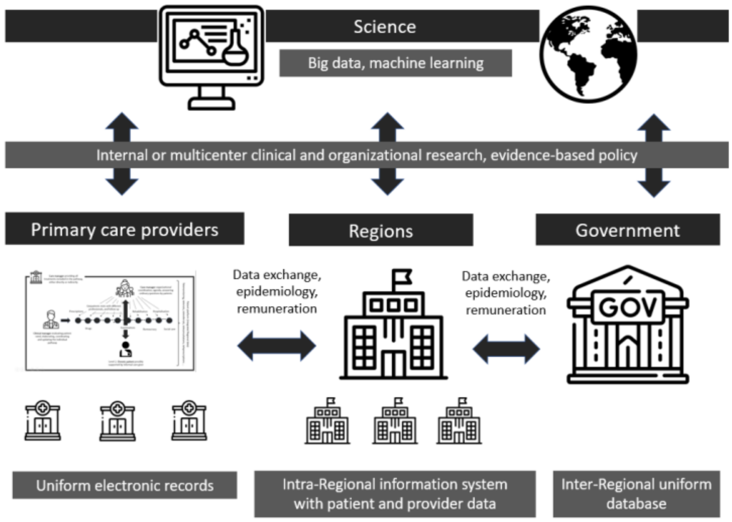

Figure 4. Model scalability. Elaborated by the authors. See acknowledgements for graphic icons credit.

This approach is also consistent with the primary and intermediate care facilities introduced by the Ministry of Health, as care managers are easy to overlap with Case di Comunità (and previous Case della Salute, for example, in the Region of Tuscany) [8,43], clinical managers can work in Case di Comunità and case managers can work in Case di Comunità and Centrali Operative Territoriali.

However, the key step is to have clinical managers, care professionals with coordination skills and integrated primary care networks as close as possible to the home of chronic patients, and able to ensure continuous, financially sustainable, integrated patient-centered care regardless of the specific name and formal office they are assigned.

3.4. Further Advancement Opportunities

Once a solid infrastructure for patient stratification and integrated care management is settled, further opportunities are offered by digitalization and remote care technology to strengthen primary care.

A first one is agreeing additional remuneration for doctors who support prevention, patient empowerment, self-care and health education. IT allows the collection of primary care outcomes through digital platforms connected with supervising agencies and the funder, making systematic monitoring and rereward possible. An example is the Quality and Outcomes Framework introduced by the British NHS in 2004 [44]. According to the program, GP contract negotiations every year are based on a set of indicators which measures some relevant public health improvements to which they have contributed. Doctors who help patients comply with therapy or reduce harmful lifestyle habits receive additional remuneration. The indicators are reported on dashboards digitally connected with the NHS and generally cover:

- the management of spread chronic conditions such as asthma and diabetes;
- the management of major public health concerns such as smoking and obesity;
- the adherence to preventative screening programs or blood pressure checks [39].

The Framework increased the impact of prevention and reduced health inequalities among disadvantaged cohorts of the population [45,46], though NHS controls were needed to minimize GP gaming [47]. Pilot experimentations on breast cancer screening in the Italian region of Tuscany confirmed these benefits [48].

Beyond individual prescriptions and advice, clinical managers and GPs can also be incentivized to coordinate the entire care pathway by recomposing the various functions (professionals, facilities and treatments) in the patient's interest. Several solutions can be implemented for this purpose, with more or less strong ties to the outcomes achieved.

Bundled payments, for instance, are (different versions of) pay-for-coordination solutions in which integrated healthcare pathways are remunerated when a clear set of pre-established outcomes is met [49,50]. The aims are (a) to clarify the outcomes that make a difference in the treatment of a certain patient or condition; (b) to design patient-oriented care pathways addressed to meet these specific outcomes; (c) to bound co-ordination on effective patient health improvement. Integrated IT and digital patient platforms are key to support this mechanism transparently and efficiently, as they are necessary to track each treatment provided, set and update goals and eventually validate remuneration (including eventual reasons to justify deviations).

Personal health budgets are another pay-for-coordination solution launched by the British NHS in 2009, in which patients are given a money sum to pay for all treatments associated with a specific health condition based on an individual pathway, agreed by the NHS and provided by public or private-accredited care professionals and facilities [51]. The budget is credited (a) directly to the patient or tutor, (b) to NHS providers, (c) to a care manager able to provide all treatments included, comprehensive of eventual social prescriptions of healthcare significance. Funding is not tied to outcomes achievement although digital data collection is mandatory to check for the appropriate use of funds [52]. A similar solution was adopted by the region of Lombardy between 2012 and 2013 with chronic-related groups, a pilot experimentation with comprehensive care budgets to treat more than 60,000 patients affected by diabetes, heart failure, chronic obstructive pulmonary disease and hypertension. The patients who underwent the program reduced the frequency of emergency department visits and inpatient admissions in comparison to the control group (patients who were normally assisted). Later on, clinical managers and GPs were given additional remuneration based on the complexity (L1, L2, L3) of patients they had in charge (see Tables 2 and 3) [14].

Setting clear outcomes by design is key to incrementing the value of integrated care pathways whether or not they are tied to provider remuneration [53]. Not only because clear goals are fundamental to address the coordination of care in a multiprofessional and multidisciplinary context; more in general, setting outcomes in advance makes it possible (a) to define the specific improvements expected, (b) to focus on what is most relevant and sustainable for a certain patient, enabling shared decision-making and facilitating compliance, (c) to reduce wasteful expenditure as a consequence; according to the words of the European Commission Expert Panel on effective ways of investing in health, to produce personal, technical and allocative value [54].

Patient-reported evaluations should be included for this purpose. The collection of PROMs in dedicated registries help grasp the patient perception on specific diseases, evaluating the benefits of different treatments, on different patients, and at different time stages [55]. Therefore, they support evidence-based clinical and allocative decisions. At the individual level, clinical managers can keep track of patients' conditions in relation to certain treatments, therapy adjustments or pathway deviations, even more by using telemedicine devices to monitor patient parameters on a connected platform. On an aggregate level, the digital collection of aggregated data on electronic registries help physicians figure out what treatments work best on which type of patient, and show them the expected benefits, relapses and relative time frames when choosing the best plan based on shared, informed decisions [56]. Funders can also provide additional remuneration to providers who report better patient-reported outcomes for the same service [57]. Finally, the collection of PROMs is employed to estimate the quality-adjusted life years gained after chronic care treatments or elective surgery interventions, in order to capture the best value for different patients [24] and/or compare the performance of different providers at the international level: for instance, an Organization for Economic Cooperation and Development (OECD) evaluation on the benefits of hip and knee replacement demonstrated an average gain of 4.3 and 3.3 years in full health respectively including a specific Italian hospital (IRCCS Istituto Ortopedico Galeazzi) and seven world areas (Australia, England, Netherlands, Sweden, Switzerland, and the Canadian regions of Alberta and Manitoba) [58].

At the big data level, the digital collection of standard questionnaires can also discover unexpected correlations between patient characteristics (e.g., age, sex, comorbidities, ethnicity) and treatment outcomes (i.e., more or less beneficial, at what stage, to what extent), when supported by big data science and machine learning algorithms. Then, these correlations offer valuable research inputs to understand whether some treatments are more or less effective in certain patients, distinguishing clinical reasons (biomedical research) from other (policy and service management research). On a local level, for instance, outcome inequalities are often the consequence of implicit physical barriers, technology bugs, fragmented care pathways, difficult service access, poor therapy compliance, patients unable to understand advice, clinicians unwilling to explain treatments plainly or answer patient questions in a way they can understand [16,24]. Then, the collection of PREMs helps to investigate the environmental and relational factors which hamper or facilitate the achievement of best possible health outcomes, identifying room for improvement in terms of care organization and/or professional skills.

If patient questionnaires are collected and integrated on platforms, they support efficient clinical and policy assessments. In chronic care management, organizational and policy research can make a difference as much as clinical and biomedical research, or more: otherwise, the risk is to have individually excellent professionals and increasing health expenditure wasted by poor coordination and management [59]. IT, big data and machine learning innovation can offer important evidence and enormous room for improvement here.

4. Limitations

The adoption of digital and remote care technologies is not free from risks and limitations. Here is a list without the ambition of being exhaustive.

- Creating a national database containing so much information on patients and providers is challenging. To be realistic, this step must be pursued gradually. Having uniform, ready-to-use regional databases should be preparatory. Care managers and/or primary care facilities should in turn have implemented compatible software themselves. Different countries and regions start at different levels right now, probably not only in Italy. Institutional co-ordination and strong leadership are fundamental to accelerate standardization.
- Cybersecurity and sensitive data protection are notoriously key issues in the contemporary technical, legal and ethical debate on technology regulation, with particular concern to artificial intelligence and machine-learning applications in healthcare [60–62]. Potential harm may follow from the use of data for purposes other than those for which they were collected and authorized (e.g., commercial use, privacy violation, or disease-related discrimination, including job loss). The same Hippocratic commitment to “first, not harm” can be jeopardized [63]. The more people have access to data, the more the risk of leaks, whether intentional or not. The consequences may become even more critical in market-driven healthcare systems, where chronic patients or patients at risk can be denied coverage. A central challenge here is to balance data safety and confidentiality on the one side and platform flexibility, (inter)accessibility and efficiency on the other.
- Liability for technology failure is another key issue. Machines will not replace doctors but likely support their ordinary diagnostic, prognostic and decision-making activity. Who is responsible for wrong decisions and prescriptions when they cause serious or irreversible harm to patients? Are patients able to discern the superficiality of a physician from the error of the machine he or she uses, eventually mandatory? Are they even interested in such a distinction, if they are considering suing? Intentions and responsibilities are often given moral relevance much more than facts themselves.
- Doctors may take wrong decisions from wrong inputs previously given by biased colleagues and researchers exactly such as reading Galen or contemporary scientific papers, as the history of medicine clearly demonstrates. It is one thing if this is an

isolated contingency, but something else if relying on machines capable of reproducing errors at much greater levels, mostly unconsciously. Loop thinking and spurious correlations are two examples [60] (pp. 16–17), [64], as most contemporary machine-learning prediction models are based on correlation and not on causation [65]. Think of a (near) future in which medical students will entirely learn to rely on algorithms and machines, without critical attitude, fundamental logical skills and individual experience. Such a risk must be contained by firmly maintaining logic, ethics, medical history and philosophy of science in graduating curricula.

- Loop thinking can also hamper scientific progress, which is a first cultural reason why machine learning should be integrated with traditional learning techniques, at least for now. A second cultural reason which may slow down the spread and effectiveness of digitalization and telemedicine can be the digital divide, both from patients unfriendly with digital technology (e.g., elderly patients, patients with disabilities or cognitive dysfunction) and care professionals unwilling to change their habits. These barriers are likely to disappear within generations. A third cultural reason can be the poor propensity to share data and work in groups, as needed by integrated care pathways and possible gainsharing policies. In case of integrated care pathways, the radical spread of chronic diseases requires indispensable efforts to change the culture of fragmentation and task-oriented care. Undergraduate training should be evaluated for this purpose [66] (pp. 100–102). In case of gainsharing, outcome-driven remuneration should be considered with caution, not to add further pressure on care professions and make them unattractive to next generations.
- The digital divide can also affect the environment in which professionals work and patients are assisted. A reliable internet connection is needed to avoid ordinary bugs in the practice of telemedicine (e.g., freezing videocalls or missing disease-related patient parameters monitored real-time at home). At the facility level, the more we lean on technology, the more we have problems if the system breaks down. Therefore, not only should the physical environment be ready to provide safe and efficient use of technology. Alternative routes should be maintained at least for emergency situations, with users aware of the phone number they should call and someone actually available to answer their concerns on time.
- Pay-for-performance, value-based schemes and outcome-driven remuneration should not end up making some patients and diseases overlooked because of cherry-picking drifts, i.e., because they are too difficult to treat, because they are affected by concomitating irreversible conditions or because health status progression is hard to measure [67]. In value-based care, "value" does not mean profitable patients, but relevant improvement for real-world patients, be it functional recovery, regression slowdown or pain control (i.e., palliative care), at sustainable costs by the payor and the community (which are equivalent in an NHS). Providers, of course, need to generate value in turn, in terms of remunerated work, but strong regulation must be enforced in order not to sacrifice patient health to profit.
- A final important issue is finding the human resources willing to work in primary care facilities, as national guidelines are very specific about it. Hospitals can be professionally more attractive than primary care facilities, and care professional shortage, especially nursing, is an issue of global concern [68,69], considering the central role of nurses in primary care enhancement. However, this is not a reason to give up on strengthening primary care, a vital strategy for all the reasons mentioned before. This problem goes beyond the focus on technology, unless care professionals are replaced by robots.

5. Conclusions

Ten years of healthcare technology development can turn the Covid pandemic from a disaster into an opportunity, as technology had the chance to spread its ordinary use [70]. Now that the emergency phase of the pandemic has been declared closed, digitalization and remote care technology can be used to preserve the quality and sustainability of universal health coverage over time, especially in the sensitive area of chronic patients and long-term care, where hospital care is frequently not appropriate and is still unable to bear the pressure.

NHS maintenance and primary care modernization are required to grasp the NextGeneration EU opportunity on time, and technology offers significant potential at multiple levels. Red flags should be considered by design, in order to rely on solid infrastructures rather than running for cover after huge investments have been made. Some limitations are probably intrinsic to the degree of technology as it is today, and may improve with technical improvements. Other can disappear within a couple of generations as they are due to demographic trends, professional culture and training. Others bring ethical, legal and safety concerns which cross technology development more generally.

Let us assume that all of this works: primary care will by considerably strengthened and the population that was previously underserved will be efficiently taken care of, even before they come to the hospital with an acute complication or emergency. The final question, on which we provocatively want to finish, is whether full coverage will itself be sustainable in aging countries. This question is crucial for an equitable allocation of limited resources and requires careful reflection on the breadth of health coverage these countries will be able to afford and justify in the coming decades.

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Scratch Where It Itches: Electronic Sharing of Health Information and Costs

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Abstract: The electronic sharing of health information holds the potential to enhance communication and coordination among hospitals and providers, ultimately leading to improved hospital performance. However, despite the benefits, hospitals often encounter significant challenges when it comes to sharing information with external parties. Our study aimed to identify the circumstances under which sharing information with external parties can result in changes in overall hospital costs, with a particular emphasis on various obstacles that hospitals may encounter, including lack of incentives or capabilities essential to facilitate effective information exchange. To achieve this goal, we obtain data from multiple sources, including the American Hospital Association (AHA) annual and IT surveys, the Center for Medicare and Medicaid Services (CMS) hospital compare dataset, and the Census Bureau's small-area income and poverty estimates. Consistent with previous research, we observed a significant reduction in hospital costs when information was shared internally but not externally. However, our findings also revealed that the sharing of health information can lead to cost savings for hospitals when they encounter challenges such as the absence of incentives and capabilities regardless of whether the information is shared internally or externally. The implication of our study is simple but strong: perseverance and effort yield positive outcomes. Only when hospitals push through challenges related to sharing information can they achieve the anticipated advantages of information sharing. Based on our results, we suggest that policymakers should strategically target hospitals and providers that face challenges in sharing health information rather than focusing on those without obstacles. This targeted approach can significantly increase policy efficiency, and we emphasize the need for policymakers to address the specific areas where hospitals and providers encounter difficulties. By doing so, they can effectively "scratch where it itches" and address the core issues hindering the successful exchange of health information.

Keywords: challenges; health information technology; information sharing; hospital costs

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1. Introduction

Sharing information across different healthcare organizations and providers is known to offer numerous advantages such as enhanced coordination, communication, and knowledge about patients [1]. For instance, when information is shared, hospitals are likely to achieve economies of scale and operational complementarity, thus reducing costs of care [2–4]. Also, hospitals are known to improve the quality of care by reducing preventable readmissions and duplicate laboratory and radiology tests when they share patient health records and clinical information with multiple stakeholders [5–7]. The prospective benefits of health information sharing were the foundation for the enactment of the Health Information Technology for Economic and Clinical Health (HITECH) Act, which is the part of the American Recovery and Reinvestment Act of 2009.

Despite the overall success of the HITECH Act in promoting the widespread adoption and utilization of health information technology, it appears that not all hospitals and providers are fully recognizing the anticipated advantages of information sharing. The impact of sharing information differs depending on factors such as the organizational setting (e.g., teaching status, integrated healthcare systems, and ER crowdedness) and patient-related aspects (e.g., severity level) [8]. Additionally, a recent study revealed that the benefits of information sharing do not arise, particularly when organizations and providers share information with those outside the system compared to those within the system [9].

These findings indicate that hospitals and healthcare providers encounter diverse and nuanced challenges when it comes to facilitating efficient and successful information sharing across various organizations and providers. A comprehensive review of the existing literature provided valuable insights into numerous critical challenges that contribute to the intricate nature of information sharing in healthcare. These challenges encompass a range of factors, including limited technical capability to electronically send or receive information, obstacles in accurately identifying and matching patients across disparate systems, concerns related to billing and financial transactions, time constraints, difficulties in accessing accurate healthcare provider addresses, etc. [10–12]. These challenges underscore the intricacies involved in achieving successful information sharing within the healthcare system.

Our study built upon prior research by expanding on the finding that the benefits of sharing information are less apparent when sharing it with external entities compared to internal ones. We aimed to explore the factors that hinder the realization of these benefits by delving into the underlying circumstances. Specifically, our study aimed to identify the circumstances in which sharing information with those outside the system can lead to changes in overall hospital costs, with a particular emphasis on the difficulties and challenges that hospitals may encounter, such as the absence of incentives or capabilities.

To achieve this goal, we first collected data from multiple sources, including the American Hospital Association (AHA) annual and IT surveys, the Center for Medicare and Medicaid Services (CMS) hospital compare, and the Census Bureau's small-area income and poverty estimates for the 2014–2016 period. We then estimated the association of information sharing and the costs of care at the hospital level. Similar to the previous literature [9], we found that the cost of care at the hospital level did not decrease when hospitals share information with those outside the system, while it did decrease with those inside the system. To our surprise, however, we found that the cost savings were salient when hospitals reported challenges such as the absence of incentives and capabilities regardless of whether they shared information with those inside and outside the system.

The findings of our study have several implications worth noting. In terms of research, this study contributes to the existing body of literature [8,9] by deepening our understanding of the diverse contexts that either enhance or hinder the impact of sharing health information. While previous findings indicated that different systems may impede the realization of improved outcomes through information sharing, our study revealed that regardless of a hospital or provider's system affiliation, the actual difficulties encountered during the process of sharing information serve as the primary determinants in generating the potential benefits. Therefore, it became evident that diligent efforts and perseverance can yield fruitful results.

For policy, our findings may help increase policy efficiency within limited resources. Policymakers should target hospitals facing challenges in ensuring information sharing rather than those without, as the ease of a task; that is, the lack of challenges, implies little room for improvement. The insignificant effects of sharing health information among hospitals that do not report challenges on cost savings suggest that they have already achieved the level at which the marginal benefit of sharing information with other stakeholders is only minimal. On the other hand, our results suggest that only hospitals that share information despite adversity can achieve the aforementioned benefits of sharing information. Using the findings from our study, policymakers can identify the groups in need and thus can direct resources toward those that are likely to have the grated impact; in other words, "Scratch where it itches".

The structure of the paper adheres to the following organization. In Section 2, we provide a detailed description of our data and model. Following that, in Section 3, we present the empirical results derived from our analysis and the discussion of these results. Finally, in Section 4, we offer the conclusions.

2. Materials and Methods

2.1. Data

We compiled data from multiple sources, including the American Hospital Association (AHA) annual and IT surveys, the Center for Medicare and Medicaid Services (CMS) hospital compare, and the Census Bureau's small-area income and poverty estimates for the 2014–2016 period. The AHA conducts these surveys annually and collects information on health IT, including obstacles to exchanging health data, vendor type, degree of electronic transitions, etc., as well as a hospital's general characteristics such as bed size, ownership type, payment, address, etc. The current study did not require review and approval from the institutional review board because the datasets utilized did not involve "human subjects".

2.2. The Model

While alpha (α) represents the y-intercept or the constant term, (β) indicates the sensitivity of the dependent variable with regard to the independent variable.

$$\begin{aligned} Hosptial\ Costs_{it} &= \alpha + \beta_1\ Information\ Sharing_{it} \\ &+ \beta_2 Bed\ Size_{it} + \beta_3 For - profit\ Ownership_{it} \\ &+\beta_4 Government\ Ownership_{it} + \beta_5 Teaching\ Hospital_{it} \\ &+\beta_6 Physician - Hospital\ Integration_{it} \\ &+\beta_7 Capitation\ Revenue\ Ratio_{it} \\ &+\beta_8 Urbanness_{it} + \beta_9 HHI_{it} \\ &+\beta_{10} Median\ Household\ Income_{it} + Year_t + \in i \end{aligned}$$

We collected our dependent variable (hospital costs) from the Medicare spending per beneficiary (MSPB) data obtained from the CMS hospital compare. This shows how much a hospital spends for an episode of care in relation to the national median. This is achieved by dividing each hospital's expenditure by the median of the national episode-weighted expenditure. Therefore, the unit of hospital costs was not relevant. This calculation allowed us to determine whether each hospital spent more, less, or approximately the same amount for an episode of care compared to all hospitals nationally. Also, by considering patient age and health status as well as geographic payment differences, this measure allowed us to control for patient characteristics indirectly.

We obtained data on our independent variables *(information sharing within the system* and *information sharing outside the system)* by utilizing a question from the AHA IT surveys that asked, "Which of the following patient data does your hospital electronically exchange/share with one or more of the provider types listed below?" The responses to this question were used to generate the variables of *information sharing within the system* and *information sharing outside the system*. We aggregated the responses to the aforementioned question to determine the overall value of *information sharing within the system*: (1) with hospitals inside of the respondent's system and (2) with ambulatory providers inside of the respondent's system. For the variable of *information sharing outside the system*, we calculated the total value of *information sharing outside the system* by summing the responses to the aforementioned questions: (1) with hospitals outside of the respondent's system and (2) with ambulatory providers outside of the respondent's system.

This implied that when the value of information sharing within the system was 0, the focal hospital did not electronically exchange information internally. Additionally, a value of 2 indicated that the focal hospital shared information electronically with both the hospital and the provider within the system. Similarly, a value of 1 suggested that they shared information with either the hospital or the provider internally. The same applied to the variable of information sharing outside the system. When the value was 0, it indicated that the focal hospital did not electronically exchange information with external parties. A value of 2 implied that the hospital shared information with both external hospitals and providers, and a value of 1 suggested that they shared information with either external hospitals or providers.

For our variables regarding difficulties that hospitals may face, we generated two binary variables: *capability-related challenges* and *incentive-related challenges*. The AHA IT survey also included the question, "Which of the following issues has your hospital experienced when trying to electronically (not eFax) send, receive or find (query) patient health information to/from other care settings or organizations? (Check all that apply)". *Capability-related challenges* was a dummy variable that assumed a value of 1 when respondents checked one of the following: (1) We lack the technical capability to electronically send patient health information to outside providers or other sources; (2) We lack the technical capability to electronically receive patient health information from outside providers or other sources; (3) Providers we would like to electronically send patient health information to do not have an EHR or other electronic system with the capability to receive the information; and (4) Providers we would like to electronically send patient health information to have an EHR; however, it lacks the technical capability to receive the information. The variable took a value of 0 in all other cases. *Incentive-related challenges* was also a dummy variable that assumed a value of 1 when respondents checked one of the following: (1) Many recipients of our electronic care summaries (e.g., CCDA) report that the information is not useful; (2) Cumbersome workflow to send (not eFax) the information from our EHR system; (3) Difficult to match or identify the correct patient between systems; (4) Difficult to locate the address of the provider to send the information (e.g., lack of provider directory); (5) We have to pay additional costs to send/receive data with care settings/organizations outside our system; and (6) We do not typically share our patient data with care settings/organizations outside our system. The variable took a value of 0 in all other cases.

Following the previous literature [4], we collected data on hospital or market characteristics from AHA annual and IT surveys and the U.S. Census Bureau's small-area income and poverty estimates to adjust for the factors that may influence hospital costs. The measurement of bed size involved the utilization of eight predefined codes derived from the AHA annual survey. Each code corresponded to the following bed size categories: (1) 6–24 beds, (2) 25–49 beds, (3) 50–99 beds, (4) 100–199 beds, (5) 200–299 beds, (6) 300–399 beds, (7) 400–499 beds, and (8) 500 or more beds. For ownership type, we included two dummy variables: *for-profit ownership* and *government ownership*. This implied that when both dummies were zero, it was a voluntary nonprofit hospital. We also controlled for teaching status, physician–hospital integration, and capitation revenue ratio, following the prior literature [4]. *Teaching hospital* was a binary variable that assumed a value of 1 when the hospital was a teaching hospital, whereas *physician-hospital integration* was a dummy variable that assumed a value of 1 when a hospital employed an integrated salary model in which physicians were hired as employees and a value of 0 in all other cases [13,14]. *Capitation revenue ratio* represented the percentage of a hospital's net revenue that was paid based on a fixed amount per patient for the provision of healthcare services. As control variables for market characteristics, we included *urbaneness*, the Herfindahl-Hirschman Index *(HHI)*, and *median household income*. The variable "*urbaneness*" was a binary indicator that assumed a value of 1 when the hospital was situated in an urban area and a value of 0 when it was located in a rural area. The *HHI* was calculated using the number of total facility admissions at the county level. While the variable representing *median household income* at the county level was sourced from the U.S. Census Bureau's small-area income and poverty estimates, all the remaining control variables were collected from AHA surveys.

3. Results

3.1. Empirical Findings

Table 1 presents descriptive statistics for a comprehensive set of 5947 hospital-year observations. Among these, the minimum hospital cost for an episode of care in relation to the national median was 0.61, whereas the maximum cost reached 1.70. Please note that hospital costs were measured by dividing each hospital's expenditure by the median of the national episode-weighted expenditure. This indicated that while it should not necessarily have been exactly 1, the mean of the hospital cost variable should have been close to 1. Also, the average bed size of 4.592 indicated that it fell somewhere between the ranges of 100–199 beds and 200–299 beds. Our sample comprised a variety of hospital types. For example, 97% of the hospitals were general hospitals, while the remaining included specialty hospitals such as heart, obstetrics and gynecology, orthopedic, and rehabilitation hospitals, among others. Moreover, our sample consisted of diverse hospital ownership types, including nonprofit (including church-operated), for-profit (individual, partnership, and corporation), and government hospitals (state, county, city, etc.). In our sample, 67% of the hospitals were nonprofits, 17% were for-profits, and the remaining hospitals were government-owned.

Table 1. Descriptive Statistics.

Variable	Mean	SD	Min	Max
Hospital costs	0.984	0.076	0.610	1.700
Information sharing within the system	1.685	0.582	0	2
Information sharing outside the system	1.543	0.740	0	2
Bed size	4.592	1.850	1	8
For-profit ownership	0.175	0.380	0	1
Government ownership	0.154	0.361	0	1
Teaching hospital	0.095	0.294	0	1
Physician–hospital integration	0.475	0.499	0	1
Capitation revenue ratio	0.074	0.261	0	1
Urbanness	0.768	0.422	0	1
HHI	0.591	0.355	0.027	1
Median household income	55,067.800	14,500.170	24,001	134,609
Capability-related challenges	0.766	0.423	0	1
Incentive-related challenges	0.626	0.484	0	1

Among our sample, 6.17% of hospitals reported that they did not share information with hospitals and providers within the system, while 14.93% of them reported not sharing information outside the system. Also, 77% of hospitals indicated that either they themselves or the providers receiving electronic information from them lacked the necessary technical capabilities. Additionally, 63% of hospitals reported facing various challenges such as the need to pay fees, a lack of a culture of information sharing with others, or encountering complex procedures that demanded additional effort.

Before explaining the results of the following three tables, we would like to highlight that our standard errors were clustered at the hospital level to account for potential correlation within each hospital. By clustering the standard errors at this level, we aimed to avoid overestimating the precision of the estimates and to provide more robust inference in cases where clustering or dependence within our data existed.

Table 2 shows the main results of our ordinary least squares (OLS) regression analyses based on STATA software regarding the effect of information sharing within and outside the system. Consistent with previous studies, we found that the coefficient of information sharing was negative and statistically significant for information sharing within the system, indicating a reduction in costs. However, the coefficient of information sharing outside the system was negative but statistically insignificant, suggesting it did not have a substantial impact on costs. Please note that our results suggest that providers and hospitals can achieve greater cost savings by sharing information with more insiders because the variables for information sharing within and outside the system were not binary. However, sharing information with more external parties did not have a significant impact on cost savings.

Table 2. The Impact of Information Sharing Within or Outside the System on Hospital Costs.

DV: Hospital Costs	(1)	(2)
Information sharing within the system	−0.007 *** [0.003]	
Information sharing outside the system		−0.003 [0.002]
Bed size	0.008 *** [0.001]	0.008 *** [0.001]
For-profit hospital	0.039 *** [0.004]	0.039 *** [0.004]
Government hospital	−0.005 [0.004]	−0.004 [0.004]
Teaching	−0.014 *** [0.004]	−0.013 *** [0.004]
Physician–hospital integration	−0.000 [0.003]	−0.001 [0.003]
Capitation revenue ratio	−0.008 * [0.004]	−0.008 ** [0.004]
Urbanness	0.019 *** [0.004]	0.018 *** [0.004]
HHI	−0.040 *** [0.005]	−0.040 *** [0.005]
Median household income	−0.000 [0.000]	−0.000 [0.000]
Constant	0.963 *** [0.010]	0.956 *** [0.009]
Observations	5947	5947
R-squared	0.179	0.177

Standard errors (in brackets) are clustered at the hospital level; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$; R-squared represents the proportion of the variance in the dependent variable.

Moreover, we observed a positive and statistically significant coefficient for bed size, which suggested the presence of diseconomies of scale rather than economies of scale. Additionally, the coefficient of for-profit hospital was positive and statistically significant, implying for-profit hospitals were more likely to offer services that are accompanied with the use of expensive equipment and procedures. The negative coefficient of teaching hospitals suggested that they can save costs compared to nonteaching hospitals. One possible explanation is that despite inconclusive findings as suggested by prior researchers [15–17], teaching hospitals may have had lower readmission rates and reduced follow-up costs, which ultimately resulted in lower overall costs compared to nonteaching hospitals [15]. The coefficients of physician–hospital integration and median household income were not statistically significant, implying that they did not significantly affect overall hospital costs. Moreover, the coefficient of capitation revenue ratio was negative and statistically significant. This indicated that providers under a capitation system, in which they receive a predetermined amount of payment per patient regardless of the actual services provided, had greater incentives to save costs compared to other revenue regimes. The positive coefficient of urbanness suggested that hospitals located in urban areas were more likely to offer costly services compared to those in rural areas. Lastly, the positive coefficient for HHI suggested that competition increased costs [18].

We conducted sub-sample analyses to observe whether the effect of information sharing with external parties varied with the existence of challenges, including lack of capabilities and incentives. First, we divided our sample into those that faced capability-related challenges (Table 3, column (1)) and those that did not (Table 3, column (2)). In addition, we divided our sample into those that faced incentive-related challenges (Table 3, column (3)) and those that did not (Table 3, column (4)).

Table 3. Impact of Information Sharing Outside the System in Relation to the Presence of Challenges.

DV: Hospital Costs	(1) Reporting of Capability-Related Challenges	(2) Nonreporting of Capability-Related Challenges	(3) Reporting of Incentive-Related Challenges	(4) Nonreporting of Incentive-Related Challenges
Information sharing outside the system	−0.004 * [0.002]	−0.002 [0.003]	−0.006 *** [0.002]	−0.000 [0.003]
Bed size	0.008 *** [0.001]	0.008 *** [0.002]	0.007 *** [0.001]	0.009 *** [0.001]
For-profit hospital	0.036 *** [0.004]	0.049 *** [0.008]	0.039 *** [0.004]	0.040 *** [0.005]
Government hospital	−0.005 [0.005]	−0.002 [0.007]	−0.001 [0.005]	−0.007 [0.007]
Teaching	−0.015 *** [0.004]	−0.008 [0.007]	−0.012 *** [0.004]	−0.016 *** [0.006]
Physician–hospital Integration	−0.002 [0.003]	0.004 [0.005]	−0.000 [0.003]	−0.001 [0.004]
Capitation revenue ratio	−0.010 ** [0.004]	−0.000 [0.007]	−0.013 *** [0.004]	0.001 [0.006]
Urbanness	0.018 *** [0.005]	0.019 *** [0.007]	0.024 *** [0.005]	0.009 [0.006]
HHI	−0.043 *** [0.005]	−0.030 *** [0.009]	−0.045 *** [0.005]	−0.033 *** [0.008]
Median household income	0.000 [0.000]	−0.000 [0.000]	0.000 [0.000]	−0.000 [0.000]
Constant	0.960 *** [0.010]	0.947 *** [0.016]	0.961 *** [0.010]	0.953 *** [0.014]
Observations	4556	1391	3723	2224
R-squared	0.186	0.146	0.203	0.151

Standard errors (in brackets) are clustered at the hospital level; *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Remarkably, we observed that the coefficients for information sharing outside the system were negative and statistically significant only in columns (1) and (3), while they were not significant in columns (2) and (4). These findings suggested that hospitals could effectively reduce costs through external information sharing only when they encountered substantial challenges related to capabilities and incentives. In other words, the prospective benefits of external information sharing could be realized by hospitals and providers solely when they overcame difficulties.

The results in Table 3 led us to further analyze whether the effect of information sharing within the system also varied with the existence of challenges, as shown in Table 4. As in Table 3, we divided our sample into those with capability-related challenges (Table 4, column (1)) and those without (Table 4, column (2)). In addition, we divided our sample into those with incentive-related challenges (Table 4, column (3)) and those without (Table 4, column (4)). As shown in Table 4, the coefficients of information sharing inside the system were negative and statistically significant only in columns (1) and (3) and not in columns (2) and (4).

Table 4. Impact of Information Sharing Within the System in Relation to the Presence of Challenges.

DV: Hospital Costs	(1) Reporting of Capability-Related Challenges	(2) Nonreporting of Capability-Related Challenges	(3) Reporting of Incentive-Related Challenges	(4) Nonreporting of Incentive-Related Challenges
Information sharing within the system	−0.009 *** [0.003]	−0.004 [0.004]	−0.009 *** [0.003]	−0.006 [0.004]
Bed size	0.009 *** [0.001]	0.008 *** [0.002]	0.008 *** [0.001]	0.010 *** [0.001]
For-profit hospital	0.036 *** [0.004]	0.048 *** [0.007]	0.038 *** [0.004]	0.039 *** [0.005]
Government hospital	−0.006 [0.005]	−0.002 [0.007]	−0.003 [0.005]	−0.008 [0.007]
Teaching	−0.015 *** [0.004]	−0.008 [0.007]	−0.012 *** [0.004]	−0.016 *** [0.006]
Physician–hospital Integration	−0.002 [0.003]	0.005 [0.005]	−0.000 [0.003]	−0.001 [0.004]
Capitation revenue ratio	−0.009 ** [0.004]	−0.000 [0.007]	−0.012 *** [0.004]	0.001 [0.006]
Urbanness	0.019 *** [0.005]	0.019 *** [0.007]	0.024 *** [0.005]	0.010 [0.006]
HHI	−0.043 *** [0.005]	−0.031 *** [0.009]	−0.046 *** [0.005]	−0.032 *** [0.008]
Median household income	0.000 [0.000]	−0.000 [0.000]	0.000 [0.000]	−0.000 [0.000]
Constant	0.968 *** [0.011]	0.950 *** [0.017]	0.968 *** [0.012]	0.959 *** [0.014]
Observations R-squared	4556 0.189	1391 0.147	3723 0.204	2224 0.153

Standard errors (in brackets) are clustered at the hospital level; *** $p < 0.01$, ** $p < 0.05$.

To our surprise, similar to what we found in Table 3, we found that the coefficients were negative and statistically significant only in columns (1) and (3) but statistically insignificant in columns (2) and (4). These results suggested that the presence of challenges played a key role in reducing hospital costs, not only when sharing information externally but also when sharing information internally.

3.2. Empirical Implications

Our findings indicated that hospitals and providers could achieve cost reductions through electronic data sharing both within their system and with external parties, but only when they face and overcome challenges and difficulties. This raised a question regarding why previous studies have shown that sharing information with external parties outside the system did not lead to the expected benefits. One possible explanation is that the mixed effects observed in those studies created a lack of clarity. Alternatively, it is plausible that hospitals and providers within the same system were better prepared to address the challenges associated with data sharing by utilizing alternative approaches when necessary.

There are several implications that can be derived from our study. In terms of research, it enhances our understanding of the factors that contribute to the attainment of prospective benefits, such as cost reduction or quality improvement, resulting from sharing health information electronically [8,9]. While previous findings suggested that different systems hindered the attainment of better outcomes through information sharing [9], our study demonstrated that this is not always the case. Hospitals can still face difficulties when they share information internally, and conversely, hospitals may not encounter any challenges even when they share information externally. Our study highlighted that the actual difficulties encountered during the information-sharing process, irrespective of whether it occurs across the boundaries of hospitals or not, ultimately determine the potential benefits. We believe that this distinction constitutes a novel contribution to the existing literature.

In terms of policy, our findings present opportunities to enhance policy efficiency. Specifically, policymakers should strategically target direct interventions toward hospitals that report challenges rather than implementing broad measures that encompass the entire population. Our findings strongly suggest that when challenges are scarce, the marginal effect of sharing information is minimal regardless of whether hospitals share information with those within or outside the system. More focus should be placed on addressing the actual obstacles and not the boundaries of hospitals. It is especially advisable to avoid solely relying on the previous literature and thus encouraging the sharing of information within the boundaries of hospitals. By focusing on those who face obstacles, policymakers can effectively target areas with the greatest potential for improvement. In other words, they should prioritize resolving the core issues and "scratch where it itches".

Nevertheless, our study identified a few limitations that open avenues to future research. Firstly, despite our efforts to control for factors impacting hospital costs based on the available datasets, it is crucial to acknowledge the presence of other variables that may still influence costs but were not included in our analysis. Additionally, due to data limitations, we lacked specific information regarding the precise changes in test or procedure volumes that contributed to the observed cost savings. Future researchers can delve deeper into understanding whether the impact of information sharing on test or procedure volumes varies in relation to the challenges encountered, thereby providing an additional dimension to our study. Moreover, future studies could explore other types of challenges such as differences in vendor platforms or legal environments across states. Specifically, although not discussed in this paper, patient privacy concerns are one of the barriers to information sharing [19] in the era of big data and artificial intelligence (AI). Future researchers can also examine whether the existence of other challenges can also affect the impact of sharing information on costs. Lastly, as our primary dependent variable was hospital costs, future studies can explore other outcome variables such as length of stay, readmission rates, and more. This expanded exploration would further enhance our understanding of the complexities involved in information sharing and its potential effects on hospital costs.

4. Conclusions

The sharing of health information has been recognized as having the potential to improve communication among healthcare providers and hospitals, leading to cost reductions and improved patient outcomes. However, realizing these benefits can be challenging for some hospitals. Building upon previous research that highlighted the benefits of sharing information within the system but not with external parties, our study aimed to investigate the factors that hinder the attainment of these benefits with a specific focus on the challenges faced by hospitals, such as a lack of incentives or capabilities.

By utilizing a diverse range of data sources, including the American Hospital Association (AHA) annual and IT surveys, the Center for Medicare and Medicaid Services (CMS) hospital compare dataset, and the Census Bureau's small-area income and poverty estimates for the period of 2014 to 2016, we found consistently across our results that hospitals and providers could effectively reduce costs through electronic data sharing whether within their own system or with external parties, but only when they confronted and overcame significant challenges.

The containment of overall hospital costs is of great interest to both researchers and policymakers. Our research highlighted the crucial significance of comprehending the diverse contexts in which the sharing of health information can either enhance or diminish its impact on cost savings. Furthermore, our findings emphasized a noteworthy opportunity to enhance policy efficiency by adopting a targeted approach. Instead of applying broad policies to the entire population, policymakers can focus their efforts on specific areas where hospitals and providers face challenges in electronically sharing health information. By addressing these specific pain points, policy interventions can lead to substantial cost savings. This approach would allow policymakers to "scratch where it itches," addressing the precise areas where improvements are most needed and maximizing the impact of policy interventions. As a result, significant savings in policy costs can be achieved while effectively addressing the barriers to information sharing and reaping the benefits it can bring.

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The Effect of Kinesio Taping Combined with Virtual-Reality-Based Upper Extremity Training on Upper Extremity Function and Self-Esteem in Stroke Patients

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Abstract: (1) Background: The purpose of this study is to investigate the effect of virtual-reality-based hand motion training (VRT) in parallel with the Kinesio Taping (KT) technique on upper extremity function in stroke patients and to present a more effective therapeutic basis for virtual reality training intervention. (2) Methods: First, 43 stroke patients were randomly assigned to two groups: 21 experimental subjects and 22 controls. The experimental group performed Kinesio Taping (KT) on the dorsal part of the hand along with virtual-reality-based hand motion training, and the control group performed only virtual-reality-based hand motion training. The intervention was conducted for a total of 30 sessions over 6 weeks. To evaluate changes in upper extremity function, the Fugl–Meyer Assessment of the Upper Extremity (FMA-UE), the Wolf Motor Function Test (WMFT), and the Motor Activity Log (MAL) (including amount of use (AOU) and quality of movement (QOM)) were evaluated. In addition, the Self-Efficacy Scale (SEF) was evaluated to examine the change in the self-esteem of the study subjects. (3) Results: The experimental group who participated in the virtual reality training in parallel with the KT technique showed statistically significant improvement (** $p < 0.01$) in the FMA-UE, WMFT, and MAL evaluations that investigate changes in upper extremity function. SEF evaluation also showed a statistically significant improvement (** $p < 0.01$). A statistically significant difference between the two groups was observed in the evaluation of FMA-UE, WMFT, MAL-QOM, and SEF († $p < 0.05$), showing that that combined intervention was more effective at improving upper extremity function than the existing VRT intervention. There was no statistical difference between the two groups in the MAL-AOU item, which is an evaluation of upper extremity function ($p > 0.05$). There was a statistically significant difference between the two groups in the amount of change in upper limb function (†† $p < 0.01$). (4) Conclusions: It was confirmed that virtual-reality-based hand motion training performed in parallel with the KT technique had a positive effect on the recovery of upper extremity function of stroke patients. The fact that the KT technique provided stability to the wrist by assisting the wrist extensor muscles appears to have improved the upper extremity function more effectively than VRT alone.

Keywords: stroke; upper extremity rehabilitation; hand function; virtual reality; Kinesio Taping

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1. Introduction

Stroke is a disease in which brain function is impaired because the blood supply is interrupted by blockage or rupture of a blood vessel in the brain due to a thrombus [1]. Stroke is the third leading cause of death in South Korea, and its aftereffects incur significant social costs [2]. Neurological symptoms in patients with stroke include motor, sensory, cognitive, language, and mood disorders, and these symptoms appear complex [3]. Among them, hemiplegia is the most common symptom in patients with stroke, and it causes movement disorders, which limit the range of daily living and social activities patients can participate in [4,5]. Restrictions on daily living and social activities in patients with stroke lead to a decrease in their quality of life and self-esteem. Therefore, to restore the ability to perform daily-living activities in patients with stroke, the upper extremity function should be restored to the hemiplegic side. Through this, basic daily-living activities such as eating, dressing, and hygiene management could be performed independently [6,7]. Currently, various therapeutic approaches are used in clinical practice to restore upper extremity function in patients with stroke, with evidence of their therapeutic effects [8,9]. A review of the literature on therapeutic approaches related to the recovery of upper extremity function in patients with stroke includes constraint-induced movement therapy, modified constraint-induced movement therapy, repetitive task training, bilateral training, electrical stimulation, virtual reality training (VRT), and robotic training [10,11]. Among them, upper extremity function training based on virtual reality has recently been highlighted in the rehabilitation field, for its ability to reorganize the brain through VRT [12]. VRT uses mirror neurons as the neurological background. The scientific principle is presented in Ref. [13]. Mirror neurons are mainly distributed in four places: the lower part of the premotor cortex of the frontal lobe, the lower part of the parietal lobe, the temporal lobe, and the front of the cerebral lobe. Mirror neurons send and receive signals and process information to learn perceived behaviors and movements [14,15]. In addition, various studies have suggested that virtual-reality-based upper extremity training improves upper extremity function in patients with stroke and has a positive effect on the performance of daily-living activities [16,17].

However, the VRT presented in the above literature is mostly shoulder and elbow joint movement training related to large movements, and VRT related to the most elaborate hand movements used in daily-life activities is lacking.

In addition, spasticity among patients with severe hemiplegia, which is the most frequent symptom of stroke, causes difficulty in controlling hand movements in virtual-reality-based fine-motor hand training [18]; thus, a smooth therapeutic approach becomes difficult. Although various interventions have been applied to reduce spasticity in patients with stroke, recent studies have reported the effects of the Kinesio Taping (KT) intervention as well as its advantages in convenience, safety, and economy. Kinesio Taping (KT) has been reported to be effective at (1) reducing inflammation and promoting range of motion through improvement of blood and lymph circulation, (2) relieving pain, and (3) increasing sensory feedback and movement in joints and muscles [19]. Kinesio Taping affects the fascia and stimulates elastic fibers through taping to help control muscle tone along with sensory stimulation during movement [20]. According to recent studies on the relationship between Kinesio Taping and muscle strength improvement, Kinesio Taping does not have a significant effect on muscle strength improvement, but results suggest that it can effect muscle fatigue reduction and support muscle activation [21]. In addition, KT can contribute to the improvement of hand movements by providing stability to wrist extensor muscles [22]. In this study, Kinesio Taping was performed together with virtual reality training to provide sensory feedback for the movement along with wrist extensor support during virtual-reality upper extremity movement training [23]. According to a study by Kim et al., when virtual training combined with Kinesio Taping was performed on patients with ankle instability, it did not affect static balance, but it did have a positive effect on dynamic balance ability. Although it does not help to improve muscle strength, it seems that it can be expected to play a supporting role in muscle activity during movement [24]. Therefore, we tried to find out what kind of changes in upper extremity function and self-esteem of stroke patients might be observed when virtual-reality-based hand motion training was performed together with Kinesio Taping. We intend to provide a complementary treatment basis for training interventions.

2. Materials and Methods

2.1. Participants

A total of 45 patients with stroke admitted to Rehabilitation Hospital B in Suwon, Gyeonggi-do, South Korea, were eligible for this study. In addition, all study participants signed a consent form for participation in the experiment. The selection criteria were as follows: diagnosed with a stroke within 6 months of the study start date; capable of following instructions, with an MMSE-K (Mini-Mental State Test-Korea version) score of 24 or higher; having a Brunnstrom stage of above 2 for the distal upper limb; capable of performing a slight hand grasp and slight finger extension, and possessing wrist extensor strength below the "poor" grade. The exclusion criteria were as follows: unilateral neglect and hemianopsia, hearing impairment, and intake of drugs related to spasticity. Of the 45 patients, 2 were excluded based on the selection criteria. Finally, a total of 43 patients participated in the study. There were no dropouts during the intervention. The sample size was calculated using the G-Power program 3.1 for the *t*-test of two groups at significance level 0.05, statistical power 0.8, and effect size 0.8 [25].

2.2. Procedure

This study was conducted from 4 May to 15 November 2020, and a total of 43 patients were divided into the experimental and control groups using a computer randomization method. A computerized (block) randomization scheme was used to randomize participants. The experimental group performed hand movement training based on virtual reality using a motion controller (Leap Motion, LM-010, San Francisco, CA, USA) along with KT (Nitto Kogyo Corporation, Kanihara, Japan), whereas the control group performed only hand movement training based on virtual reality. Both the experimental and control groups were trained for 40 min per session for a total of 30 sessions, 5 times a week for 6 weeks. Figure 1 shows the Consolidated Standards of Reporting Trials (CONSORT) diagram of participant recruitment.

2.3. Intervention

In the experimental group, Kinesio tape was directly applied by an occupational therapist to the dorsal part of the hemiplegic side, and the tape was attached from the dorsal part of the arm to the distal interphalangeal joint of each finger (Figure 2). The tension applied to the Kinesio tape was set to 50%, and it was set for the purpose of fixing and activating the wrist extensor [22,26]. Then, while sitting on a chair in front of a desk equipped with motion controller equipment, the patients were instructed to perform warm-up hand movements first so that the controller could recognize the movement of the affected hand in a straight-back position. Afterwards, they were asked to perform a training program of their choice (Figure 3). A total of six hand motion movement training programs were offered, based on virtual reality that allows patients to select and perform the program according to the difficulty they want and provide an additional explanation of the execution method according to the difficulty. The training program consisted of (1) petal tearing, (2) robot head fitting, (3) paper airplane flying, (4) paper airplane fitting, (5) block making, and (6) block stacking (Figure 4) [27]. The VRT participants performed warm-up exercises for hand movements, such as fist, scissors, and paper, and individual finger movements for the first 5 min. In the VRT, each participant selected a VRT program for 15 min each in the first and second halves, and a 5 min break was provided between the first and second halves of the program. The control group performed hand motion training based on virtual reality as in the experimental group, but the KT technique was not applied.

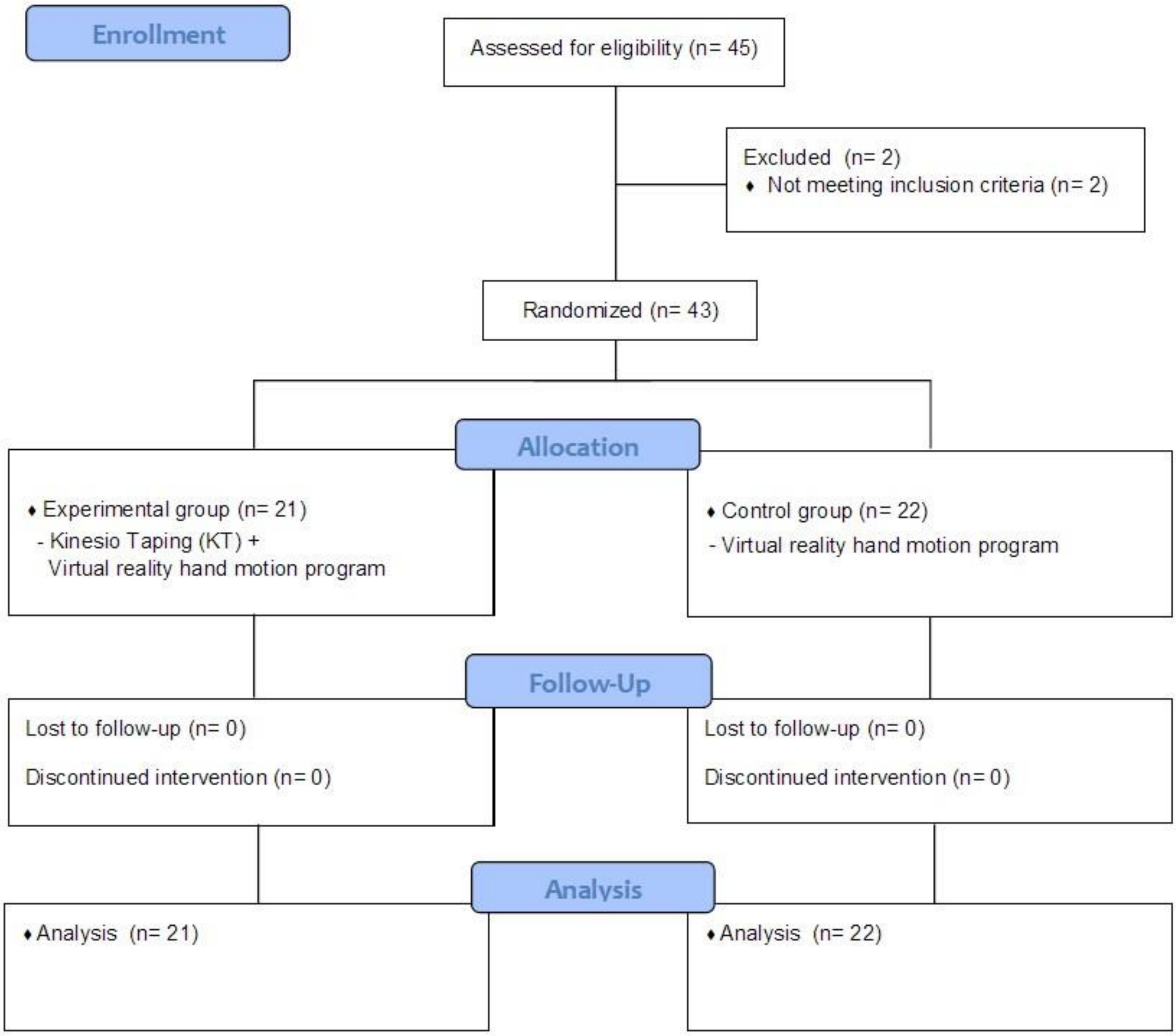
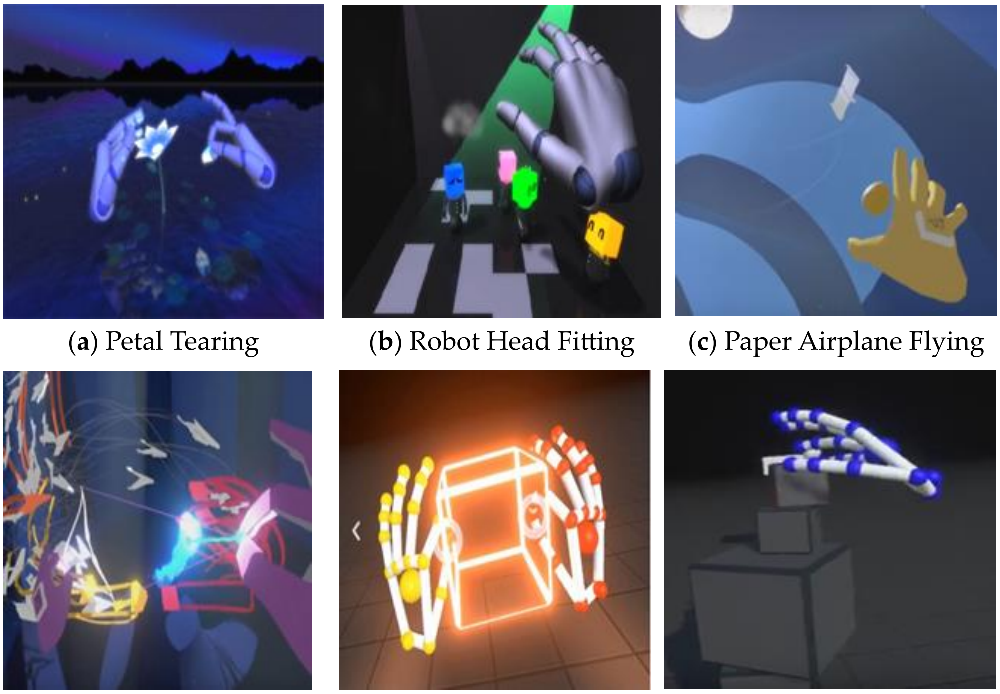


Figure 1. CONSORT diagram of participant recruitment.

Figure 2. Kinesio Taping applied to the dorsal part on the hemiplegic side.

Figure 3. Virtual-reality-based hand motion movement training.



(**a**) Petal Tearing (**b**) Robot Head Fitting (**c**) Paper Airplane Flying

(**d**) Paper Airplane Fitting (**e**) Block Making (**f**) Block Stacking

Figure 4. Virtual reality hand motion program.

2.4. Outcome Measures

2.4.1. Fugl–Meyer Assessment for the Upper Extremity (FMA-UE)

The Fugl–Meyer motor function evaluation is a modified Brunnstrom classification for the development of hemiplegia. In this study, only shoulder and elbow (18 items), wrist (5 items), hand (7 items), and upper extremity (3 items) coordination ability were evaluated during the Fugl–Meyer assessment, to evaluate only upper extremity function. Evaluation items were scored 0–2 points depending on the degree of performance: 0 points, not performed; 1 point, partially performed; and 2 points, completely performed. The overall score included all functions of the upper and lower limbs. However, in this study, only the upper extremities were evaluated; thus, the maximum score was 66. The reliability of the inspector for this evaluation tool is 0.96 [28,29].

2.4.2. Wolf Motor Function Test (WMFT)

The WMFT is a tool for evaluating upper extremity function in patients with stroke. The tasks are composed of progressing levels of functional movements of the upper extremities from a low-difficulty task to a high-difficulty task. It is evaluated using performance time, which measures the quantity of movement in the upper limbs, and the functional ability scale, which measures the quality of movement. The function score scale evaluates the quality of movement and consists of a 6-point scale with a lowest score of 0 (not performed) and a highest score of 5 (normal movement). The total score is 75 points, with higher scores indicating better upper extremity function. This evaluation tool has a high reliability of 0.88 [30].

2.4.3. Motor Activity Log (MAL)

The MAL, which was created by Taub in 1993, evaluates the quantitative use and qualitative movement of the affected hand during daily-living activities in patients with stroke, through forced–guided exercise therapy. This evaluation tool consists of 30 items related to daily-life behavior and is divided into Amount of Use (AOU) and Quality of Movement (QOM). The evaluation items include moving, doing housework, communicating, eating, dressing, and manipulating the environment. The tool consists of a 6-point scale, with scores ranging from 0 (not performing at all) to a maximum of 5 (performing as before onset). The evaluation score for each item is calculated by adding the total score and dividing it by the number of evaluation items. The internal consistency of this evaluation tool is a = 0.87 for the MAL-AOU and a = 0.90 for the MAL-QOM. Limits of agreement range from −0.70 to 0.85 for the MAL-AOU and from −0.61 to 0.71 for the MAL-QOM, indicating reproducibility sufficient to detect an individual change of approximately 12–15% of the range of the scale [31].

2.4.4. Self-Efficacy Scale (SEF)

The SEF was developed by Sherer and Maddux (1982), and a modified and supplemented tool for patients with stroke was used in Kim's study. The general SEF scale refers to the belief in one's abilities and consists of 14 items on a 10-point scale, ranging from 1 point (not at all confident) to 10 points (completely confident)—the higher the score, the higher the sense of self-efficacy. This evaluation tool has a high reliability of 0.92 [32].

2.5. Statistical Analysis

Data collected were statistically processed using SPSS Statistics for Windows, version 18.0 (SPSS Inc., Chicago, IL, USA). For the general characteristics of the study participants, the mean and standard deviation were calculated using descriptive statistics, and homogeneity was verified using the chi-square test. A paired *t*-test was used to examine changes in upper extremity function before and after the intervention in the experimental and control groups, and an independent *t*-test was performed to examine the differences between the two groups. An independent *t*-test was performed to compare the amount of change between the two groups before and after the experiment. The significance level for all statistical data was set at $p = 0.05$. In addition, the effect sizes (Cohen d) of the changed scores between the two groups were calculated. Effect sizes of 0.2, 0.5, and 0.8 represent small, moderate, and large effects, respectively.

3. Results

3.1. Participants' Characteristics

The general characteristics of the subjects who participated in the experiment are as follows. A total of 43 patients participated in this study; 21 participants in the experimental group underwent hand motion training based on virtual reality in parallel with KT and 22 participants in the control group received only hand motion training based on virtual reality. No significant difference was found between the two groups according to the participants' sex, age, stroke type, side of stroke, or time since stroke onset ($p > 0.05$). The general characteristics of the study participants are listed in Table 1.

Table 1. Characteristics of participants.

Characteristics	Experimental Group (*n* = 21)	Control Group (*n* = 22)	X^2/t	*p*
Age (year), mean ± SD	59.00 ± 12.66	63.09 ± 9.66	−1.186	0.243
Gender (male/female)	11/10	13/9	0.433	0.667
Type of stroke (Hemorrhage/Infarction)	11/10	15/7	−1.688	0.100
Side of stroke (Right/Left)	12/9	13/9	−0.741	0.463
Time since onset of stroke (months), mean ± SD [1]	3.81 ± 1.66	3.86 ± 1.28	−0.119	0.906

[1] SD: standard deviation.

3.2. Comparison of Changes in Upper Extremity Function in Groups before and after Intervention

Upper extremity function changes in the experimental group and control group before and after the intervention are as follows. In the experimental group, the FMA-UE score before and after the intervention improved from 22.00 ± 5.12 to 27.33 ± 5.25, showing a significant difference (** $p < 0.001$). In the control group, the FMA-UE score before and after the intervention improved from 22.41 ± 5.73 to 23.55 ± 6.03, and a significant difference was found (** $p < 0.001$). In the WMFT evaluation, the experimental group's score improved from 18.48 ± 4.78 to 21.71 ± 5.02, and a significant difference was noted (** $p < 0.001$). The control group also had an improved evaluation score, from 17.41 ± 8.23 to 18.05 ± 5.43 points, showing a significant difference (* $p < 0.05$) (Table 2). Finally, in the MAL-AOU items, the experimental group showed significant improvement (** $p < 0.001$) from 0.91 ± 0.32 before intervention to 2.41 ± 0.51 after intervention, and the control also improved from 1.13 ± 0.34 before intervention to 1.90 ± 0.60 after intervention (* $p < 0.01$). There was no statistical difference between the two groups in the MAL-AOU item ($p > 0.05$). In the MAL-QOM items, the experimental group showed significant improvement (** $p < 0.001$) from 0.94 ± 0.37 before the intervention to 2.09 ± 0.78 after the intervention, and the control group also improved from 1.15 ± 0.30 before the intervention to 2.15 ± 0.56 after the intervention, showing significant differences (** $p < 0.001$) (Table 2). Cohen's d effect size was 0.74, 0.5, 0.23, and 1.32 for the FMA-UE, WMFT, MAL-AOU, and MAL-QOM, respectively.

Table 2. Comparison of results between experimental group and control group.

	Experimental Group			Control Group			Between Groups *p*-Values
	Before Treatment	After Treatment	*p*-Value	Before Treatment	After Treatment	*p*-Value	
FMA-UE	22.00 (5.12)	27.33 (5.25)	<0.000 **	22.41 (5.73)	23.55 (6.03)	<0.000 **	0.034 †
WMFT	18.48 (4.78)	21.71 (5.02)	<0.000 **	17.41 (8.23)	18.05 (5.43)	<0.036 *	0.027 †
MAL-AOU	0.94 (0.37)	2.09 (0.78)	<0.000 **	1.15 (0.30)	2.15 (0.56)	<0.000 **	0.782
MAL-QOM	0.91 (0.32)	2.41 (0.51)	<0.000 **	1.13 (0.34)	1.90 (0.60)	<0.000 **	0.015 †
SEF	15.33 (3.74)	21.95 (4.21)	<0.000 **	15.64 (4.53)	19.05 (4.82)	<0.000 **	0.041 †

FMA-UE: Fugl–Meyer Assessment for the Upper Extremity; WMFT: Wolf Motor Function Test; MAL-AOU: Motor Activity Log Amount of Use; MAL-QOM: Motor Activity Log Quality of Movement; SEF: Self-Efficacy Scale. The values are mean ± standard deviation, * $p < 0.05$, ** $p < 0.001$ by Paired *t* test, † $p < 0.05$ by independent *t* test.

3.3. Comparison of Changes in Self-Efficacy within Groups before and after Intervention

Changes in self-efficacy in the experimental and control groups before and after the intervention are as follows. In the experimental group, the SEF score improved from 15.33 ± 3.74 points before the intervention to 21.95 ± 4.21 points after the intervention, showing a significant difference (** $p < 0.001$), and the control group also had an SEF score of 15.64 ± 4.5 points before the intervention, which improved to 19.05 ± 4.82 points after the intervention, showing a significant difference (** $p < 0.001$) (Table 2). Cohen's d effect size was 0.71 for the SEF.

3.4. Comparison of Changes in Upper Extremity Function and Self-Efficacy between Groups before and after Intervention

Changes in upper extremity function and self-efficacy between the two groups before and after intervention are as follows. The change in upper extremity function after the intervention between the experimental and control groups showed a significant difference only in the FMA-UE, WMFT, MAL-QOM, and SEF items († $p < 0.05$), and a significant difference was not noted in the remaining items ($p > 0.05$) (Table 2).

3.5. Comparison of Changes in Upper Extremity Function and Self-Efficacy in Groups before and after Intervention

Changes in upper extremity function and self-efficacy in the experimental and control groups before and after the intervention are as follows. The experimental group showed a significant change in FMA-UE, WMFT, MAL-QOM and evaluation scores, more than the control group (†† $p < 0.01$). In the SEF test, the amount of change in the evaluation score was significantly greater in the experimental group than in the control group († $p < 0.05$) (Table 3, Figure 5).

Table 3. Changes in both groups before and after Intervention.

	Experimental Group	Control Group	*p*-Value
FMA-UE	5.33 (4.32)	1.14 (1.16)	<0.000 ††
WMFT	3.24 (2.82)	0.64 (1.32)	<0.001 ††
MAL-AOU	1.15 (0.65)	0.99 (0.59)	<0.417
MAL-QOM	1.49 (0.48)	0.76 (0.73)	<0.000 ††
SEF	6.62 (4.85)	3.41 (2.88)	<0.011 †

FMA-UE: Fugl–Meyer Assessment for the Upper Extremity; WMFT: Wolf Motor Function Test; MAL-AOU: Motor Activity Log Amount of Use; MAL-QOM: Motor Activity Log Quality of Movement; SEF: Self-Efficacy Scale. The values are mean ± standard deviation, † $p < 0.05$, †† $p < 0.001$ by independent t test.

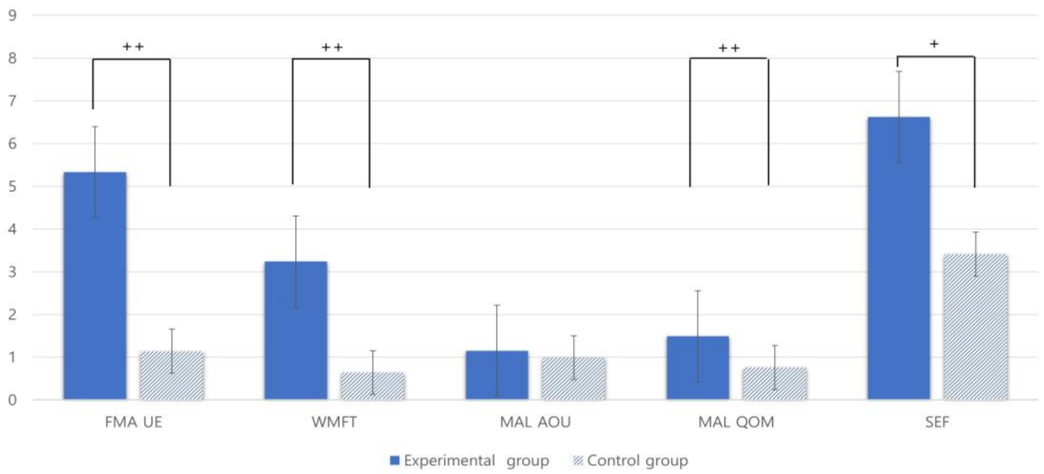


Figure 5. Changes in Both Groups before and after Intervention. The values are mean ± standard deviation, † $p < 0.05$, †† $p < 0.001$ by independent t test.

4. Discussion

This study aimed to investigate the effects of virtual-reality-based hand movement training in parallel with KT on upper extremity function and self-efficacy in patients with stroke. In this study, statistically significant improvement was shown not only in the experimental group, in which KT and VRT were performed in parallel, but also in the control group, in which only VRT was performed. In the evaluation results of the experimental group that performed KT and VRT in parallel, the upper extremity function improved overall after the intervention, and functional movements were mainly improved in the wrist and hand as a result of the FMA-UE and WMFT. In the FMA-UE evaluation, scores improved significantly in the movement items on the hand and wrist, and in the WMFT evaluation, the item involved in moving objects using the hands saw a significantly improved score. However, when compared to the minimal clinically important difference (MCID) value of the FMA-UE assessment tool in previous studies, the fact that the statistically significant difference in this study is not always meaningful to patients should be considered in future studies [33]. Following VRT for 18 sessions over 6 weeks in patients with chronic stroke, VRT was effective at improving upper extremity function [34], and VRT using Xbox, which was applied for 6 weeks, revealed consistent results for improving upper extremity function, except for the wrist [35]. However, unlike previous studies, KT was used to provide stability to the wrist and extensor muscles, the distal movement of the hand, and the proximal movement of the upper extremity caused by wrist stiffness and muscle weakness. Functional movement was improved. In addition, the SEF evaluation showed that self-esteem improved compared to before intervention in the experimental group that underwent both KT and VRT. These results were consistent with those in previous studies showing that patients' pain relief and self-esteem improved following the application of the KT technique in 30 patients with stroke, and [36] a virtual-reality-based game training program improved upper hand function and self-esteem in 42 hospitalized patients [37]. In the comparison between the experimental group and the control group, significant differences were found in the FMA-UE, WMFT, MAL-QOM, and SEF evaluation items. Considering these results, the stability of the wrist and proper extension motion are important factors for more effective restoration of upper extremity function in patients with stroke. There was no statistical difference between the two groups in the MAL-AOU item, which is an upper limb function evaluation, and the reason for this result is that both groups showed improvement in the MAL-AOU item after intervention. Through this, it was found that the frequency of use of the damaged upper limb can be improved only by intervention with virtual reality training. However, there was a difference between the two groups in the MAL-QOM item, indicating that the Kinesio Taping (KT) method, which played an auxiliary role in activating wrist muscles, had a positive effect on qualitatively improving upper limb movement. Moreover, when comparing the change in self-efficacy between the two groups, the experimental group showed a significant change. Restriction of hand function, which appears to be due to stiffness of the wrist and decreased muscle strength, limits participation in many daily-living activities, which appears to affect self-efficacy. The VRT systems used in previous studies have disadvantages in that they require expensive equipment and are subject to spatial limitations in performance. In addition, most of the previous VRT programs only performed training according to the proximal movement of the upper extremity while holding the controller in the hand, so there were many limitations in training for the most sophisticated hand movements used in daily living. Therefore, the KT and VRT systems used in this study are expected to be more effective at improving the distal movement of the upper extremity, that is, the functional movement of the hand.

This study has some limitations. First, the results of the study have limited generalizability due to the small number of participants. Second, it is difficult to ascertain the continuity of the treatment effect on the study participants. We hope that studies with a larger number of participants will be conducted to compensate for these limitations in the future. Prospective studies are needed to investigate the continuity of treatment effects over time. Finally, in the field of occupational therapy, a study is warranted to investigate whether virtual reality intervention for the recovery of upper extremity function in patients with stroke has a positive effect through interaction with other treatments.

5. Conclusions

In the results of this study, both VRT training and intervention methods combining VRT and KT were effective at improving the upper hand function of the study subjects, but virtual reality hand motion training combined with Kinesio Taping improved the upper hand function more effectively than the existing virtual reality hand motion training. From the research results, it was found that stability in the wrist is important for recovering the hand function of stroke patients, and the KT used in this study provides stability to the wrist through muscle activation that affects the wrist and finger elongation. Therefore, it seems that functional recovery in the upper extremity was more effective than when only the existing VRT training was conducted. In the future, when applying virtual-reality-based treatment to stroke patients, functional movement of the wrist should be considered. Finally, through this study, it is hoped that various therapeutic grounds for the study of therapeutic interventions based on virtual reality will be presented.

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healthcare

Article

Use of Digital Healthcare Communication to Improve Urologists' Surveillance of Lithiasis Patients Treated with Internal Urinary Drainage Pre- and Post-COVID-19 Period

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Abstract: The COVID-19 pandemic has greatly affected lithiasis patients, which has led to an increase in the number of internal stents that have been installed. In this paper, two studies were carried out, a clinical study and a quantitative study. The aim of the first study was to evaluate the incidence and the prevalence of bacterial urinary colonization in patients with obstructive urolithiasis who needed internal stents implanted. In the second study, a multiple linear regression was created to identify the opinion of urologists regarding the importance of using digital technologies to improve the communication process. The result of the clinical study illustrates that the prevalence of urinary colonization in patients with internal stents carried out for obstructive urolithiasis was 35%, with this value being influenced by co-infection with COVID-19. The results of the quantitative study illustrated the fact that urologists are open to using new online technologies to facilitate communication with patients. The results have high importance for both doctors and patients, illustrating the main factors that have the ability to influence the communication process. The hospital managers should take into account the results obtained in this study when they choose to use certain online communication technologies with patients.

Keywords: internal stents; obstructive urolithiasis; COVID-19; disruptive technologies; online communication

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1. Introduction

1.1. The Use of New Communication Technologies in the Medical Field

According to the World Health Organization (WHO), e-Health is the use of information and communication technology in health and other related fields [1]. Information and communication technologies (ICTs) have also been introduced in the health sector, with many healthcare departments being positively influenced by their use. The use of ICT in health is a means of supporting this field of activity [2]. The use of various technological tools in medical facilities can significantly help employees, and especially nurses, as well as medical service providers in general, to improve the level of medical care provided to patients. These technologies contribute to improving the quality of services provided, as well as other evaluation indicators in this field of activity [3]. There is a wide range of information and communication technologies used to support and deliver healthcare. Mair [4] proposed four general areas to be included in the e-health system that include a variety of ICTs. These are management systems, communication systems, electronic decision support systems and information systems. Management systems enable the acquisition, storage, transmission and display of administrative or clinical activities related to patients, such as electronic health records (EHRs) [4].

The European Union states that applying eHealth to the whole range of professions in the health sector has the potential to break fresh ground to access healthcare and increase the overall efficiency of the health sector. According to the European Commission, eHealth and telemedicine are based on the freedom of movement of services applicable to healthcare through the Directive on Electronic Commerce. eHealth is an emerging field at the crossroads of three fields: medical informatics, public health and business. The World Health Organization (WHO) has defined eHealth as "the cost-effective and safe use of ICT in support of health, related fields and research" [5]. Telemedicine [6] is the provision of assistance services and medical information using innovative technologies, especially ICT, in situations where a medical professional and the patient (or two medical professionals) are in different locations. Telemedicine [7] covers only the curative aspect of the healthcare sector and includes any remote interaction between patients and healthcare professionals and between healthcare professionals, whether synchronous or asynchronous. A generally accepted definition in several European countries is the one offered by the European Commission: according to which, telemedicine has the role of improving prevention, diagnosis, treatment, monitoring, health management and lifestyle.

mHealth (mobile health) [8] is one of the components of eHealth that is based on technologies such as smartphones and digital assistants in order to provide information and care services in the medical field. Among the services provided, the following can be mentioned: health monitoring, disease reporting and useful information for a healthy lifestyle. The use of mHealth tools [9] can favor an increase in primary and preventive health services used, the collection of specific data, the establishment of a treatment plan and the timely submission of medical analysis results [10]. Digital tools specific to the medical field, such as electronic medical records, data registries, portable monitoring or reporting devices, electronic therapy and educational platforms have the potential to improve access to health and provide personalized services for patients [11]. Digital devices that integrate data into services and electronic support for decisions, resources and interventions improve patient–provider communication [11].

1.2. The Importance of Using Internal Stents in Urology

The use of internal stents has become a current practice in urology departments worldwide. Made of polyurethane or silicone, the internal stent is flexible and autostatic, with curved ends that allow it to be held between the kidney at its upper end and the urinary bladder at its lower end [12–14]. Regardless of the purpose of its insertion—preventive, curative, palliative or other indications, the internal stents must ensure the flow of urine from the kidneys to the bladder [15,16]. Once inserted, the time of indwelling of the internal stents may vary from a few days to a few months, depending on the indication. Its removal moment must be chosen carefully, considering that a too-short period can be ineffective, and a too-long period can lead to complications (calcifications, obstructions, etc.) [17–19]. Only a few studies have been performed for the evaluation of the incidence and prevalence of patients with bacteriuria and urinary colonization among internal stent carriers, regardless of their indication. Additionally, studies on urinary tract infections usually include all patients with significant bacteriuria, symptomatic or not, without actually separating infections from urinary tract colonization [20,21]. In complicated urolithiasis with complete obstruction and/or secondary infection, an endo-prosthesis may be temporarily required, whatever the surgical method subsequently approached [22]. An ultrasound-guided percutaneous nephrostomy would be performed in the case of physiological urinary drainage failure [23]. The bacteria that colonize ureteral endoprosthesis develop in colonies, adhere to the internal stents, multiply and secrete "slime" as an extracellular polysaccharide matrix, in which salts and urinary proteins are subsequently incorporated [24,25]. This biofilm favors the adhesion of germs, protecting them from defense mechanisms and microbial agents [26–29].

The COVID-19 pandemic has greatly affected the work carried out by urologists. During it, medical personnel were put in a position to solve complex problems that they had not faced until that moment. In addition, patients with kidney problems who became infected with the SARS-CoV-2 2 virus showed some additional reactions that required immediate intervention by physicians. The complexity of the urological problems that appeared during the COVID-19 pandemic in lithiasis patients, as well as the difficulty of communicating with them due to the restrictions imposed at the national level, led us to carry out a thorough analysis of the problems that appeared in patients treated with internal stents, as well as how communication with them could be improved, in order to reduce possible complications that may arise later, due to non-compliance with the deadlines for extracting/changing medical devices. The research included two studies, namely, a clinical study and a quantitative study. The clinical study aimed to identify the incidence and prevalence of urinary bacterial colonization in patients with obstructive urolithiasis treated with internal stents during the COVID-19 pandemic. The second study had, as its starting point, the clinical results obtained following the conducting of the first clinical study, as well as physicians' opinions regarding the communication problems that arose during the COVID-19 pandemic between patients and physicians due to the restrictions imposed at the national level. Based on these results, a quantitative study was carried out that had the role of determining the perception of Romanian urologists regarding the role and importance of the use of new technologies in terms of improving the communication process with lithiasis patients pre- and post-COVID-19 period.

2. Materials and Methods

2.1. Clinical Study

Clinical Study Design and Research Sample

The clinical study was carried out in the Urology Department of "Dr. Carol Davila" Central Military Emergency University Hospital, between January 2020 and June 2022 (the hospital was not assigned as a COVID-19 support hospital), using a batch of 212 patients. The inclusion criteria were as follows: any patient with an indwelled internal stent for obstructive urolithiasis, who gave his/her consent to participate in the study whatever their sex, age, comorbidities and complications. Patients who did not agree to participate in the study and pregnant women were excluded (there is no integrated Obstetrics—Neonatology department within "Dr. Carol Davila" Central Military Emergency University Hospital). Pre-operative biochemical evaluations and bacteriological examinations (urinary and internal stent sampling) were performed in D0, D2, D30 and D60 dynamics, on non-selective media (BCP = bromocresol purple lactose and CLED = cystine–lactose–electrolyte-deficient). RT-PCR tests were carried out for patients with suspected COVID-19 disease during hospitalization (14 patients were detected as being COVID-19-positive). A probabilistic antibiotic treatment was administered for 5 days (2 days Cefort and 3 days Levofloxacin) in the case of positive bacteriology. All collected data were statistically analyzed using IBM SPSS software.

2.2. Statistic Survey

2.2.1. Survey Design and Research Sample

In order to fulfill the purpose of the research, a quantitative study was carried out using 108 urologists working in Romania. The research was carried out between January 2023 and February 2023. The sampling method that was used in this study was that of the snowball. The questionnaire was sent to the doctors that were working at this moment in some hospitals. After that, they were asked to forward the questionnaire to their colleagues (urological doctors) working in the same unit. The data collection was performed with the help of a questionnaire that was posted on an online platform and distributed to the respondents.

The first question was a filter and had the role of selecting only those who were part of the research community, namely the urologists in Romania. At the end of the questionnaire, there were several questions that had the role of building the profile of the respondents who participated in this study. In the questionnaire were also questions aimed at identifying the doctors who had installed internal stents so far, as well as the frequency with which they had installed such medical devices. In the questionnaire, there were also questions that had the role of presenting the experience of doctors with the lithiasis patients from a communication process perspective. Thus, through the questions from the questionnaire, we identified the communication difficulties encountered by doctors, the main problems caused by faulty communication and the opinion of the doctors regarding how new technologies can help them to improve the communication process with their patients.

The other questions had the role of fulfilling the purpose of the research. In order to measure the relationship between the variables, a 7-point Likert scale was used. The dependent variable at the level of the linear multiple regression model was the perception of physicians regarding the importance of using new technologies to improve the communication process with lithiasis patients treated via internal urinary drainage pre- and post-COVID-19 period. The independent variables analyzed at the level of the regression model were the advantages perceived by urologists regarding new technologies of online communication with lithiasis patients, the perceived disadvantages, the perceived risks, the current communication process with lithiasis patients, the experience of urologists in using new communication technologies, the trust of urologists in new online communication technologies, the empathy (openness of physicians) in using new online communication technologies, the security of new online communication technologies, the cost of new online communication technologies, the notoriety of new online communication technologies, the image of new technologies of online communication among urologists and patients' access to new communication technologies, as well as the possibility of conducting training among patients regarding the use of these applications.

2.2.2. The Hypotheses That Were the Basis of the Quantitative Study

H1: *The advantages perceived by urologists regarding new online technologies have a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H2: *The disadvantages perceived by urologists regarding new online communication technologies have a direct and negative impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H3: *The risks perceived by urologists regarding new online communication technologies have a direct and negative impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H4: *The current communication process with lithiasis patients has a direct and negative impact on the perception of physicians regarding the importance of using new technologies to improve the communication process with lithiasis patients.*

H5: *The experience of urologists in using new communication technologies has a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H6: *The confidence of urologists in new online communication technologies has a direct and positive impact on the perception of physicians regarding the importance of using them to improve the communication process with lithiasis patients.*

H7: *The physicians' empathy in using new online communication technologies has a direct and positive impact on the physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H8: *The security of new online communication technologies has a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H9: *The cost of new online communication technologies has a direct and negative impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H10: *The notoriety of new online communication technologies has a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H11: *The image of new online communication technologies among urologists has a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H12: *Patients' access to new communication technologies has a direct and positive impact on physicians' perception of the importance of using them to improve the communication process with lithiasis patients.*

H13: *The possibility of training in the use of new communication technologies has a direct and positive impact on the perception of physicians regarding the importance of using them to improve the communication process with lithiasis patients.*

3. Results

3.1. Clinical Study Results

The study group included 212 patients, and of which 127 were men (60%) and 85 were women (40%), with a sex ratio M/W of 1.49. The average age of the patients was 55 years old, with extremes of 19 and 80 years old. Fourteen patients were found to be COVID-19-positive during hospitalization, remaining asymptomatic. They presented hyperalgesic nephritic colic or calculi larger than 5 mm in diameter, which were non-pelvic/meatal-located, with little chance of spontaneous elimination. In the present study, the indication for the internal stent was complicated urolithiasis in 82% of the cases (174 patients) with uretero-hydronephrosis, bilateral in 39% of the cases (68 patients) and unilateral in 61% of the cases (106 patients). From the point of view of urinary stone localization, the distribution was as follows: 28% on the right (59 patients) and 72% on the left (153 patients); 52% pelvic ureteral stones (110 patients) and 48% pyelic lithiasis (102 patients).

A group of 98 patients (46%) presented acute kidney failure, with the consequence of ischemic parenchymal atrophy secondary to uretero-hydronephrosis, requiring the internal stent insertion in emergency mode. In the other 54% (114 patients), the act was performed via medical appointment. There was a spontaneous expulsion of the stone after the insertion of the internal stent in 95 patients with pelvic ureteral lithiasis (45% of the group), probably due to ureteral dilatation secondary to the presence of the endoprosthesis. Urine monitoring revealed positive bacteriology in 11% of the group (23 patients), pre-operatively on day 0 (D0) and post-operatively for 19.5% (41 patients) on the second day (D2), 28% (59 patients) on day 30 (D30) and 35% (74 patients) on day 60 (D60) (Table 1).

The study revealed an internal stent colonization rate of 39% (83 patients) versus a urinary colonization rate of 35% (74 patients). Eight COVID-19-positive patients presented urinary colonization, representing a rate of 58%.

Table 1. Positive urinary bacteriology.

Number of Days of Double Internal Stent Insertion	Positive Urinary Bacteriology	
	Number of Patients	%
D_0	23	11
D_2	41	19.5
D_{30}	59	28
D_{60}	74	35

Source: clinical study conducted by the authors.

Table 2 presents the different germs that were identified, with the predominance of *Escherichia coli*, *Klebsiella pneumoniae* and *Enterococcus faeccalis*, both at the urinary level and in the ureteral stents.

Table 2. The bacterial germs identified at the urinary level and in the ureteral stents.

Bacterial Germ	Number of Patients	
	Urinary-Colonized	Internal-Stent-Colonized
Escherichia coli	23	31
Klebsiella pneumoniae	17	13
Enterococcus faecalis	14	16
Enterobacter cloaecae	2	4
Serratia marcescens	2	0
Staphylococcus hominis	5	0
Staphylococcus aureus	2	10
Others	9	9

Source: clinical study conducted by the authors.

The monitoring of the bacteriological profile of the urine for the group of 129 patients with non-colonized internal stents showed that only 19 patients (15%) presented subsequent urinary colonization, and 85% (110 patients) remained urinary-non-colonized. In the group of patients with colonized internal stents (83 patients), only 15 (18%) remained bacteriologically negative throughout the study, and 68 patients (82%) had one or more episodes of urinary tract infection.

The colonization of ureteral internal stents plays an essential role in the pathogenesis of urinary infections, increasing their occurrence. In this study, 98 patients (46%) with urolithiasis had emergency internal stent insertion, and 62 (64%) of them had internal stents colonized at D60. The other 114 patients had the internal stent insertion carried out via appointment, and only 30 (27%) of them had colonized internal stents at D60.

3.2. Statistical Study Results

Analyzing from the perspective of the profile of the respondents, it should be stated that 4.6% of those who participated in the study were women, while 95.4% of the physicians were men. Regarding the distribution according to the age of the respondents, 49.1% of those who participated in the study were aged between 36 and 45, and 25.9% of them were aged between 46 and 55, while 25% of them were aged between 25 and 35. Regarding the institution where they worked, 79.6% of the urologists who participated in the study mainly worked in a state medical facility while 20.4% of them worked in the private system.

The results of the quantitative study illustrated the fact that all of the physicians who participated in the research had, up until now, mounted at least one internal stent. Regarding the frequency with which they resorted to this medical procedure, 10.2% of those who participated in the study stated that, daily, they were involved in an internal stent installation/extraction procedure, 24.1% of them stated that they used this medical technique 2–3 times a week, 32.4% of them specified the fact that they had patients who required such a procedure once a week and 20.4% of the respondents specified the fact that they used this medical technique 2–3 times a month. A smaller part of the respondents (13%) stated that they used this technique less often, more precisely once a month. Regarding the process of communication with lithiasis patients, 88% of those who participated in the study stated that they encountered difficulties because patients did not show up for appointments to replace or extract the mounted internal stent, which led to the appearance of certain complications. The main problems identified by urologists following poor communication with lithiasis patients were delays in changing internal stents (51.9%), delays in removing internal stents (22.2%) and balms regarding the prescribed treatments (12%), as well as a series of adverse effects that were not treated in time due to poor communication (13.9%) (Table 3).

Table 3. Problems arising from poor communication with lithiasis patients.

Outcomes of Poor Communication with Lithiasis Patients	Frequency	Percentage (%)
Delays in changing internal stents	56	51.9
Delays in the extraction of the internal stents	24	22.2
Problems regarding prescribed treatments	13	12.0
The occurrence of adverse effects following the installation of the internal stents	15	13.9

Source: statistical study conducted by the authors.

All of these problems arising from poor communication with patients have led to the emergence of ailments among them. Thus, 50% of the urologists mentioned the fact that all of these caused damage to the kidney, 11.1% of them stated that some patients lost their kidneys because they did not come to a medical facility in time, 10.2% of the physicians specified the fact that all of the problems caused trouble in mounting a new internal stent and 1.9% of them specified the fact that some delays led to the impossibility of mounting a new internal stent. A total of 26.9% of those who participated in the study specified other medical problems that the patients faced because they did not come to a medical facility in time.

Regarding the extent to which new technologies could help urologists to improve their communication with patients and reduce the risks that may arise due to poor communication, 92.6% of those who participated in the study stated that new technologies have the ability to improve the communication process with lithiasis patients, while 7.4% of them stated that they were not so effective in solving this problem.

The Proposed Multiple Linear Regression Model

At the level of the quantitative research, a multiple linear regression model was created that aimed to determine how the independent variables at this level had the ability to influence the dependent variable. To analyze the multiple linear regression model, we used the analysis of variance method (ANOVA). This method helped us to identify the relationship between the dependent variables and the independent variables. The data were analyzed using the SPSS program.

The dependent variable analyzed at the level of the linear regression model was the physicians' perception of the importance of using new online technologies to improve the communication process with lithiasis patients treated via internal urinary drainage pre- and post-COVID-19 period. The independent variables considered were as follows: the advantages perceived by urologists regarding new online communication technologies, the perceived disadvantages, the perceived risks, the current communication process with lithiasis patients, the experience of urologists in using new communication technologies, the confidence of urologists in new online communication technologies, the empathy (physicians' openness) in using new online communication technologies, the security of new online communication technologies, the cost of new online communication technologies, the awareness of new online communication technologies, the image of new online communication technologies among urologists, patients' access to new communication technologies and the possibility of training patients regarding the use of these technologies.

A multiple linear regression model was carried out, based on the following formula:

$$Y = \beta 0 + \beta 1 \times X1 + \beta 2 \times X2 + \beta 3 \times X3 + \beta 4 \times X4 + \ldots + \beta n \times Xn + \varepsilon$$

The components of this formula are as follows: Y (the dependent variable); $\beta 0$ (the constant); $\beta 1 - \beta n$ (β coefficients for the independent variables); $X1 - Xn$ (the model parameters estimation) and ε (the standard error).

Starting from this formula, the multiple linear regression model was drawn up for the study:

Physicians' perception of the importance of using the new technologies to improve the communication process with lithiasis patients treated by internal urinary drainage before and post-COVID-19 period = $\beta 0 + \beta 1 \times$ The advantages perceived by urologists regarding new online communication technologies with lithiasis patients + $\beta 2 \times$ The perceived disadvantages + $\beta 3 \times$ The perceived risks + $\beta 4 \times$ The current communication process with lithiasis patients + $\beta 5 \times$ The experience of urologists in the use of new communication technologies + $\beta 6 \times$ The confidence of urologists in new online communication technologies + $\beta 7 \times$ The empathy (physicians' openness) in the use of new online communication technologies + $\beta 8 \times$ The security of new online communication technologies + $\beta 9 \times$ The cost of new online communication technologies + $\beta 10 \times$ The notoriety of new online communication technologies + $\beta 11 \times$ The image of new online communication technologies among urologists + $\beta 12 \times$ Patients' access to new communication technologies + $\beta 13 \times$ The possibility of carrying out training among patients + ε.

Regarding the reliability of the scale, it was calculated using Cronbach's alpha coefficient. In this statistical study, the indicator was 0.746 > 0.7, highlighting in this way the viability of the variables that was taken into consideration in the linear model regression (Table 4).

Table 4. Reliability statistics.

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
0.746	0.759	13

Source: statistical study conducted by the authors.

Regarding the results obtained at the level of the linear multiple regression model, it should be stated that the value of R is 0.775 while that of R square is 0.600 (Table 5). This aspect illustrates the fact that 60% of the variation in physicians' perception regarding the importance of using new technologies to improve the communication process with lithiasis patients treated via internal urinary drainage pre- and post-COVID-19 period is explained by the independent variables that were taken into account at the level of the model.

When analyzing from the perspective of the validity of the model, it can be observed that the value of Sig. is 0.000. Since this value is less than 0.05, the model is considered to be a valid one. From the table above (Table 6), it can be seen that the standard error has a value of 1.056, while the value of F is 10.862. At the analysis level, there are 13 degrees of freedom (df) and the mean square value is 12.104 (Table 6).

Table 5. Indicators of the multiple linear regression model.

Indicators	Validation Criteria
R	0.775
R Square	0.600
Adjusted R Square	0.545
Std. Error of the Estimate	1.056
R Square Change	0.600
F Change	10.862
df1	13
df2	94
Sig. F Change	0.000

Source: statistical study conducted by the authors.

Table 6. ANOVA table.

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	157.353	13	12.104	10.862	0.000
Residual	104.749	94	1.114		
Total	262.102	107			

Source: statistical study conducted by the authors.

In the table of coefficients (Table 7), it can be seen that not all of the independent variables can be taken into account at the level of the multiple linear models, because the value of Sig. for these is greater than 0.05. The variables that were not taken into account were the security of new online communication technologies, the cost of new online communication technologies, the notoriety of new online communication technologies, the image of new communication technologies among urologists, the access of patients to new communication technologies and the possibility of carrying out training among patients regarding the use of these new technologies.

Based on the results obtained previously, the formula of the linear multiple regression model is as follows:

Physicians' perception of the importance of using the new technologies to improve the communication process with lithiasis patients treated by internal urinary drainage pre- and post-COVID-19 period = 7.182 + 0.785 × The advantages perceived by the urologists regarding new communication technologies with lithiasis patients was − 0.666 × The perceived disadvantages were − 0.265 × The perceived risks were − 0.206 × The current communication process with lithiasis patients was + 0.341 × The experience ofurologists in the use of new communication technologies was + 0.250 × The confidence ofurologists in new online communication technologies was + 0.586 × The empathy (physicians' openness) in the use of new online communication technologies was + 1.056.

Table 7. Table of coefficients.

Model	Unstandardized Coefficients		Standardized Coefficients	Sig.
	B	Std. Error	Beta	
(Constant)	7.182	1.029		0.000
The security of new online communication technologies	−0.030	0.109	−0.029	0.786
The current communication process with lithiasis patients	−0.224	0.110	−0.206	0.045
The cost of new online communication technologies	0.013	0.111	0.012	0.909
The notoriety of new online communication technologies	−0.090	0.070	−0.106	0.204
The risks perceived by urologists	−0.305	0.131	−0.265	0.022
The advantages perceived by urologists	0.867	0.194	0.785	0.000
The image of new communication technologies among urologists	−0.175	0.183	−0.150	0.343
The experience of urologists in the use of new communication technologies	0.342	0.147	0.341	0.022
The disadvantages perceived by urologists	−0.742	0.201	−0.666	0.000
Patients' access to new online communication technologies	−0.278	0.185	−0.176	0.136
The confidence of urologists in new online communication technologies	0.335	0.157	0.250	0.035
The possibility of carrying out training for lithiasis patients	−0.242	0.134	−0.195	0.075
Physicians' empathy toward new online communication technologies	0.577	0.123	0.586	0.000

Source: statistical study conducted by the authors.

4. Discussion

The COVID-19 pandemic has caused a series of problems for both physicians and patients. The restrictions imposed at the national level as well as the fear of infection with the new virus led patients to be more fearful and to cancel the appointments that they had, even though they suffered from certain conditions that required urgent interventions. For lithiasis patients, this was a real problem, as delays in changing or extracting the internal stents led to complications, which caused physicians to face some difficulty in solving these problems. Considering these things, it must be stated that new technologies have a very important role in terms of improving the communication process with lithiasis patients. Thus, e-health [30], mobile health [31] and telemedicine [32,33] are just some of the technologies that can be used to improve the healthcare industry [34]. Healthcare providers around the world are constantly adopting various technologies to meet increasing regulatory requirements for patient care and safety. In addition, they address two important perspectives: the growing need to reduce healthcare costs as well as the need to continuously improve the quality-of-care services, while maintaining the operational efficiency of healthcare organizations [35].

Communication systems can be used to fulfill several objectives related to aspects of diagnosis, management, counseling, education and support. They can be applied to facilitate communication between healthcare professionals or between professionals and patients. There is a wide range of communication systems, from e-mail and mobile phones to telemedicine and telehealth systems. Decision support systems are automated systems accessible from various devices such as computers, mobile phones or personal digital assistants (PDAs) [36]. They support decision-making for healthcare professionals and help them to practice various activities in accordance with clinical guidelines and care plans. Information systems, such as web-based resources and e-health portals, refer to the use of Internet technology to access medical information sources [37].

The term eHealth [38,39] can describe "a technical development, a state of mind, a way of thinking, an attitude to improve the health sector at the local, regional and global level through the use of information and communication technology" [40,41]. The current trend in eHealth systems is to focus on the patient. Thus, the patient actively takes part in the management of his/her health, being supported by a dynamic environment of innovative services aimed at improving access to care. eHealth [42] focuses on prevention and empowering consumers to proactively manage their own health. From the healthcare provider's perspective, eHealth increases efficiency by decreasing hospitalizations and the length of stay.

In order for a digitalization approach to be successful, existing healthcare practices need to be streamlined, simplified and redesigned, as they need to be thought about differently from the traditional paper-based system [43]. Telemedicine encompasses "examinations, monitoring and treatment, as well as educational sessions, processed using ICT-based systems that allow direct access to experts and patient information, regardless of location" [44]. Telemedicine [45] can be applied using any media and connection technology, such as video communications, e-mail, electronic monitoring equipment and web portals [46]. The definition provided by the American Telemedicine Association is "the use of medical information exchanged from one site to another through electronic communications in order to improve the clinical health status of the patient, including applications and services that use two-way video, e-mail, smartphones, wireless tools and other forms of telecommunication technology" [47].

At this moment, consumers' preferences regarding the use of digital technologies in the medical field are not fully known. Patients suffering from more serious conditions such as cancer consider new medical technologies as a means of high-level information but also as a form of support in decision-making [48]. More work is needed to identify barriers to access, especially for patients with severe conditions, who also have other financial or educational problems [49]. If digital technologies in the medical field are not implemented based on careful strategic planning, which takes into account existing barriers, supporting factors, needs and opportunities for patient involvement, they can cause negative effects regarding their implementation [50,51].

The COVID-19 pandemic has had important medical, social and economic repercussions and has required an unprecedented relocation of human, hospital, financial and research means worldwide [52]. Urologists were forced to undertake joint urological practices with health imperatives related to COVID-19 (patients held in isolation, modification of the operating schedule, prioritization of some procedures, rescheduling consultations). The COVID-19 pandemic had a very strong impact on the communication process between patients and doctors. The restrictions imposed at the national level as well as the fear of infection with the new virus have led patients to be more reserved in terms of making appointments in hospitals. The development of the Internet and information and communication technologies [53] in the recent period of time has had a very important role, with studies illustrating the fact that they contribute, to an important extent, both to increasing the productivity of physicians [54] and to the degree of satisfaction felt by patients.

The clinical study illustrates that the emergency insertion of ureteral prostheses showed a 64% prevalence of internal stent colonization in D60, which is significantly higher than scheduled insertion (27%). The prevalence of urinary colonization increases with the indwelling time of ureteral prostheses from 11% to 35% at D60. Due to the risk of post-COVID-19 complications, the monitoring of the kidney function for the 14 patients diagnosed as being COVID-19-positive will be needed.

The quantitative study that was carried out among urologists in Romania illustrated the fact that they frequently carry out installation activities of internal stents for patients with kidney diseases, with a large part of them carrying out such interventions weekly (32.4%). The results illustrated the fact that 88% of the respondents encountered difficulties in the communication process with stone patients during the COVID-19 pandemic, but also after its end. A total of 51.9% of urologists stated that poor communication between them and patients led to delays in changing internal stents, while 22.2% of them stated that poor communication led to a delay in the extraction of internal stents. All of these aspects automatically caused the appearance of medical problems among patients, with 50% of the urologists mentioning the fact that these delays caused damage to the patients' kidneys to a certain extent, and 10.2% of them stating that they encountered subsequent difficulties in fitting a new internal stent. A total of 11% of the respondents specified the fact that there were also situations where, due to poor communication, patients did not show up in time to change or extract their internal stent, a fact that even led to the loss of the kidney. A large part of those who participated in the study (92.6%) considered that new online technologies could bring added value to the communication process with lithiasis patients. After analyzing the linear regression model, it was noticed that the initially proposed model is a valid one, with the recorded value of Sig. being 0.000 < 0.05. In addition, it was noticed that the variation in the dependent variable at the level of the multiple linear regression model was explained in the proportion of 60% by the independent variables that were taken into account.

Regarding the strengths of the clinical study, it has offered a lot of information regarding the impact that the SARS-CoV-2 virus had on lithiasis patients, it has provided valuable information regarding the risk of urinary colonization for these patients who have internal stents and the study has also provided information regarding the post-COVID-19 complications that can occur for these patients. The strengths of the statistical study are as follows: the study provides an overall picture of the perception of urologists regarding the importance of using new technologies to improve communication with lithiasis patients and it illustrates the main problems that can be solved through the use of these technologies, as well as the factors that have the ability to influence the perception of physicians regarding the use of these technologies.

Regarding the weaknesses of the clinical study that was carried out, it must be stated that it was conducted on a limited number of respondents (212). In order to have a broader picture of the studied problem, larger studies should be conducted to certify the findings identified on a larger scale. Regarding the weaknesses of the quantitative research, it must be stated that a first aspect refers to the limited number of respondents who participated in the study. In addition, at this level, only a few of the variables that have the ability to influence the perception of physicians regarding the importance of using new technologies to facilitate the communication process with lithiasis patients were taken into account.

In the future, in order to better understand the studied topic, in-depth interviews should be conducted with urologists in Romania to better understand how online communication technologies can be used in this field, in order to facilitate communication with lithiasis patients. In addition, certain focus groups should also be conducted with patients, to observe the extent to which they would agree to use certain applications or technologies if it meant communicating with urologists more easily, and to find out, in real time, the treatments that they need, and the period in which they should see a physician to change or remove the internal stents that they have. In addition, future studies based on this topic should be conducted in both private and public health facilities to observe whether there are differences in the communication process at the levels of the two types of institutions. All of these aspects can create a broader picture of the presented topic, highlighting the most appropriate way in which online communication technologies can be used to facilitate communication with lithiasis patients.

5. Conclusions

Disruptive technologies can be considered to be an optimal solution for solving the communication problem. Better communication between stone patients and urologists would ensure strict adherence to appointments and allow specialists to learn the subsequent reactions that patients have, in real time. The clinical study illustrates that for patients with urolithiasis indwelling internal stents, 39% was the prevalence of colonized internal stents and 35% was the prevalence of urinary colonization (58% in the case of those who were COVID-19-positive). In patients with non-colonized internal stents, the incidence of urinary colonization was 15%, while 82% of the patients with colonized internal stents were also urinary-colonized, presenting one or more episodes of urinary infection. The risk of urinary colonization is significantly higher in patients with already-colonized ureteral internal stents. In the statistical study, we noticed that the perception of physicians regarding the importance of using new technologies to improve the communication process with lithiasis patients treated via internal urinary drainage pre- and post-COVID-19 period is directly and positively influenced by the following: the advantages perceived by urologists with regard to new technologies of online communication with lithiasis patients, the experience of urologists in the use of new communication technologies, the trust of urologists in new technologies of online communication and the openness of physicians in the use of new technologies at the level of the communication process, and that it is influenced in a negative way by the following: the disadvantages perceived by urologists regarding new technologies of online communication with lithiasis patients, the perceived risks and the current communication process with lithiasis patients. The results obtained in this paper present increased importance for doctors, patients and hospital managers. The hospital managers can identify the perception of the doctors regarding how new communication technologies can be used in hospitals to improve the communication process with patients. In addition, they have valuable information regarding the importance given by doctors to certain factors when they want to improve the communication process with lithiasis patients. Starting from these results, a series of measures can be taken both within state hospitals and within private clinics to implement new methods of communication with these patients, taking into account the influencing factors mentioned in this study.

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Review

Development and Use of Assistive Technologies in Spinal Cord Injury: A Narrative Review of Reviews on the Evolution, Opportunities, and Bottlenecks of Their Integration in the Health Domain

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Abstract: Assistive technologies are increasingly taking a leading role in supporting people with spinal cord injury (SCI). This narrative review of reviews intends to contribute by making a map point investigating the integration of ATs in SCI. The methodology of the review was based on: (I) a search of PubMed and Scopus and (II) an eligibility assessment using specific parameters. The outcome highlighted the following: -The evolution of ATs considered in the context of SCI, considering ATs as both products and/or services in standalone and/or networked devices, and as processes of delivery. -Innovative technologies could play an important role in improving the quality of life and in minimizing costs in healthcare. -The international scientific community has identified ATs as one of the six strategic development areas in SCI. The overview also allowed the detection of some problems: (I) The ethical and regulatory aspects have been addressed in a weak way and only in specific and limited cases. (II) There is a lack of studies on the use and applications of ATs in SCI with a focus in multiple domains (e.g., costs, acceptance, dissemination, problems, regulatory aspects, ethical aspects, and other issues important for integration into the health domain). This review highlights the need for further studies and activities focused on integrating consensus in multiple domains, including ethics and regulations, to aid researchers and decision-makers in the field.

Keywords: assistive technology; medical device; spinal cord injury; disability

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1. Introduction

This study's scope is located within the area of neuromotor and sensory disabilities, with a particular focus on those associated with spinal cord injury (SCI). These disabilities have a significant impact on the independence and quality of life of those affected. The spinal cord is a bundle of nerves that sends information between the brain and the rest of the body. A spinal cord injury can happen due to a traumatic event and can cause a reduction or absence of movement, sensation, and function of body organs below the level of the injury [1–4]. The severity and location of the injury can result in a range of symptoms from pain or numbness to paralysis and incontinence. The outcome varies from complete recovery to irreversible disability, and complications can occur in both the short and long term after the injury. Complete SCI means the spinal cord is irreversibly compromised, whereas incomplete SCI means the person retains some motor and/or sensory function below the site of injury. On average, in the US [2], there are around 12,000 (40 cases per million inhabitants) SCIs. The main causes are road accidents (48%), falls (16%), sports accidents (10%), trauma from aggression, such as with a firearm (12%), and accidents in the workplace. It should be considered that the higher the damage is positioned on the spine, the more serious the paralysis is likely to be. Table 1 provides an overview of the correlation between the location of the lesion and the resulting impairment in function in the case of tetraplegia. Assistive technologies (ATs) enable individuals with disabilities to live healthy, productive, independent, and dignified lives, and to participate in education, the labor market, and civic life [5]. Without these technologies, people with disabilities may face exclusion and isolation, leading to poverty and an increased impact of disease and disability on individuals, families, and society. Over time, technological aids for the disabled have improved in regard to accessibility, evolution, and perception, both in terms of common opinion and institutional viewpoints [5,6]. As society continues to age and grow, assistive technologies play an increasingly important role in improving the quality of life, access to resources and life activities, and work opportunities for individuals with disabilities. Assistive technologies must be tailored to individual problems, ranging from muscle weakness to the inability to breathe, move the head, and speak [7–9]. ATs provide a great opportunity to support people with different typologies of disabilities. It is therefore important to address the issue of their development, integration, and use in the SCI population.

Table 1. Mapping the relationship between lesion location and functionality in tetraplegia.

Area	Functionality of the Respiratory System	Functionality of the Neuromuscular System
C1–C4	Mechanical breathing is required	Arms are totally paralyzed
C5	Problems with coughing. Requests for support in removing the secretions are probable	Paralysis of the muscles of triceps, hands, and wrists is present
C6	The same as above	Paralysis of the wrist flexors, triceps, and hands
C7–C8	The same as above	There is a difficulty in releasing and grasping and some force lacking in the muscles of the hands

The integration of assistive technologies (ATs) with SCI has been a topic of research since 1994 [10], with advancements in technology such as robotics, virtual reality, Artificial Intelligence (AI), brain–computer interfaces (BCIs), and miniaturized electronics offering opportunities to improve support for individuals with disabilities. However, to fully realize these benefits, several issues need to be addressed, including developing algorithms and introducing regulations for stable applications in the health domain.

Reviews play an important role in categorizing and cataloguing themes emerging from different experiences in scientific fields, serving as a practical tool for both scientists and decision-makers, and paving the way for stabilizing the scientific field. Reviews also provide preliminary scientific evidence for the design of agreement initiatives, guidelines, Health Technology Assessment reports, Comparative Assessment Reports, or Consensus Conferences.

The purpose of this overview is to analyze how the published reviews are moving around the field of the design and integration of ATs with SCI treatment and support, and therefore to answer the following question: "*How is the integration of ATs and the SCI population described in the reviews*"?

Secondary aims of this overview include:

- Analyzing the movement and trends of published reviews in the field of the design and integration of ATs with SCI.
- Answering the question of how the relationship between ATs and SCI is addressed in these reviews.
- Identifying the themes that scientists are dedicating the most attention to.
- Recognizing the current research trends in this newly developed scientific sector.
- Providing insight into research directions and identifying gaps and bottlenecks in the field.

2. Methods

To ensure consistency, we employed a Standard Narrative Checklist, specifically designed for reviews falling under the narrative category (available online at: [11]). Since our investigation focused on assistive technologies in this field, we conducted targeted searches on Pubmed and Scopus for relevant reviews. Our overview comprised components that exclusively explored the aforementioned topic.

The composite key used in the search is reported in Box 1.

Box 1. The proposed composite key.

("assistive technology"[Title/Abstract] OR "assistive technologies"[Title/Abstract]) AND ("spinal cord injury"[Title/Abstract] OR "paraplegia"[Title/Abstract] OR "tetraplegia"[Title/Abstract] OR "quadriplegia"[Title/Abstract] OR (("paralysing"[All Fields] OR "paralysis"[MeSH Terms] OR "paralysis"[All Fields] OR "paralyse"[All Fields] OR "paralysed"[All Fields] OR "paralyses"[All Fields]) AND "of lower limbs"[Title/Abstract]) OR (("paralysing"[All Fields] OR "paralysis"[MeSH Terms] OR "paralysis"[All Fields] OR "paralyse"[All Fields] OR "paralysed"[All Fields] OR "paralyses"[All Fields]) AND "of upper limbs"[Title/Abstract]))

This overview was carefully crafted with a consideration of five parameters (N1-N5) that have been evaluated on a scale ranging from one (minimum) to five (maximum). In addition to these parameters, there is also a binary assessment (N6: yes/no). The parameters are as follows:

N1: Clarity of introduction and rationale for the review.

N2: Appropriateness of review design.

N3: Clear description of methods.

N4: Clear presentation of results.

N5: Justification of conclusions based on results.

N6: Full disclosure of potential conflicts of interest by authors.

These parameters have been thoughtfully selected to ensure the comprehensiveness and quality of this overview.

3. Results

At the time of this overview, the search using the composite key yielded 220 relevant papers in total, out of which 27 were reviews (listed as [12–38]); the remaining 193 were scientific papers. The field of study in question emerged roughly 30 years ago, circa 1993, with the first review article published in 1999. All selected reviews met the criteria of having a "Yes" result for parameter N6, and a score of at least three for parameters N1 to N5.

The results of the overview were organized in such a way as to report both the expectations of the first studies and the emerging themes in the more recent reviews. This was done in order to retrace expectations on the one hand, and on the other, to highlight developments in this area.

The first paragraph, Section 3.1 "*Assistive Technologies for Spinal Cord Injuries: A Review of Pioneering Research*", therefore provides a review of the pioneering research.

The second paragraph, Section 3.2 "*Emerging and Consolidated Themes in the Reviews: A Comprehensive Analysis*", is divided into four sub-paragraphs (Sections 3.2.1–3.2.4) relating to emerging themes.

Sub-paragraph Section 3.2.1 "*Unlocking the Potential of Assistive Technologies: A Comprehensive Analysis of Intervention Areas and Determinants*" reports studies that have focused on the areas of intervention and on the health determinants related to Ats.

Sub-paragraph Section 3.2.2, "*Economic Impacts, Social Acceptance, and Quality of Life: An Analysis*" reports studies dedicated to the important aspects related to the integration and acceptability of Ats in the health domain.

Sub-paragraph Section 3.2.3, "*Ethics and Regulatory Compliance*" is dedicated to the ethical and regulatory aspects, as dealt with by the studies.

Sub-paragraph Section 3.2.4, "*Advancing the Integration of Assistive Technologies in Spinal Cord Injury through Technical Innovation*" reports the studies dedicated to the contribution of technological innovation in the field of AT.

3.1. Assistive Technologies for Spinal Cord Injuries: A Review of Pioneering Research

An initial analysis of early reviews sheds light on the expectations of scholars regarding the development of assistive technologies (ATs) and whether those expectations have been met. Overall, the first available reviews were optimistic about the potential of ATs in this field, citing several key factors: devices for passive standing [33], advancements in sensors, control electronics, equipment, and telecommunications due to bioengineering and telehealth [29,31], and the expected growth of neural interface systems (NISs) for individuals with paralysis [30]. Other authors also predicted that this technological progress would lead to greater accessibility and affordability of ATs [32].

The review by Gear et al. in 1999 [33] concentrated on the technological innovations in rehabilitation medicine, with a focus on the potential of devices for passive standing to address chronic immobilization pathologies in individuals with spinal cord injury. According to the authors, these devices could offer significant benefits, such as reducing decubitus plagues, preventing demineralization, minimizing cardiovascular issues, and maintaining muscle tone through the upright position they facilitate.

Cooper et al. in 2004 [31] identified significant opportunities for scientific and economic growth in the field of bioengineering for SCI support, with advancements in control, sensor, instrumental electronics, and telecommunications expected to play a significant role.

Donoghue et al. in 2007 [30] envisioned NISs as promising technologies with potential applications in support interfaces, neurological and sensory rehabilitation, diagnosis, management, and in the construction of medical knowledge around brain function.

Bendixen et al. [29] evaluated the usefulness of telehealth as an encouraging method for daily monitoring and rehabilitation in SCI in a 2009 study, citing successful experiences in applying telehealth models to complex polytrauma cases in combat-wounded individuals.

Finally, McKinley et al.'s 2004 study [32] addressed the cost of ATs, highlighting the affordability of many available options that can provide essential support to individuals with SCI.

Table 2 summarizes the highlights in the pioneering studies.

Table 2. Evidence in pioneering studies.

Ref.	Highlights
[29]	Telehealth evaluated as an encouraging method for daily monitoring and rehabilitation in SCI, reporting successful experiences in models applied to combat-wounded individuals
[30]	NISs considered to have promising potential in support interfaces, neurological and sensory rehabilitation, diagnosis, management, and in the construction of medical knowledge around brain function
[31]	Identified significant opportunities for scientific and economic growth in the field of bioengineering for SCI support, with advancements in electronics expected to play a significant role
[32]	Predicted that the technological progress would lead to greater accessibility and affordability of ATs
[33]	Predicted that verticalization devices could offer significant benefits in reducing decubitus plagues, preventing demineralization, minimizing cardiovascular issues, and maintaining muscle tone

3.2. Emerging and Consolidated Themes in the Reviews: A Comprehensive Analysis

The reviews in the range of [12–38] explored a variety of issues related to ATs, such as the intervention areas [13], the determinants of health and the key factors [34], and innovative technological integration. Many of these reviews focused on the effectiveness of ATs, including robotics, Functional Electric Stimulation (FES), and brain–computer interfaces (BCIs) in clinical rehabilitation [12,15,17,18,20,23–28,35,36,38]. The economic impact, acceptance, and quality of ATs were also examined [16,19,22,36,37], along with ethical and regulatory considerations [12,21]. In addition to products such as robotics and FES, some reviews also studied the assignment processes of ATs. For example, managing databases of stem cells for SCI were considered to be ATs [14]. This aligns with the World Health Organization's definition of AT, which includes services that aid in the delivery of assistive products beyond the products themselves [39]. Overall, this research suggests that ATs have enormous potential to support clinical rehabilitation, through both innovative products and services.

3.2.1. Unlocking the Potential of Assistive Technologies: A Comprehensive Analysis of Intervention Areas and Determinants

The clear assignment of the intervention area in international consensus initiatives and the identification of health determinants influencing the acceptance of an AT are key factors. Two studies [13,34] (Table 3) addressed these issues separately.

Table 3. Evidence from studies considering both the areas of intervention and the determinants of health.

Reference	Highlights
[13]	The consensus at the SCI 2020 conference assigned to the ATs 6 areas, regarding technological facilitation, prosthetic and robotic interventions and therapies across the spectrum of mild/moderate/severe"
[34]	Detected the socio-structural factors and environmental factors impacting people with SCI (including built environment, housing, transportation, assistive technology, and natural environment)

The study conducted by Morse et al. [13] presented the consensus findings of the participants at the SCI 2020 conference, which included regulators, researchers, clinicians, healthcare professionals, stakeholders, patients, caregivers, and persons with SCI. The study highlighted six areas that were identified (literary quotation): "(1) opportunities in the acute post-injury phase; (2) innovating repair, plasticity, and regeneration in the subacute and chronic periods; (3) with us, not for us: community activity and priorities; (4) neuromodulation to improve neurological function months and years after SCI; (5) health and secondary health effects of chronic SCI; and (6) technological facilitation, prosthetic and robotic interventions and therapies across the spectrum of mild/moderate/severe". Interestingly, ATs were found to have a specific dedicated area, i.e., domain 6, while also playing a crucial role in domain 1 and domain 2.

Gurung et al. [34] investigated the determinants of health correlated to ATs with particular attention paid to the modifiable factors that impacted the health of community-dwelling people with SCI. The review found that socio-structural factors (such as social attitudes, health care access, information access, and funding and policies) and environmental factors (including built environment, housing, transportation, ATs, and natural environment) impacted people with SCI. Future research should investigate the effects of these modifiable factors using qualitative methods and community-based participatory research, and considering individual characteristics and resources.

3.2.2. Economic Impacts, Social Acceptance, and Quality of Life: An Analysis

Five studies addressed the economic impact, acceptance, and quality of life, or service aspects related to ATs, for people with SCI [16,19,22,36,37] (Table 4). One study by Gallagher et al. [16] focused on the wheelchair and its relationship with people with SCI, examining aspects such as satisfaction, performance, and participation. They found that the implementation and seating of the AT affected the ability of people with SCI to participate equally in society and highlighted the need for international policies to assure equal access to resources and investigations covering multiple domains.

Table 4. Evidence from studies exploring economic impacts, social acceptance, and quality of life.

Reference	Highlights
[16]	The implementation and seating of the AT affects the ability of people with SCIs to participate equally in society. There is the need for international policies to assure equal access to resources and investigations covering multiple domains.
[19]	ATs interfacing with PCs can improve independence, participation, and self-esteem.
[22]	Investing in specific rehabilitation protocols and ATs that enhance mobility could improve health conditions and minimize costs for people with SCI.
[36]	The main needs, expectations, and barriers of people with quadriplegia and caregivers in relation to the self-help devices that are currently used for daily tasks was detected.
[37]	ATs can improve functions of the upper limbs in SCI patients, but it is challenging to draw generalizable conclusions because of a lack of investigations covering multiple domains.

Another study by Baldassin et al. [19] specifically investigated how personal-computer-based ATs could improve the quality of life of people with SCI. Many studies suggested that these ATs could improve independence, participation, and self-esteem. Orejuela-Zapata et al. [37] collected and discussed the main needs, expectations, and barriers of people with quadriplegia and caregivers in relation to the self-help devices that are currently used for daily tasks. The major advantages, disadvantages, and challenges of the existing ATs were exposed and discussed in order to evaluate whether an existing technology could be combined with others to expand its scope, enhance its performance, or solve its limitations, with the aim of improving the adherence of the quadriplegic population to these technologies and enhancing their quality of life.

Readioff et al. [36] reported that there was no clear clinical consensus on the effectiveness of the current ATs for the cervical SCI population at the time of their study. They highlighted that ATs could improve functions of the upper limbs in SCI patients, but that it was challenging to draw generalizable conclusions because of a lack of investigations covering multiple domains.

Finally, Miller et al. [22] focused on costs and the potential positive impact of ATs on physical activity levels for people with SCI in the US. They found that investing in specific rehabilitation protocols and ATs could improve health conditions and minimize costs for people with SCI.

Overall, these studies showed the importance of ATs in improving the lives of people with SCIs and highlighted the need for continued research, investment in this area, and targeted insights into multiple domains of intervention.

3.2.3. Ethics and Regulatory Compliance

Only two literature reviews tackled ethical and regulatory concerns, but they focused on specific sectors rather than addressing them on a general level [12,21] (Table 5). Burwell et al. [21] discussed the ethical implications of using brain–computer interfaces (BCIs) as ATs in SCI patients, highlighting the challenges that arise from the direct connection to the brain. They identified several ethical, social, and legal issues concerning personhood, stigma, autonomy, privacy, research ethics, safety, responsibility, and justice. However, they concluded that few international recommendations have been developed to address these challenges. Meanwhile, Pirrera et al. [12] explored the regulatory complexities of tongue-barbell-piercing-based ATs. These complexities are very common in highly technologically innovative systems in the health sector, such as robotics and diagnosis using artificial intelligence. The authors [12] highlighted the potential regulatory frameworks applicable to these systems for alternative and augmentative communication based on the tongue piercing, emphasizing the intricate regulatory processes involved.

Table 5. Evidence from studies investigating ethics and regulatory compliance.

Reference	Highlights
[12]	Discussed the potential regulatory frameworks applicable to ATs, emphasizing the intricate regulatory processes involved with particular reference to the ATs using the tongue barbell piercing.
[21]	Identified several ethical, social, and legal issues in BCIs concerning personhood, stigma, autonomy, privacy, research ethics, safety, responsibility, and justice. Few international recommendations have been developed to address these challenges.

3.2.4. Advancing the Integration of Assistive Technologies in Spinal Cord Injury through Technical Innovation

The integration of assistive technologies (ATs) was subjected to numerous investigations, with 14 studies delving into their technological effectiveness, specific applications, and clinical targets [12,15,17,18,20,23–28,35,36,38].

Table 6 reports the detected contributions of the technologies in ATs.

Readioff et al. [36] reviewed the literature on ATs developed to help individuals with SCI at the cervical level and categorized the ATs into five types of ATs: neuroprostheses, orthotic devices, hybrid systems, robots, and arm supports. Pirrera et al. [12] highlighted the state of the art of ATs based on the tongue barbell piercing, emphasizing their high acceptance in mechatronics integration, particularly in quadriplegia patients with severe movement limitations. Klein and Baumeister [15] analyzed mechatronics and robotics as ATs for food administration, highlighting their limited use also in the most developed countries. Clark et al. [17] advocated for the integration of virtual reality (VR) and robotics for rehabilitation to increase its efficacy. Fridén and Lieber [18] suggested the use and integration of ATs, such as FES, for upper extremity recovery after surgeries in tetraplegia. Vibhuti et al. [35] also focused on VR and investigated the effectiveness of home-based exercise treatment for individuals with neuromotor impairments. The study concluded that home-based systems could provide efficacious therapy and facilitated the development and integration of better methods for rehabilitation. Palermo et al. [20] focused on powered exoskeletons (PEXOs) for clinical applications, highlighting their potential to minimize secondary medical complications in SCI patients. Lajeunesse et al. [23], on the other hand, showed skepticism regarding the performance of PEXOs for mobility among SCI patients. Tung et al. [24] focused on ATs for pressure ulcer prevention in SCI, identifying specific categories supporting self-management but pointing out low-to-moderate effectiveness. Rup highlighted BCI's promise, though further specific studies are necessary to gauge its applicability in the clinical setting [25]. Charters et al. [26] reviewed electronic portable assistive devices in SCI and suggested the use of portable electronic reminders as a practice guideline. Bryden et al. [27] focused on youth and identified key ATs, including therapeutic and functional stimulation, EMG biofeedback, and ATs for access to the computer. Kalsi-Ryan and Verrier [28] presented a study that found FES therapies useful and valuable during the subacute phase of recovery for persons with disability caused by quadriplegia. Lastly, Athanasiou et al. [38] discussed the impact of spinal cord injury on brain connectivity and organization. Whereas changes in brain structure have been extensively studied, knowledge regarding brain connectivity following SCI is lacking. This, according to the authors, could affect to the proper choice of AT.

Overall, the studies (Table 6) suggest that these technologies can help individuals with disabilities to manage their daily lives, prevent complications, and enhance their mobility and rehabilitation. The overview highlights that there is a wide variety of assistive technologies (ATs) available for different clinical targets and specific applications, with potential applications in pressure ulcer prevention, rehabilitation, food administration, youth therapy, spinal cord injury, and brain connectivity. These technologies include neuro-prostheses, orthotic devices, hybrid systems, robots, arm supports, tongue barbell piercings, mechatronics, robotics, virtual reality, functional electrical stimulation, powered exoskeletons, brain–computer interfaces, and electronic portable assistive devices. The effectiveness of some of these technologies varies, and further specific studies are necessary to gauge their applicability in the clinical setting. However, many of these technologies have shown potential to improve the lives and wellbeing of individuals with disabilities. Further research is required to determine their optimal effectiveness and applicability in clinical settings.

Table 6. Evidence from studies regarding technological issues.

Reference	Highlights
[12]	Reported the state of the art of ATs based on the tongue barbell piercing, emphasizing their high acceptance in mechatronics integration, particularly in quadriplegia
[15]	Analyzed mechatronics and robotics as ATs for food administration, highlighting their limited use also in the most developed countries.
[17]	Advocated for the integration of virtual reality and robotics for rehabilitation to increase the efficacy of rehabilitation protocols
[18]	Suggested the use of ATs based on FES for upper extremity recovery after surgeries in tetraplegia
[20]	PEXOs for clinical applications were discussed, highlighting their potential to minimize secondary medical complications in SCI patients
[23]	Skepticism was formulated regarding the performance of PEXOs for mobility in SCI patients
[24]	Listed ATs for pressure ulcer prevention in SCI, identifying specific categories supporting self-management, but pointing out low-to-moderate effectiveness
[25]	Highlighted BCIs' promise; however, further specific studies were suggested to gauge their applicability in the clinical setting
[26]	Reviewed electronic portable assistive devices in SCI and suggested the use of portable electronic reminders as a practice guideline
[27]	Focused on youth and identified key ATs, including therapeutic and functional stimulation, EMG biofeedback, and access of ATs to the computer
[28]	Indicated that FES therapies were useful and valuable as ATs during the subacute phase of recovery for persons with disability caused by quadriplegia
[35]	Indicated that virtual reality in home-based systems could provide efficacious therapy and facilitate the development and integration of other methods in rehabilitation
[36]	ATs were categized into: neuroprosthesis, orthotic devices, hybrid systems, robots, and arm supports
[38]	Reported that whereas changes in brain structure have been extensively studied, knowledge regarding brain connectivity following SCI is lacking; this could impact to the proper choice of an AT

4. Discussion

4.1. Highlights

Studies on ATs used in SCI have a rich history of about thirty years [10]. Reviews play a crucial role in creating Evidence-Based Medicine, which is necessary for integrating and consolidating medical practices in the health domain. This narrative review of reviews aimed to contribute by mapping the key themes related to the introduction of ATs in this field, reporting opportunities and problems.

The integration of ATs used in SCI within the health domain is a complex and challenging task. Based on the evolution of the term [39], ATs can include various technologies, such as products with high mechatronics, information technology, services, and processes for the telematic distribution of information. ATs can work alone or as part of a digital network. Therefore, when addressing the integration of ATs used in SCI in the health domain, three crucial issues must be considered.

First, if an AT works in a digital network, it inherits the complex problems of (i) telemedicine, (ii) electronic health, and (iii) mobile health, and includes regulation, ethics, and the need for stability in routine applications [40,41]. It is evident that, depending on the applications in a digital network, an AT can belong (reporting non-exhaustive examples) to: -(i), the case of telerehabilitation [29]; -(ii), the case of stem cell database services for ATs in multiple sclerosis [14]; -(iii) the case of systems based on the tongue barbell piercing [12].

Second, when an AT works alone, the peculiarities of the technologies and the methods of application must be considered.

Finally, when an AT must be provided, implications at the national system level come into play. A thorough analysis of emerging issues with reference to these three points is essential when addressing the integration process in the health domain.

The expectations from the first studies (Table 2) on the development of ATs included the potential for devices for passive standing [33] to address chronic immobilization pathologies in individuals with spinal cord injury (SCI). Advancements in sensors, control electronics, equipment, and telecommunications due to bioengineering were also expected to play a significant role [31]. NISs for individuals with paralysis were also considered promising technologies with potential applications in support interfaces, neurological and sensory rehabilitation, diagnosis, management, and the construction of medical knowledge around brain function [30]. Additionally, there was a prediction that this technological progress would lead to the greater accessibility and affordability of ATs through telehealth as an encouraging method for daily monitoring and rehabilitation in SCI [32]. Overall, the initial reviews were optimistic about the potential of ATs in this field. Almost all expectations have been met.

However, compared to the forecasts, the costs of ATs have not decreased as expected, and this causes diffusion problems. For example, in the poorest countries [42], NISs have presented critical issues in the realm of BCIs, as highlighted in more recent studies [12,21,25].

The overview highlighted the importance of considering both intervention areas and health determinants (Table 3) when designing and implementing ATs for people with SCI [13,34]. It is important to engage a diverse range of stakeholders, including people with SCI, in the development and implementation of ATs to ensure they meet the needs of the community [13]. Additionally, the impact of socio-structural and environmental factors should be considered in conjunction with individual characteristics and resources [34]. These findings can inform the development of more effective ATs and improve the overall health and wellbeing of people with SCI.

The opportunities for the technological development (Table 6) of the use of assistive technologies (ATs) are vast and varied, as demonstrated by the numerous studies that investigated their effectiveness, applications, and clinical targets. The technologies were shown to play an important role. The technologies highlighted in the studies include targets [12,15,17,18,20,23–28,35,36,38], neuro-prostheses, orthotic devices, hybrid systems, robots, arm supports, tongue barbell piercings, mechatronics, robotics, virtual reality, functional electrical stimulation (FES), powered exoskeletons (PEXOs), brain–computer interfaces (BCIs), and electronic portable assistive devices. These technologies have potential applications in assistance, pressure ulcer prevention, rehabilitation, food administration, youth therapy, and brain connectivity. The studies highlighted the efficacy, acceptance, and value of using ATs as therapeutic interventions and for self-management in individuals with SCI. The reviews demonstrated that:

- The advancement and increasing use of ATs present an opportunity for improving the quality of life of individuals with disabilities.
- Different types of ATs have potential applications in various clinical targets, such as assistance, pressure ulcer prevention, rehabilitation, food administration, youth therapy, and brain connectivity.
- Home-based systems, virtual reality, and electronic portable devices present opportunities for effective therapy and better management of neuromotor disorders.
- FES, PEXOs, and BCIs have been found to be useful and valuable as ATs and therapeutic interventions during the recovery phase for persons with disability caused by quadriplegia.

However, some critical issues and needs for further study have also emerged in specific sectors. For example:

- Skepticism exists regarding the performance of PEXOs for mobility among SCI patients [23].
- A low-to-moderate effectiveness of ATs for pressure ulcer prevention in SCI has been identified [24].
- There are limits in the application of BCIs [25].
- There is a lack of knowledge regarding brain connectivity following SCI, which could impact the proper choice of ATs [38].
- Mechatronics and robotics as ATs for food administration have limited also in the most developed countries [15].

The overview investigated the economic impact, acceptance, quality of life, service aspects, and effectiveness of assistive technologies (ATs) for people with SCI [16,19,22,36,37]. The studies focused on various ATs such as wheelchairs, personal-computer-based ATs, and self-help devices. The studies suggested (Table 4) that ATs could improve independence, participation, self-esteem, functions of the upper limbs, physical activity levels, and overall quality of life of people with SCIs. However, the effectiveness and generalizability of ATs remain uncertain, and more research, investment, and targeted insights into multiple domains of intervention are necessary to ensure equal access to resources and improve the lives of people with SCIs.

The existing literature on ethical and regulatory concerns in assistive technology is limited and was focused on specific sectors or technologies [12,21] (Table 5). There is a need for a comprehensive exploration of the ethical and regulatory challenges associated with ATs on a general level. Such research could help policymakers to develop appropriate regulatory frameworks and guidelines to ensure the safe and ethical use of ATs for the benefit of all users.

4.2. Emerging Criticisms and Need for Further Research

The overview showed, in addition to some specific problems [15,23–25,38] categorized by type of AT (Table 6), some areas needed for further study in relation to both the ethical and regulatory aspects (Table 5) and technology assessments capable of covering multiple domains (Table 4).

4.2.1. Comparison with Recent Publications Focused on Ethics and Regulations

As highlighted in the results, ethical and regulatory aspects were addressed in some specific cases and in a limited way [12,21].

We conducted on Pubmed a search regarding the past three years that included all types of articles dealing with ethics and regulations to compare the trends found in the reviews. Despite the pivotal role played by ATs during this period, due to the pandemic, no studies focusing specifically on ethical and regulatory aspects were found. After conducting a search using the composite key in Box 2, position 1 and applying various filters, 10 relevant studies emerged. However, three of these were reviews that had already been covered in our overview. Out of the remaining seven, only five [43–47] touched upon the specific topic of interest (regarding ethics or regulation), and even then, this was only in a secondary or complementary manner, serving to confirm the trends seen in the overview of reviews.

Armstrong-Wood et al. [43] found that individuals with SCI encountered difficulties accessing their smartphones due to motor impairment, which can limit their hand or finger movement. To overcome these barriers, they might rely on ATs, although these methods could result in compromising their privacy and independence. Kubiak and Sklar [44] reported that the internet presented an opportunity to reduce barriers to social participation and increase social integration for individuals with tetraplegia; however, race, ethnicity, and income inequities limited access to internet providers, computers, and ATs, especially for Black and Hispanic individuals. The study conducted by Kim et al. [45], based on a focus group, emphasized the significance of protecting the privacy and rights of vulnerable individuals, such as those with tetraplegia, from exploitation or harm. Lau and Moumbar [46] presented a preliminary protocol for the use of a Lower-Limb Robotic Exoskeleton, which could only be tested on healthy individuals due to regulations, raising ethical concerns regarding the exclusion of individuals with disabilities from involvement in the testing process. Yao et al. [47] testified that Filipinos with SCI faced significant challenges in accessing ATs, and that occupational justice was not fully achieved in this population. Further exploration of the experiences of individuals with SCI in using ATs, according to the authors, could help occupational therapists to identify ways to address these challenges and advocate for greater recognition of occupational rights.

4.2.2. Comparison with Recent Publications Focused on Technology Assessment

The results also highlighted the lack of comprehensive studies that address the use and applications of ATs in multiple domains [16,36], and that include comparisons, costs, acceptance, dissemination, regulatory and ethical aspects, and other relevant issues for integration into the healthcare domain.

We conducted on Pubmed a search regarding the past three years that included all types of articles dealing with these aspects to compare the trends found in the reviews. Despite the pivotal role played by ATs during this period, due to the pandemic, no studies focusing specifically on multiple domains were found. After conducting a search using the composite key reported in Box 2, position 2 and applying various filters, 14 relevant studies emerged. However, four of these were reviews that had already been covered in our overview and two were not pertinent. The other studies focused only on single domains [48–55], confirming the trends of the overview of reviews.

Box 2. The used composite keys.

Search: ((assistive technology[Title/Abstract]) OR (assistive technologies[Title/Abstract])) AND ((spinal cord injury[Title/Abstract]) OR (paraplegia[Title/Abstract]) OR (tetraplegia[Title/Abstract]) OR (quadriplegia[Title/Abstract]) OR (paralysis of lower limbs[Title/Abstract]) OR (paralysis of upper limbs[Title/Abstract])) AND ((ethics) OR (regulation) OR (rule) OR (standard)) Filters: from 2020/4/7–2023/4/7 Sort by: Publication Date
Search: ((assistive technology[Title/Abstract]) OR (assistive technolo-gies[Title/Abstract])) AND ((spinal cord injury[Title/Abstract]) OR (paraple-gia[Title/Abstract]) OR (tetraplegia[Title/Abstract]) OR (quadriplegia[Title/Abstract]) OR (paralysis of lower limbs[Title/Abstract]) OR (paralysis of upper limbs[Title/Abstract])) AND ((acceptance[Title/Abstract]) OR (consensus[Title/Abstract]) OR (assessment[Title/Abstract]) OR (satisfaction[Title/Abstract])) Filters: from 2020/4/7–2023/4/7 Sort by: Publication Date

Yurkewich et al. [48] investigated the feasibility and effectiveness of using an exoskeleton-supported rehabilitation program for people with hand impairments after stroke or SCI. The intervention was assessed using Goal Attainment Scaling (GAS), the Box and Block Test (BBT), the System Usability Scale (SUS), the Motor Activity Log, and the Fugl-Meyer Assessment. Results showed that the intervention was feasible and effective. The study proposed by Forslund et al. [49] examined the long-term effects of SmartDrive, a rear drive power assist device, on mobility, everyday activity, and shoulder pain among spinal-cord-injured manual wheelchair users. The results indicated a tendency toward decreased pain and increased satisfaction with performance and independence when using the device. The work presented by Ottoboni et al. [50]: -introduced MAIA, a multifunctional, adaptive, and interactive AI system for controlling assistive devices. -Explored the acceptability of MAIA to end users through semi-structured interviews with patients and caregivers. Factors such as motivation, ease of use, and personal factors like gender, fragility levels, and psychological aspects of body image also impacted the acceptability. Marquez et al. [51] analyzed the relationship between environmental factors present in parasports, such as attitudes, support, services, AT, and policies. The study also validated the Assistive Technology Device Predisposition Assessment (ATD PA-Br). Overall, the study suggested that technology and services should act as facilitators of parasport performance. Butzer at al. [52] investigated the acceptance of a robotic hand exoskeleton. User tests demonstrated that its low weight, unintrusive size, high wearing comfort, and appealing appearance contributed to user acceptance and usability in daily life. Thorsen et al. [53] assessed a non-invasive method, called myoelectrically controlled functional electrical stimulation (MeCFES), for improving the tenodesis grip of people with tetraplegia. Results from the IPPA (Individual Prioritised Problems Assessment) questionnaire indicated the issues people with tetraplegia hope to solve with a neuroprosthesis for the hand. The satisfaction resulted very high. Monforte et al. [54] explored the process of becoming a long-term wheelchair user by means of a case study. The case study was based on an innovative approach conjugating a posthumanist perspective and qualitative methods, such as interviews and observation. Rice et al. [55] investigated the effects of using an anterior tilt-in-space power seat function on the functional activities, physical health, and user satisfaction of power wheelchair users. Results showed significant improvements in the safety of meal preparation and functional reach in the vertical direction. However, participants found the safety equipment restrictive.

4.3. Emerging Recommendations

In-depth research on specific scientific articles also highlighted the trends that emerged in the overview of reviews regarding both the poor investigation of ethical and regulatory aspects (Table 5) and the absence of studies on technology assessments capable of covering multiple domains (Table 4). Concerted actions involving experts, international scientific societies, and stakeholders could be useful for tackling these strategic issues more decisively. Initiatives such as the Consensus Conference on robotic rehabilitation in Italy can provide shared documents on applications, organization models, training, regulations, and ethics [56,57]. This review highlights the need for further studies and activities focused on integrating consensus in multiple domains, including ethics and regulations, to aid researchers and decision-makers in the field.

4.4. Limitations of the Overview

The narrative overview has limitations. The review considered reviews in English and one in German (available in Pubmed). The reviews in different languages, not available in Pubmed or Scopus, were not considered. PubMed and Scopus databases were consulted, and only peer-reviewed papers were considered in the review.

Future work should focus on the detected themes, directly analyzing the articles published after the overview on the identified themes and updating the medical knowledge by theme.

5. Conclusions

In conclusion, the overview highlighted, through an analysis of the reviews, the evolution of ATs in the context of SCI, identifying the emerging fields of interest, with consideration of opportunities and problems. Technologies have been highlighted as playing an important role in improving the quality of life and minimizing costs in healthcare. The international scientific community identifies Ats as one of the six strategic development domains in SCI. However, the ethical and regulatory aspects have been addressed in a weak way and only in specific and limited cases. Even the acceptance of AT devices has not been extended to all technologies. What is missing are studies on the use and applications of ATs in SCI with a focus in multiple domains. They must include comparisons, costs, acceptance, dissemination, problems, regulatory aspects, ethical aspects, and other issues important for their integration into the health domain. This review highlights the need for further studies and activities focused on integrating consensus in multiple domains, including ethics and regulations, to aid researchers and decision-makers in the field.

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Article

Teledermatology Evaluation and Feedback Systems: A Tool for Improving Care

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Abstract: Chile is a country where teledermatology has been growing exponentially since the implementation of a single national asynchronous teledermatology platform for the public system in December 2018. To ensure the quality of care in teledermatology systems, it is crucial to evaluate the fulfillment of basic specifiers such as ICD-Diagnosis, therapeutic suggestions, and diagnostic suggestions, among others. This article aims to evaluate the teledermatology system of the Chilean public health service by analyzing 243 randomly extracted consultations, representative of the 20,716 electronic consultations performed during 2020. Compliance with basic specifiers is evaluated. From these, fulfillment of core teledermatology functions, such as diagnostic and therapeutic suggestions, is observed in most consultations. There are statistically significant relationships between the patient's destination (primary health center [PHC] or face-to-face referral), pharmacological prescription, coverage of the drug prescribed by the public system, and the education received by the consulting physician. If the consultation is resolved in the PHC, there is a higher chance for pharmacological prescription, prescribing mostly drugs that are covered by the government. This is less likely to occur when patients are referred for face-to-face evaluation. A targeted evaluation of education, pharmacological prescriptions, and their applicability is key to improving the quality of teledermatology systems.

Keywords: teledermatology; information systems; quality of care; feedback systems

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1. Introduction

The advance in information and communication technologies has promoted tools such as telemedicine as a viable alternative for delivering health care [1,2]. Teledermatology (TD) is a branch of telemedicine that has gained a presence in the healthcare systems over the last decade [3]. Due to the visual nature of the skin examination and the visual expression of dermatological diseases, the use of TD rises as a potential tool for diagnosing and managing skin conditions by distance [4]. Given that the diagnostic workup in dermatology mostly relies on visual clues, the clinical presentation of most dermatological conditions can be documented by imagining technologies, making the specialty ideally suited for this model of delivering specialized healthcare attention and supporting clinical decision-making [3].

Studies regarding the implementation of TD systems within the healthcare systems, as a tool to support access to specialized care, have shown comparable outcomes to conventional face-to-face consultation in terms of accuracy in diagnosis, management, and clinical outcomes, in settings where face-to-face consultation is not available or access to specialist consultation is severely limited [5–7]. In addition, several studies suggest that TD is a cost-effective tool that allows for the reduction of waiting times and efficient use of specialized resources and optimizes the relevance of referrals to face-to-face evaluation by the specialty, ultimately improving access to health care in populations with limited access [8–11].

Modern-day TD is usually divided into three different modalities: live interactive, store-and-forward, and a hybrid model including both of the previously mentioned modalities. The most used and studied modality is the store-and-forward TD model, where a clinician, usually at a primary healthcare center, summarizes the clinical history and relevant findings of the physical examination of a patient, captures images of the lesion or lesions involved, and uploads them into a TD platform. Then, a dermatologist evaluates the consultation and delivers a diagnostic and therapeutic suggestion. When compared to the live interactive model, it has lower equipment costs and improved utilization of specialist resources, and patients feel more comfortable [12]. Nevertheless, the use of live interactive or hybrid models can be of greater value for certain clinical scenarios such as case follow-up or to support clinical decision-making when the suspected pathology requires timely intervention.

For the particular case of Chile, given the geographical and demographical distribution of the country, developing a TD platform for the public system to reach isolated communities is considered a public health measure of utmost importance [13]. Note that Chile is a long and vast territory with 4329 km in length, poor land connectivity between cities, with a rurality index of 12.1% and 15% of the territory corresponding to islands [14]. Furthermore, there is an uneven distribution of specialists across the country, where one-third of the dermatologist's available work for the public sector, and from them, more than a half concentrate in the central regions of Chile, specifically in Santiago, the capital of Chile, and its surroundings [15]. This uneven distribution leads to an over-representation of specialists based on the population they cover in urban centers, while more isolated areas have little to no access to specialized care [16,17]. In addition, access to dermatological care in the public health system in Chile has been historically limited, with a documented gap between supply and demand that makes dermatology one of the highest-demanded specialties in the country [18]. Note that the public system covers 80% of the Chilean population, and dermatology consultation accounts for 2.7% of all consultations for specialized care in the public sector [17]. This, in turn, determines a considerable limitation on access to dermatological consultation, which translates into long waiting times, averaging 341 days for face-to-face dermatological evaluation [19].

Given this context, in December 2018, the Chilean Ministry of Health implemented a TD platform for the public sector, covering all primary healthcare centers of the Chilean territory [20]. This project was part of a greater project called Digital Hospital, which aims to implement telemedicine systems across the specialties of the public sector in order to promote timely and efficient access to specialist evaluation, regardless of the geographical location of the patient [20]. For the case of dermatology, the platform works as a store-and-forward TD system, where the primary healthcare physician, with the previous consent of the patient, takes images of the dermatological lesion or lesions involved in the case and uploads them to the TD platform, along with the clinical history and main findings of the physical examination. From there, a dermatologist at an urban center evaluates the case and gives diagnostic and therapeutic suggestions. In addition, to strengthen primary care, a brief education from the specialist regarding the suspected pathology is usually included in the response.

In the Chilean healthcare system, the primary health centers function as a gateway to the secondary and tertiary levels of attention, where most of the specialized resources are found. The general practitioner of the primary care is in charge of solving common pathology and referral to the specialist if needed, under established criteria, based on the diverse healthcare programs that organize the flow of referral to secondary and tertiary levels on each specialty. For the case of dermatology, this flow of patients to more specialized levels of attention should start with the case evaluation via the TD platform, where a specialist can suggest referral to face-to-face evaluation with a dermatologist or can suggest management in the primary healthcare center. Nevertheless, if the primary healthcare physician suspects a specific dermatological disease that has to be managed by specialists, direct referral to specialty centers is always available.

Originally, the TD system was first envisaged as a support tool for the general physician in primary care with rapid specialist suggestions on the case. However, it is now being implemented as a common channel for referral to dermatology and not limited to cases where the primary care physician is uncertain of the diagnosis or management. Nowadays, Chile is experiencing a transitional phase in the referral system to the specialty, introducing the TD platform as the initial step for specialist evaluation.

Regarding pharmacological interventions, the public system delivers pharmacological coverage for most first-line treatments of diverse dermatological pathology. This is achieved either by the coverage offered by the primary healthcare, the coverage offered by the telemedicine program, or the coverage offered by the secondary level. In the case of primary healthcare, primary healthcare centers have a set of established topical and systemic drugs used to treat common skin pathology. These are prescribed by the primary healthcare physician and are covered by the public system, at no out-of-pocket expenditure for the patient. Note that the availability and diversity of this pharmacological arsenal vary according to each specific primary healthcare center, depending on the resources and local supply of drugs.

Moreover, the telemedicine program in the TD cell includes coverage of first-line treatment associated with specific diagnoses, offering treatment coverage for acne, rosacea, psoriasis, non-specified dermatitis, vitiligo, and fungal infections. These drugs are indicated by the dermatologist in the therapeutic suggestion included in the response to the teleconsultation. Afterward, treatment is prescribed in the primary healthcare setting, with adequate supervision from the specialist. Finally, if the patient is referred to the secondary level for specialist evaluation, the secondary level also delivers coverage of drugs that are commonly used in dermatology.

Recent studies on the implementation of the Chilean TD program in the public sector show that 57.55% of the consultations continue management in the primary health centers [13], without the need for a face-to-face evaluation by the specialist, highlighting the resolutive role of the primary health and thus optimizing referral to the secondary level. In addition, there is an average response time of 3.5 days [13], which promotes timely and efficient access to diagnostic and therapeutic suggestions by a specialist.

Nevertheless, when it comes to telemedicine systems, to ensure the best possible service, it is crucial to constantly evaluate their quality [21] since failures in this area can lead to substantial diagnostic and therapeutic errors [22]. There are several methods to evaluate the quality of telemedicine systems, most adopting a qualitative approach [23]. Thus, the evaluation of TD systems implemented throughout different healthcare systems is based mostly on indicators such as user satisfaction [24,25], physician satisfaction [26], education systems [27], and economic impact [28]. However, there are no current publications on audited data on asynchronous electronic consultations to assess the quality of information processing, general practitioner education, organization, and information storage.

In this sense, the current standards of the British Association of Dermatologists (BAD) recommend auditing TD systems data at least once a year to assess the quality of these systems [29]. This article aims to show the evaluation and feedback system of the TD system from the Chilean public health service, by auditing the data of the electronic consultations received during the year 2020.

Large telemedicine systems often have a considerable loss of information due to errors in digiting the response. From this, targeted evaluation of the compliance with basic TD specifiers such as ICD-10 coded diagnosis, therapeutic suggestion, therapeutic indication, the applicability of the response, education to the consulting physician, and final destination of the patient is analyzed on the response from the specialist.

2. Materials and Methods

Cross-sectional, observational study of asynchronous electronic consultations uploaded to the TD platform of the Digital Hospital project, dermatology cell from the Ministry of Health of Chile (MINSAL) in 2020. From the universe of the consultations with responses during 2020, a representative sample size is randomly withdrawn and audited. The representative sample size was calculated according to the guidelines proposed by the Chilean Ministry of Health for sample size calculation in healthcare systems quality evaluation [30].

2.1. Patients and Settings

As mentioned in the introduction, the TD platform of the public health system covers all the primary healthcare centers of the Chilean territory.

The patients included in the registry are patients that consult at any given primary healthcare center with a specific skin disease. Patients are evaluated by a general practitioner, who requires a diagnostic or therapeutic suggestion by a specialist, to either treat the patient's pathology in the primary healthcare setting or referral to the secondary level.

2.2. Procedure

All patients who require a specialist evaluation for a given dermatological disease in the primary healthcare setting are evaluated by a general physician, who summarizes the clinical history and main clinical findings of the physical examination and takes clinical images of the lesion or lesions involved, with the patient's consent. These clinical images include a macroscopic picture of the lesion showing its topographic distribution, a macroscopic picture of a single lesion, a zoom-in capture of a single lesion, and a dermoscopic image if applicable and if a portable dermatoscope is available at the center. Afterward, the clinical images and medical history are uploaded to the TD platform. Then, the case is assigned to a dermatologist working at a referral center according to the availability of telemedicine hours for a given dermatologist. At the time of the study, there were 43 dermatologists working on the TD platform. Once the case is evaluated and the response from the specialist is recorded, targeted evaluation of basic specifiers that ensure the quality and usefulness of the response is analyzed.

From a representative sample size of the 20,716 teleconsultations recorded in 2020 on the TD platform of the public system, the responses are evaluated according to compliance with basic specifiers found in Table 1. If a patient is prescribed a certain drug associated with the diagnoses of acne, rosacea, non-specified dermatitis, vitiligo, psoriasis, and fungal infections, the drugs are available to the patient at no out-of-pocket expenditure. The applicability of the response is evaluated as a pharmacological prescription that is included in the drugs covered by the government, either through primary healthcare or through the telemedicine program. A more detailed description of the basic specifiers evaluated can be found in Table 1.

Compliance greater than or equal to 80% with an error margin of 5% is considered the threshold for compliance (Table 2).

The test hypothesis is evaluated through Pearson's Chi-square test to assess whether there are statistically significant relationships between the variables of the presence of therapeutic suggestion versus resolution in primary healthcare, resolution in primary healthcare versus drug prescription, drug prescription versus drug covered by the public system, and finally patient's destination (either resolution in the primary healthcare or referral for face-to-face specialist evaluation) and education received by the physician making the teleconsultation.

In addition, a descriptive analysis of the place of resolution of the consultation, together with the most frequent diagnoses, is included.

Table 1. Specifiers evaluated in the response of the teleconsultation.

Specifier	Description
Diagnostic suggestion	The teleconsultation response form is reviewed; the written diagnosis must be included in addition to the ICD 10 coded diagnosis.
ICD 10 Diagnosis	Indicate which final ICD 10 diagnoses were recorded by the dermatologist in the teleconsultation.
Therapeutic suggestion	The teleconsultation form is reviewed; the therapeutic orientations must be clearly recorded. They can be pharmacological or non-pharmacological indications. Pharmacological measures are specified in the following point. Non-pharmacological measures are the general measures provided to each patient for therapy management.
Pharmacological indication	Consider in the pharmacological aspect: medication, dosage, vehicle, and time of treatment.
Therapeutic applicability	This indicator applies if the case is subject to pharmacological indication. The therapeutic suggestion must be in accordance with what is included in the basket of drugs provided by the public healthcare system.
Education	The therapeutic suggestion must provide educational content to the primary healthcare physician: Practical advice for case management.
Destination of the patient after the consultation	The teleconsultation form must have marked in the indications tab: Option 1: Management at the primary healthcare center Option 2: Secondary Face-to-face referral Option 3: others: Referral to the medical ward, referral to another specialty (indicating which one), or incomplete data. Assessment of the number of patients that continue in the primary healthcare center via teledermatology is evaluated at this point.

Table 2. Guideline for compliance with the specifiers evaluated in the response to the teleconsultation.

Aim of the Indicator	Indicator	Error Margin	Compliance Threshold	Verifiers	Checklist
To Evaluate compliance in completing the basic content required for the response to the teleconsultation.	Number of asynchronous tele-consultations that comply with the minimum contents required for the response to the teleconsultation in a period of 1 year	5%	≥80%	Representative Sample size calculation out of the universe of teleconsultations performed in 2020, provided by the Superintendencia de Salud. Randomly selected cases. The response must include: 1. Diagnostic suggestion 2. ICD 10 diagnosis 3. Therapeutic suggestion 4. Therapeutic indication 5. Applicability of the response. 6. Education. 7. Destination of the patient after the consultation.	Complies/does not comply

2.3. Statistical Analysis

The descriptive analysis of the demographic variables and the analysis of pathologies diagnosed were performed using Stata software (Stata/SE 16.0 for macOS, Copyright 1985–2019 StataCorp LLC, College Station, TX, USA). All figures were developed using Microsoft Excel (Office 365, Microsoft Excel v16.66.1 for macOS, Copyright 1985–2022 Microsoft Crop, Redmond, WA, USA). Chi-Square test was used to test for statistically significant relationships between the destination of the patient (primary healthcare or Face-to-face referral), pharmacological prescription (yes or no), the applicability of the prescription (whether the drug indicated is included in the basket covered by the public healthcare system), and education received by the physician who makes the consultation in the primary healthcare (yes or no).

2.4. Ethical Aspects

The data analyzed were obtained from an anonymous database from the TD Cell of the Digital Hospital project of the Chilean Ministry of Health. The study was approved by the Ethics Committee of the Servicio de Salud de Antofagasta, Antofagasta, Chile. The analysis was conducted in compliance with the Declaration of Helsinki of ethical principles for medical research.

3. Results

From the total universe of 20,716 electronic consultations evaluated during 2020, a representative sample size of 243 consultations was randomly extracted.

The most frequent diagnoses observed were contact dermatitis 8.23% (*n* = 20), psoriasis 5.35% (*n* = 13), viral warts 4.94% (*n* = 12), atopic dermatitis 4.94% (*n* = 12), seborrheic keratosis 4.53% (*n* = 11), and unspecified skin malignancy 3.29% (*n* = 8). On the other hand, the presence of basic specifiers is summarized in Figure 1.

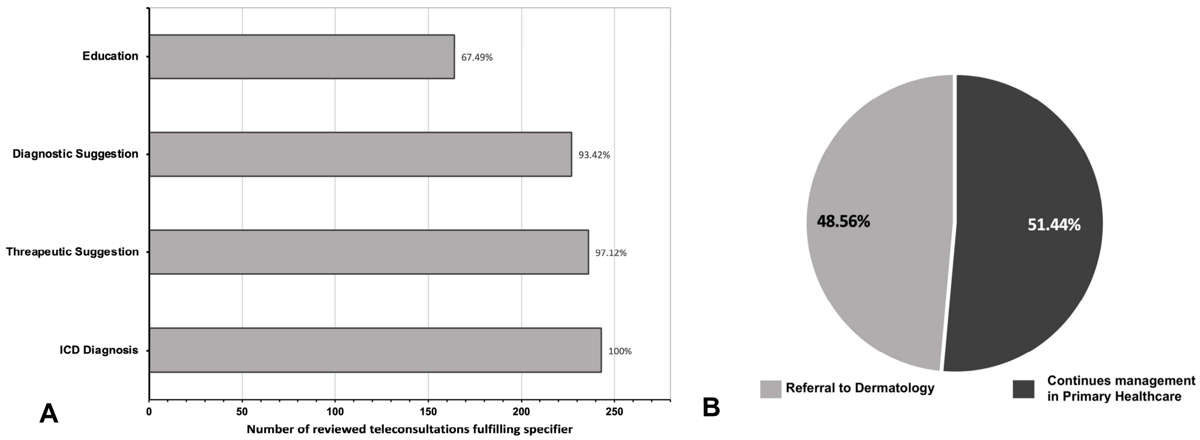

Figure 1. (**A**) Fulfilment of core teledermatology functions as targeted evaluation of specifiers in the response of the reviewed teleconsultations. (**B**) Final destination of patients after the teleconsultation.

Regarding management, non-pharmacological management was present in 65.02% (*n* = 158) of patients, while pharmacological indication was observed in 34.98% (*n* = 85) of cases. Of the 85 patients that were prescribed a drug, 80% (*n* = 68) were drugs covered by the public system, while 20% (*n* = 12) were drugs not covered by the public system. (Figure 2).

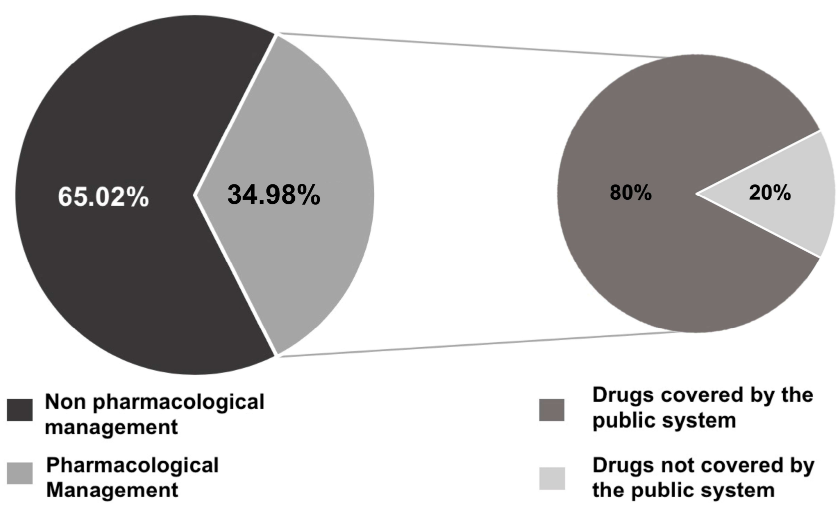

Figure 2. Management indicated in the interconsultation and therapeutic applicability (covered vs. not covered by the public system) when a pharmacological indication was prescribed.

For diagnostic suggestion, 115/125 (92%) patients that continued treatment in primary healthcare received a diagnosis. On the other hand, 112/118 (94.92%) referred to face-to-face evaluation did so. The destination of the patient and the presence of a diagnostic suggestion did not show statistically significant relationships ($p = 0.84$).

Moreover, therapeutic suggestions in patients that continued management in primary care were present in 123/125 (98.4%) consultations. In turn, a therapeutic suggestion in patients referred to face-to-face care was present in 113/118 (95.76%) of these consultations. Pearson's Chi-square test showed that these variables were independent ($p = 0.219$).

For pharmacological indication, patients that continued management on the primary healthcare were prescribed a drug in 61/125 (48.80%) locations. The pharmacological indication in patients referred to face-to-face care was present in 24/118 (20.34%) cases. There was a statistically significant relationship between the patient's destination and drug prescription ($p < 0.01$).

Regarding the pharmacological indication itself, 68/85 (80%) of the patients had prescribed drugs covered by the public health system, regardless of their place of destination. In addition, 100% of the patients who continued management in primary healthcare received drugs covered by the public health sector. For those referred to face-to-face evaluation with a pharmacological prescription, 29% of patients received drugs included in the public plan. There is a significant relationship ($p < 0.001$) between the patient's destination and the pharmacological indication of a drug included in the public health plan.

Finally, for education, there is a statistically significant relationship ($p = 0.004$) between the patient's destination after consultation and the education received by the primary healthcare physician. From this, 95/125 (76%) of the teleconsultations that resolved in primary care received education from the dermatologist. In contrast, 69/118 (58.47%) of the consultations that were referred to face-to-face evaluation did so.

4. Discussion

The evaluation of telemedicine systems is key for improving the quality of care and ensuring the best possible service [31]. For TD systems, the standard recommendation is that data audition and quality evaluation should be performed yearly [29]. In Chile, TD is a field experiencing accelerated growth following the implementation of a single national TD platform for the public system in late 2018 [13]. Since this platform covers all the primary healthcare centers of the Chilean territory, ensuring efficient information processing, storage, and compliance with basic specifiers in the response is of utmost importance. Given this context, this is the first audit of the Chilean TD system since the implementation of the aforementioned platform.

As information processing, clinical records, and information flow in large telemedicine systems are key for the adequate functioning of the platforms and suppose a logistical challenge in expanding telemedicine systems, evaluating the proper functioning of those processes is of utmost importance.

From the specifiers established in Table 1, it is observed that the vast majority of consultations comply with the basic functions that are expected from a TD system. Diagnostic and therapeutic suggestions are found in most of the consultations evaluated (Figure 1A). This implies that core TD functions, such as supporting the primary care physician with diagnostic and therapeutic assistance, are efficiently fulfilled. However, ICD-coded diagnosis was recorded in 100% of the consultations because it is a mandatory field in the Chilean TD platform; thus, 100% compliance is expected. Although ICD diagnosis is recorded, it is also of utmost importance to record the diagnostic suggestion, as the diagnosis given by the specialist might be more specific and helpful and provide greater insight into the case, than the standardized ICD-coded diagnosis. Nevertheless, it is also valid if the professional evaluating the teleconsultation estimates that the diagnosis provided in the ICD code is sufficient to provide the diagnosis, and thus, it does not record a more specific diagnosis suggestion on the response.

Regarding the educational role of TD, education by the dermatologist to the primary care physician is present in 164 (67.49%) of the referrals. For more than three-quarters of the consultations resolved in primary healthcare, the primary healthcare physician received education regarding the pathology from the consulting dermatologist. In contrast, when these consultations were destined for face-to-face evaluation, fewer dermatologists performed an adequate discussion of the case. Considering the important educational role of TD systems, case discussions and constant feedback between the specialist and the general physician help strengthen the role of primary care in solving and referring adequately and thus should be performed in most teleconsultations. This ultimately improves the appropriate use of the platform and optimizes the flow of attention, generating a positive loop between the primary healthcare physician and the dermatologist at the referral centers. This is further supported by a considerable amount of evidence that suggests that telemedicine education has helped medical residency programs [27], general practitioners [32], and patients [33].

In terms of management in the primary healthcare by TD, 51.44% (n = 125) of the teleconsultations continued treatment in the institution of origin, with a face-to-face referral of 48.56% (n = 121). Similar studies published in Chile show that management of dermatological disease in primary care, with the support of TD, can be as high as 64%, with a face-to-face referral of 30.1% [19]. In turn, articles on TD in Spain show a 50.82% resolution by TD, with a face-to-face referral of 49.01% [34], which is consistent with the findings of this study.

This is important to highlight since this evidence suggests that TD is an effective tool in managing at least one-half of the dermatological consultations in primary care, without the need for face-to-face evaluation by the specialist.

As for pharmacological interventions, this study shows a low prescription of drugs. It is important to highlight that a considerable number of skin diseases, especially in the primary healthcare context, can be self-limited or can be efficiently managed with adequate non-pharmacological interventions. This is an important factor to consider when developing drug coverage policies.

Moreover, most patients referred to an in-person evaluation did not receive a pharmacological indication. This correlates with the finding that a drug prescription depends on the patient's destination, where management in primary care is significantly related to a pharmacological intervention ($p < 0.05$).

From the total number of pharmacological indications (n = 85), 80% (n = 68) were applicable therapeutic alternatives covered by the government. Although the telemedicine program covers the first-line treatment for a limited amount of diagnosed-based prescriptions, the prescription of drugs covered by either the primary healthcare or the telemedicine program is high, which in turn optimizes access to treatment. As seen on the most frequent pathologies diagnosed in the studied teleconsultations, dermatitis and psoriasis, which are covered by the telemedicine program, account for a considerable portion of the diagnostic suggestions, while other pathologies, such as viral warts, which are also frequent to observe in the primary care, are not. Nonetheless, this study shows that most of the prescribed drugs were within the drugs provided by the public system, optimizing the applicability of the established therapy, as out-of-pocket expenditure or other related factors would not hinder access to treatment. This phenomenon is observed in 100% of the patients who received their treatment in primary care. In contrast, a lower percentage of patients referred to face-to-face care received a drug included in the public plan. Given the aforementioned reasons, we believe that the prescription of drugs covered by the public sector should be a factor of specific evaluation when auditing TD systems. This would promote the use of these pharmaceutical options, educate the consulting dermatologists about these alternatives, or in turn, help develop policies of coverage based on patients' necessities.

Lastly, it is worth mentioning that this study has limitations. First, the study was conducted during the COVID-19 pandemic. For this reason, the consultations received and the patient's destination after the consultation might have been biased secondary to the epidemiological context at the time. Given the restrictive measures imposed by the Chilean government in 2020 [35], patients' mobility to either a primary healthcare center or a face-to-face evaluation might have been limited. Knowing that the entrance to the Chilean TD system is via primary healthcare through an in-person consultation with a general physician, the pandemic could have negatively impacted the volume of consults uploaded to the platform. As shown in Figure 3, there is a notable reduction in the teleconsultations evaluated during 2020 as compared to 2019. This is consistent with the overall reduction in consultations to the specialty reported in other settings [36,37] and with the documented reduction of more than 50% of consultations to the specialty observed in the public system in Chile during 2020 [38].

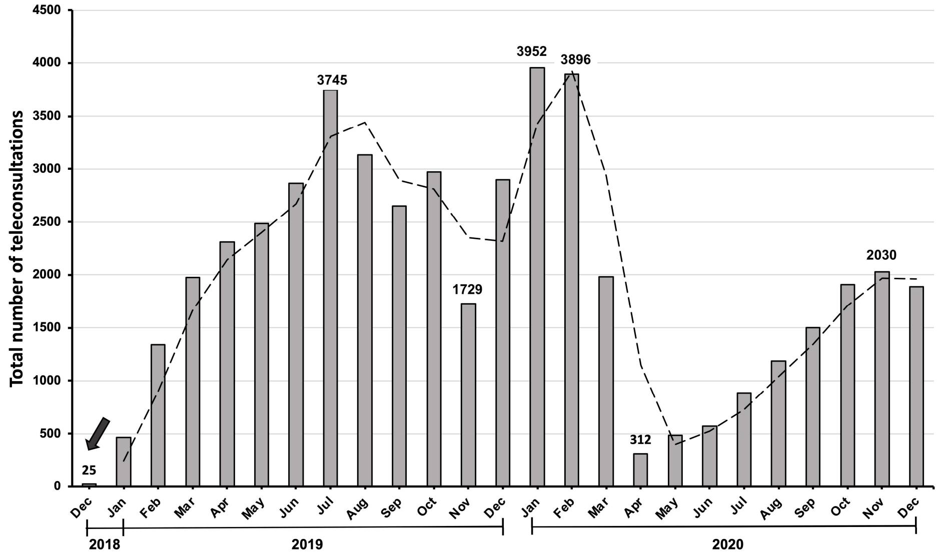

Figure 3. Monthly temporal progression of the total number of teleconsultations to the specialty since the implementation of a national teledermatology platform (marked with arrow) in December 2018 [13]. Adapted from Ref. [13].

Moreover, there are differences in the use of the TD platform by the different primary healthcare centers across the territory. Some centers use TD as diagnostic support in common dermatoses, while others use it as a triage and referral tool for malignant skin pathology. These differences in the approach of every center to the use of TD as a tool for a specialist evaluation, and to support clinical decision-making could account for notable differences observed between diagnosis, degree of resolution in the primary healthcare, and the number of referrals to secondary care [39].

Nevertheless, the most frequent diagnosis observed and the frequency of referral for face-to-face evaluation showed similar results as compared to larger studies performed in Chile and other countries. In addition, the large sample size of 20,716 electronic consultations and the random extraction of a representative sample size attenuates the effect that the epidemiological situation of the country or the specific use of the platform by individual centers might have played in the consultations.

Finally, it is worth mentioning that strengthening primary care by promoting the educational functions of TD systems is a valuable outcome that promotes network collaboration among the different levels of healthcare attention. This ultimately improves the use of the healthcare system as a unit centered on the user. For these reasons, specific evaluation of the compliance with the educational specifier in TD is an important policy to develop once the most basic specifiers such as diagnostic and therapeutic suggestions are completely fulfilled. In addition, targeted evaluation of the applicability of the response is key to ensuring the proper functioning of the TD systems, as accessible prescriptions ensure the delivery of effective and timely treatment.

5. Conclusions

This is the first article that aims to evaluate TD systems through the auditing of data from the Chilean public TD platform since its implementation in December 2018. Aspects such as education, pharmacological indications, and applicability should be the focus of attention to improve TD systems and should be actively evaluated on the audits. On the other hand, the items of diagnosis, diagnostic suggestion, and therapeutic suggestion are present in the majority of the consultations, showing that these systems fulfill their basic functions. In addition, although this study reports a low prescription of pharmacological interventions, the majority of the drugs prescribed were covered either by the telemedicine program or by primary care. This is important to highlight, because, although the telemedicine program covers treatment for a limited number of dermatological diagnoses, when complemented with the drugs available in primary healthcare, most of the patients with a pharmacological indication received the drug at no out-of-pocket expenditure, optimizing prompt and efficient access to treatment. We believe that this experience can help other telemedicine systems implement similar data auditions and serve as feedback tools to improve care systems and evaluate their quality.

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Article

Challenges of Integrating New Technologies for Orthopedic Doctors to Face up to Difficulties during the Pandemic Era

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Abstract: In the field of orthopedics, competitive progress is growing faster because new technologies used to facilitate the work of physicians are continuously developing. Based on the issues generated in the pandemic era in this field, a research study was developed to identify the intention of orthopedic doctors to integrate new medical technologies. The survey was based on a questionnaire that was used for data collection. The quantitative study registered a sample of 145 orthopedic doctors. The data analysis was performed based on the IBM SPSS program. A multiple linear regression model was applied, which analyzed how the independent variables can influence the dependent variables. After analyzing the data, it was observed that the intention of orthopedic doctors to use new medical technologies is influenced by the advantages and disadvantages perceived by them, the perceived risks, the quality of the medical technologies, the experience of physicians in their use, and their receptivity to other digital tools. The obtained results are highly important both for hospital managers and authorities, illustrating the main factors that influence doctors to use emergent technologies in their clinical work.

Keywords: orthopedics; new technologies; pandemic era; quantitative research

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1. Introduction

Since the introduction of mechanization in the first industrial revolution, technology and innovation have been heavily used in healthcare. Industry 4.0, by integrating the Internet and new technologies (e.g., communication technology (ICT), digitization, artificial intelligence (AI), Internet of Things (IoT), cloud technology, cloud computing, known additive manufacturing (AM), and Big Data and cyber systems), initiated a "paradigm shift" in how patient care is delivered globally across all specialties, including orthopedics [1,2].

In the orthopedic field, new technologies help physicians in the early diagnosis of various conditions, the faster development of innovative treatments, and the perioperative surveillance of patients. The overall goal of technologies in orthopedic surgery is to improve surgical accuracy and achieve faster postoperative rehabilitation, as well as to provide optimized services for patients [3]. Technological innovations have a very important role in preoperative surgical planning, the precise intraoperative placement of implants, the restoration of biomechanical parameters, and the efficient execution of orthopedic procedures. In trauma care, computer-assisted virtual reality, 3D printing techniques for planning the surgical management of acetabular fractures, real-time navigation, and computer-guided and robot-assisted surgery (RAS) applications have grown exponentially in total hip arthroplasty and in tumor reconstruction surgery [4–6].

Self-monitoring and reporting technology (SMART) and sensor-based implants have contributed to improved diagnoses provided by physicians, objective intraoperative assessment of soft tissue balance in total knee arthroplasty, and postoperative patient monitoring [7]. Studies have illustrated that advanced technological rehabilitation in hospitals and at home using wearable or implantable sensors is the future [8]. However, there is debate regarding the cost-effectiveness of such an intervention given the need for a steep learning curve and universal applicability in healthcare in underdeveloped countries [7].

Additive manufacturing (AM), also known in the specialized literature as three-dimensional (3D) printing, represents the process of joining materials to create objects from a 3D digital model layer by layer [9]. For many years, this technology has been used in many industries such as in the realm of jewelry making, engineering, fabrics, etc. [9]. Chuck Hall created stereolithography (STL) in 1984 [10]. Since then, this technology has become more and more used due to its versatility, ease of use, and precise control in terms of the manufacturing process but also in terms of the possibility of making complex shapes and structures. Therefore, the printed patterns have the potential to intentionally possess properties that are highly sought after for biomedical applications [9]. In the medical field, AM technology is used to create customized medical instruments, drug delivery systems, engineered tissues, scaffolds for bone regeneration, prosthetic sockets, orthoses, or guides as well as surgical implants [11]. In the last decade, there has been an increasing trend towards the customization of business models and technological advances, which has led to the reduction in costs and expertise required in the exploitation of AM [12]. "Computer-aided design" (CAD) also began to be used in the medical field, being seen as a process of using computer software to help facilitate the activities carried out by medical personnel [13].

There are various techniques for measuring and modeling existing objects (including the human body) to create digital models that we can work on using CAD software. The most used methods include computed tomography (CT) and 3D scanning [11]. Three-dimensional scanning is the most practical and comfortable solution to capture topography. There is a lot of affordable hardware and software, the training requirement is minimal, and it can be very effective [14]. Acquisition time and spatial resolution differ greatly between 3D scanners, ranging from a few minutes to longer and from 0.1 mm to several millimeters [15,16]. The most used systems are laser techniques and structured light methods. The laser technique uses a handheld device to project a laser beam onto the surface, while a sensor measures the distance to the projector.

Digital reconstruction, CAD modeling, and conversion to STL format are performed with appropriate software, with several free alternatives available on the market [17,18]. In the biomedical field, the use of AM technology is increasing, being particularly widespread in the manufacture of orthoses. However, it is still a relatively new approach, with orthotics starting to be 3D printed less than a decade ago. The manufacture of orthoses and prostheses is still largely manual and because of this, the result depends on the human resource involved [11].

The advantages of orthoses made with the help of AM technology are the following: production is possible at lower costs, the possibility of making changes more easily, and faster manufacturing. Patients usually feel more comfortable with prosthetic sockets made with AM appliances than with traditional, hand-made sockets [11,19]. AM technology has been used to facilitate the manufacture of orthoses in a number of situations, namely spinal orthoses, knee orthoses, ankle-foot orthoses, wrist orthoses, foot orthoses, chronic pain relief, or peripheral nerve damage. Custom wrist orthoses for chronic wrist pain [20] or for splinting a healing fractured bone can also be made using AM technology. A recent literature review evaluated a 3D-printed wrist orthosis for a Colles fracture [21]. Radiographs of the wrist were performed periodically to observe both the angle of inclination of the palm, the angle of cubital deviation, and the height of the beam.

Three-dimensional technology is increasingly used in orthopedics. An exponential growth of digital applications in this field of activity is expected in the coming years. Computer technologies play a crucial role in the orthopedic field. Until recently, surgical planning was typically performed manually on fluoroscopic images. These are currently being replaced by advanced planning software that incorporates multimodal and patient-specific medical data. In addition to pre-operative planning, digital technologies have begun to increasingly support the work carried out by doctors. For example, during arthroplasty procedures, computer-assisted techniques [22] have been shown to be superior to conventional implantation techniques in terms of both their consistency and accuracy [23–27].

Robotic solutions are used in many fields to reduce human error, increase accuracy and ensure reproducibility [28–31]. However, they are still not widely adopted clinically in different disciplines. The main disadvantages of robotic solutions in surgery refer to their intellectual and haptic adaptive behavior, which is minimal; the existence of limitations in terms of integrative interpretation and action in complex situations; poor patient registration; complex configuration; invasive fiducial implantation; and interrupting the workflow [30].

While robotic technologies are mainly aimed at supporting doctors with precise and planned mechanical actions, Augmented Reality (AR) technology enhances the surgeon's work by increasing the medical information available. AR refers to the real world augmented with virtual information, as opposed to Virtual Reality (VR), where the user experiences a completely virtual setting [32,33]. The growing interest in AR in orthopedics and trauma is not new. Surgical procedures in orthopedic surgery frequently use visual data, such as medical images obtained both pre- and intra-operatively, and often include mechanical steps, such as the screw or implant. Therefore, such technical tasks intensify the use of AR in this field.

Artificial intelligence-based techniques have significantly contributed to the improvement of medical imaging through data acquisition, reconstruction, analysis, and interpretation [34]. Artificial intelligence identifies the imaging examination that the patient needs by incorporating information extracted from the patient's medical record and determines the appropriate protocol for it [35]. Artificial intelligence can also increase data acquisition speed in nuclear magnetic resonance (NMR) imaging and reduce radiation dose in computed tomography (CT) [36]. The area where artificial intelligence is most used is image interpretation, where AI is used to support radiologists in data interpretation, avoid human errors, and increase diagnostic accuracy.

1.1. How AI Works in Analyzing Medical Datasets

AI-based algorithms have been used to recognize the arthroplasty component on plain radiographs, thereby providing a set of images and key imaging features that a radiologist would normally use to distinguish between different types and brands of implants [37]. In this way, the AI-based system tries to match the known characteristics with the parameters of the implant, thus making an assessment. After this process is completed, the accuracy of the system is established by comparing the established and known (correct) results, and inaccuracies or additional information can be manually entered into the system, and thus the process can be repeated. With the help of computing power and algorithm refinement capability, the AI system can learn to self-assess its performance and improve by modifying its internal algorithmic codes [38].

To maximize the predictive power, the AI index algorithm is increasingly refined after being exposed to training datasets, which leads to improved iteration accuracy [39]. This case requires completely different iterative programming, where the program has the autonomy to write its own coding instructions and is thus a step forward towards achieving full automation, this process is called Deep learning (DL) [40–43].

Deep learning (DL) eliminates the need for human operator input in the algorithm refinement process, thereby reducing the time to achieve a viable system. The algorithmic performance of modern DL neural networks allows the artificial foundation of multi-layered "evolutionary plexuses", just like the neural system of the human brain [44,45]. Most deep learning systems incorporate some form of artificial neural network (ANN), having a series of iterative processing steps between the input and output layers [46–48].

1.2. The Use of New Technologies in Orthopedic Practice

In orthopedic practice, the computer has the role of processing data sets belonging to several patients. By means of specialized coding, it has the ability to recognize specific patterns [46,48,49]. Computer software based on artificial intelligence can significantly contribute to the management of patient information. Before using artificial intelligence to fully manage data, orthopedic doctors must understand the technological potential of this technology in the healthcare system. Artificial intelligence algorithms have been used in orthopedics, including for the diagnosis of fractures and osteoarthritis and for establishing bone strength [34].

Some studies have illustrated that, in the orthopedic field, AI has the ability to detect wrist fractures as well as spinal compression on radiographs more easily and quickly (as opposed to medical specialists) [34,50]. Artificial intelligence can help automate the grading of lumbar disc pathology on MRI using different grading systems with nearly 100% accuracy [51]. AI enables automatic segmentation of the area of interest, thus increasing the quality of image analysis, with many studies focusing on the segmentation of knee cartilage [52]. AI-based image interpretation can be very accurate, but requires large training data sets, which are expensive.

A benefit offered by AI in the medical field refers to the possibility of predicting clinical outcomes for patients based on data sets as well as medical imaging. Assessing risks and predicting outcomes has always been a challenge in clinical medicine. In orthopedics, ML can be used in patient management, providing a patient-specific postoperative complication rate after the surgery is performed [53]. Artificial intelligence can increase the accuracy of diagnosis, this aspect mitigating the risk of misdiagnosis. In this way, doctors have the ability to determine the correct medical procedure for each patient.

Currently, AI-based systems have been used in various ways, such as in the identification of fractures and osteoarthritis, the identification of bone mineral density, and the assessment of bone age [34,54]. The activity of orthopedic doctors depends to a high extent on the imaging examination performed, so they can provide a correct diagnosis and treatment only after analyzing the images in question. In this case, artificial intelligence can optimize the acquisition, reconstruction, analysis, and interpretation of images, thus providing effective help to orthopedic doctors [55–57].

1.3. The Use of Robots in the Orthopedic Field

In recent years, robots [58] have started to be used more and more in the medical field. AI technology can help orthopedic doctors in the diagnostic process. An example of technology that can be used in this regard is the IBM Watson Health cognitive computing system that uses ML to create a cancer treatment support system with the intention of improving diagnostic identification. Orthopedic surgery began to incorporate robotic technologies in 1992 with the introduction of ROBODOC for total hip replacement [59]. This is an active-autonomous, image-based robotic system that has assisted surgery in cementless total hip arthroplasty (THA) [60]. This technology has not been very successful due to the complexity and long duration of the surgical procedure [61].

Another early image-guided autonomous robotic system was CASPAR, used for THA and total knee arthroplasty. To date, no major adverse effects related to the use of CASPAR have been reported [62]. RIO (Robotic Arm Interactive Orthopedic System) is another robotic system that requires the active participation of the doctor in the knee arthroplasty procedure. This robotic system generates a 3D model of the patient's anatomy that helps the doctor develop a preoperative plan. Most orthopedic surgery robots such as RIO are used for knee or hip arthroplasty [63].

The robotic arm has the ability to assist doctors in performing minimally invasive surgical interventions, offering them other advantages such as three-dimensional imaging, 7 degrees of articulation, and the possibility of operating remotely. An example of this is the TianJi robot. This is an orthopedic field robot that can perform whole spine (spinal instrumentation), pelvis, and knee procedures [64,65]. The robot works through a robotic arm that uses a real-time navigation system with a high degree of precision. Machine learning has various uses in the orthopedic field, such as fracture detection, bone tumor diagnosis, mechanical loosening of hip implants, and osteoarthritis grading [66]. The importance of AI and ML in the orthopedic field is in a constant process of growth, in line with the evolution of research in the field.

In 2019, the first remote multicenter orthopedic surgery using 5G technology was performed by Professor Wei Tian. Robots have started to be used more and more in recent years, especially in surgery due to their precision in performing operations with reduced risks of bleeding in a shorter time. Currently, the use of robots in the operating room is still in an early stage of development; however, there is increased interest among medical and research professionals. Although several robots have already been used to perform surgeries, there is insufficient evidence of their effectiveness over time. In theory, robotic systems are mainly used to prevent misdiagnosis and massive bleeding and to reduce the burnout of physicians in this field.

The COVID-19 pandemic has influenced to a very high extent the activity carried out by physicians. They had to treat patients in special conditions, and very often they had to use digital technologies to get in touch with patients who are far away. Orthopedic specialists also had to face the existing pressures during the period of COVID-19. The complications that arose due to contact with the new virus put the medical staff in a difficult position and because of this they had to resort to additional solutions to face these difficulties. New technologies have facilitated the work of specialists, facilitating the performance of surgical interventions. Thus, physicians had the opportunity to save time and financial resources in carrying out these interventions. Currently, in Romania, new medical technologies are used in a rather low proportion within the state health facilities. However, there are some private clinics or hospitals that benefit from advanced technological equipment, which allows physicians to thoroughly investigate certain cases and provide appropriate treatments in a much shorter time.

Considering the multitude of medical technologies currently existing in the field of orthopedics as well as their role in facilitating the activities carried out by medical personnel, we considered it necessary to carry out quantitative research aimed at identifying the intention of orthopedic doctors to use the new medical technologies in the activities they carry out in this pandemic era. In this study, a multiple linear regression model was carried out. The independent variables that were taken into account at the level of this multiple linear regression model were previously analyzed at the level of other specialized studies. These were the following [67–75]: ease of use, promotional activities carried out regarding new medical technologies, advantages perceived by orthopedic doctors regarding new medical technologies, physicians' experience in using these medical technologies, their receptivity regarding the use of new medical technologies, the quality of existing new medical technologies in the field of orthopedics, the disadvantages perceived by physicians regarding these technologies, the reliability in time of new medical technologies, and the risks perceived by orthopedic doctors regarding the use of new medical technologies, as well as the acquisition cost of new medical technologies.

The main aim of this study was to identify the degree of use of the new technologies in orthopedics and the receptivity of orthopedic doctors to use the new medical technologies in this field. The secondary aims established at the level of this research were to identify the perception of the doctors regarding the importance of the new technologies in the field in which they practice; to identify the sources of information used by the respondents to inform themselves about the new technologies; to identify how often the orthopedic doctors are using the new medical technologies within the medical units; to identify the types of medical technologies that the respondents would like to use in their daily activities; and to identify the main benefits obtained by the doctors following the use of the new medical technologies in this field.

1.4. The Research Hypotheses Were the Following

H1. *The easy use of new medical technologies on the market has the ability to directly and positively influence the intention of orthopedic doctors to use these technologies in their work.*

H2. *Promotional activities carried out for new medical technologies have the ability to directly and positively influence the intention of orthopedic doctors to use these technologies in their work.*

H3. *The advantages perceived by orthopedic doctors regarding new medical technologies have the ability to directly and positively influence their intention to use these technologies in their work.*

H4. *Orthopedic doctors' experience in using new medical technologies has the ability to directly and positively influence their intention to use these technologies in their work.*

H5. *Orthopedic doctors' receptivity to the use of new medical technologies has the ability to directly and positively influence their intention to use new medical technologies in their work.*

H6. *The quality of new medical technologies has the ability to directly and positively influence the intention of orthopedic doctors to use these technologies in their work.*

H7. *Disadvantages perceived by orthopedic doctors regarding new medical technologies have the ability to directly and negatively influence their intention to use new medical technologies in their work.*

H8. *The reliability of new medical technologies in the field of orthopedics has the ability to directly and positively influence the intention of orthopedic doctors to use these technologies in their work.*

H9. *The risks perceived by orthopedic doctors regarding new medical technologies have the ability to directly and negatively influence their intention to use these technologies in their work.*

H10. *The acquisition cost of new medical technologies in the field of orthopedics has the ability to directly and negatively influence the intention of orthopedic doctors to use these technologies in their work.*

This research provides information regarding the main variables that underlie the decisions of orthopedic doctors regarding the use of new medical technologies. The results provide clear information regarding the main factors behind the intention of orthopedic doctors to use these technologies in the private or state clinics where they work.

2. Materials and Methods

2.1. Survey Design

The data collection was carried out with the help of a questionnaire that was later distributed to the respondents. Regarding the way in which the research instrument was created, it should be stated that the first question at its level was a filter, with the role of selecting only orthopedic doctors who work in a clinic or in a hospital in Romania. Later, there were several questions through which it was desired to identify the opinion of physicians regarding the usefulness of new medical technologies in the field of orthopedics. In the last part of the questionnaire, several questions were used to identify information regarding the orthopedic doctors who participated in this study and the activities they carry out. Regarding the type of scale used to measure the link between the variables, it should be noted that the 10-point Likert scale was used. The sampling method used was that of the snowball. Regarding the sample, the quantitative study was carried out on 145 orthopedic doctors in Romania. The research was carried out between December 2022 and January 2023.

Analyzing from the perspective of the respondents' profile, it should be stated that, of the total of 145 respondents who participated in the study, most of them (38.6%) were between 36 and 45 years old and 33.1% of them were between 25 and 35 years old, while 20% of the orthopedic doctors who participated in the study were aged between 46 and 55 years. A smaller proportion of those who participated in the research (8.3%) stated that they were over 55 years old. Regarding the gender distribution of the respondents, the majority of those who participated in the study (90.3%) were men, while 9.7% of them were women. A total of 29% of orthopedic doctors worked in a hospital or clinic in Bucharest or Ilfov, while 71% of them worked in another health facility in the country. Studying from the perspective of the type of health facility in which the respondents work, 50.3% of them stated that they worked both in a state hospital and in a private health facility, 28.3% of them only worked in a state health facility, while 21.4% of them worked in a private clinic (Table 1).

Table 1. Presentation of the respondents' profile.

Category		Frequency	Percentage (%)
Gender	Male	131	90.3
	Female	14	9.7
Age	25–35	48	33.1
	36–45	56	38.6
	46–55	29	20
	Over 55	12	8.3
Place where the physicians practice	In Bucharest-Ilfov	42	29
	In a different county in the country	103	71
Health facility where the respondents work	State	31	21.4
	Private	41	28.3
	Both in a state health facility and in a private one	73	50.3

2.2. Regression Model

The regression model that was carried out at the level of this study had the role of determining the link between the dependent variable (the intention of orthopedic doctors to use the new medical technologies in the pandemic era) and the independent variables: the ease of use, the promotional activities carried out regarding the new medical technologies, the advantages perceived by the orthopedic doctors regarding the new medical technologies, the experience of physicians in using these medical technologies, their receptivity regarding the use of the new medical technologies, the quality of the new medical technologies existing in the field of orthopedics, the disadvantages perceived by physicians regarding these technologies, the reliability over time of new medical technologies, the risks perceived by orthopedic doctors regarding the use of new medical technologies as well as the acquisition cost of new medical technologies.

The following formula was used to create the linear multiple regression model [76]:

$$Y = \beta 0 + \beta 1 * X1 + \beta 2 * X2 + \beta 3 * X3 + \beta 4 * X4 + \ldots + \beta n * Xn + \mathcal{E} \quad (1)$$

Within it, the following indicators can be found: Y (the dependent variable at the level of the linear multiple regression model), the β coefficients, the constant (β0), the standard error (Ɛ) as well as the model parameters (X). Applying the previous formula to the model made in this study, the following emerge:

The intention of orthopedic doctors to use the new technologies in the medical field
=
β0 + β1 ∗ Ease of use of new medical technologies + β2 ∗ Promotional activities carried out regarding new medical technologies + β3 ∗ The advantages perceived by orthopedic s doctors regarding the new medical technologies + β4 ∗ The experience of physicians in the use of these medical technologies + β5 ∗ The receptivity of orthopedic doctors regarding the use of new medical technologies + β6 ∗ The quality of the new medical technologies existing in the field of orthopedics + β7 ∗ The disadvantages perceived by physicians regarding the new medical technologies + β8 ∗ Reliability over time of new medical technologies + β9 ∗ The risks perceived by orthopedic doctors regarding the use of new medical technologies + β10 ∗ acquisition cost of new medical technologies + Ɛ

3. Results

In the first part of the quantitative study, the opinion of orthopedic doctors regarding the new medical technologies existing on the market as well as their role in the pandemic era was analyzed. Following the analysis and interpretation of the results, it was noticed that orthopedic doctors believe that these technologies are very important in the field in which they practice. The main sources of information that they use to document themselves about the new technologies appearing on the market in the field of orthopedics are internships abroad (28.3%), specialized publications (13.8%) as well as profile websites where detailed information is presented regarding the advantages offered by new technologies, and the costs incurred for them as well as their usefulness in this field (13.8%). A total of 12.4% of the physicians who participated in the study stated that they obtained information about these technologies from the national and international symposia they attended, 9.7% of them stated that they read existing articles on social networks, while 5.5% of them participated in various online courses. A total of 16.6% of the physicians stated that they documented from other sources (Table 2).

Table 2. The sources of information used by the respondents to inform themselves about the new technologies on the market in the field of orthopedics.

Sources of Information Used	Frequency	Percentage (%)
Symposia	18	12.4
Specialized publications	20	13.8
Specialized sites	20	13.8
Social networks	14	9.7
Internships abroad	41	28.3
Courses held online	8	5.5
Others	24	16.6

The specialists in orthopedics who participated in the study stated that, currently, within the health facilities where they mainly carry out their activity, they use the new medical technologies to a small extent. Only 15.9% of those who participated in the study stated that they had used the new technologies in the field so far, while a large part of them (84.1%) stated that they did not have this opportunity but would want to be able to use them in the next period of time. Regarding the technologies that the respondents would like to use later, most of them (42.1%) stated that they would like to use technologies based on artificial intelligence, 28.3% of them mentioned that they would like to carry out investigations based on a series of robots, 12.4% of those who participated in the study would like to work with technologies based on 3D Printing technology, 9.7% of them would like to use IoT technology for solving the problems they encounter, while 7.6% of the respondents would like to use augmented reality (Table 3).

Table 3. The new technologies that orthopedic physicians would like to use in the next period of time.

Technologies	Frequency	Percentage (%)
Iot	14	9.7
Artificial intelligence	61	42.1
Robots	41	28.3
3D printing	18	12.4
Augmented Reality	11	7.6

Regarding the main advantage of the new medical technologies that can be used in orthopedics, in Table 4, it can be seen that 31.7% of the orthopedic doctors who participated in the study stated that they facilitated the work carried out by the medical staff. A total of 30.3% of them specified the fact that these technologies have the ability to provide detailed information about various conditions that patients suffer from, 26.9% of them considered that reducing the execution time of certain surgical interventions is the most important advantage, 7.6% of them believed that they had the role of reducing costs, while 3.4% of them believed that the higher success rate obtained from the use of these technologies was their main benefit.

Table 4. Respondents' perception of the main benefit obtained by orthopedic doctors following the use of the new medical technologies in this field.

Technologies	Frequency	Percentage (%)
They facilitate the activity of medical specialists	46	31.7
They reduce the performance time of some interventions	39	26.9
They reduce the costs of carrying out some interventions	11	7.6
Higher success rate with certain treatments	5	3.4
They provide detailed information on specific conditions	44	30.3

Analyzing the results obtained at the level of the linear multiple regression model, it can be seen that the value of R is 0.944, while the value of R Square is 0.890, which illustrates the fact that 89% of the variation of the dependent variable is explained by the independent variables considered at the level of this model. The value of Adjusted R Square is 0.882 while the standard error registers the value of 0.584 (Table 5).

Table 5. Model summary.

R	R Square	Adjusted R Square	Std. Error of the Estimate	R Square Change
0.944	0.890	0.882	0.584	0.890

Following the analysis, it was noticed that the value of F is 108,850, and the value of the degrees of freedom is 10 (df1), respectively, 134 (df2). The value of Mean Square is 37,061. Since the value of Sig. < 0.05, the proposed model is accepted (Table 6).

Table 6. ANOVA analysis.

Model	F	df	Sum of Squares	Mean Square	Sig.
Regression	108.850	10	370.610	37.061	0.000
Residual		134	45.624	0.340	
Total		144	416.234		

Analyzing the table of coefficients, in Table 7, it can be seen that only 6 of the 10 independent variables that were considered at the level of the linear multiple regression model were accepted, registering a value of Sig. < 0.05. The independent variables that can be included in the regression model are the advantages perceived by orthopedic doctors with regard to the new medical technologies, the experience of physicians in using these medical technologies, their receptivity to the use of the new medical technologies, the quality of existing new medical technologies in orthopedics, the disadvantages perceived by physicians regarding these technologies as well as the perceived risks. The four variables for which the value of Sig. was greater than 0.05 are the ease of use of the new medical technologies (Sig. = 0.867), the promotional activity carried out for these medical technologies (Sig. = 0.349), the reliability of the new medical technologies (Sig. = 0.056) as well as the cost of acquisition of the new technologies (Sig. = 0.476).

Table 7. Table of coefficients.

	Unstandard. Coeff.		Stand. Coeff.	t	Sig.	Correlations			Collinearity Statistics	
	B	Std. Error	Beta			Zero-order	Partial	Part	Tolerance	VIF
(Constant)	−0.086	0.281		−0.308	0.759					
The ease of use of the new medical technologies	0.005	0.028	0.006	0.168	0.867	0.231	0.015	0.005	0.677	1.477
The promotional activities carried out	0.022	0.024	0.031	0.939	0.349	0.228	0.081	0.027	0.750	1.333
The perceived advantages	0.240	0.031	0.316	7.694	0.000	0.751	0.554	0.220	0.486	2.058
The experience of physicians in the use of the new technologies	0.259	0.036	0.307	7.121	0.000	0.776	0.524	0.204	0.440	2.272
The receptiveness of physicians in the use of the new technologies	0.222	0.038	0.254	5.912	0.000	0.746	0.455	0.169	0.442	2.261
The quality of the new technologies	0.289	0.029	0.351	10.064	0.000	0.676	0.656	0.288	0.673	1.487
The disadvantages of the new technologies	−0.060	0.025	−0.080	−2.409	0.017	0.305	−0.204	−0.069	0.739	1.354
The reliability of the new technologies	0.055	0.028	0.073	1.926	0.056	0.498	0.164	0.055	0.573	1.747
The perceived risks	−0.060	0.026	−0.076	−2.275	0.024	0.278	−0.193	−0.065	0.731	1.368
The acquisition cost of the new technologies	−0.020	0.028	−0.026	−0.715	0.476	0.417	−0.062	−0.020	0.613	1.633

Applying the indicators obtained in Table 5 (Std. Error of the Estimate) and in Table 7 (β coefficients and the constant) within Formula (1) of the multiple linear regression model, the following formulas are obtained:

The intention of orthopedic doctors to use the new technologies in the medical field = 0.316 ∗ The advantages perceived by orthopedic doctors regarding the new medical technologies + 0.307 ∗ The experience of physicians in the use of these medical technologies + 0.254 ∗ The receptivity of orthopedic doctors regarding the use of the new medical technologies + 0.351 ∗ The quality of the new medical technologies existing in the field of orthopedics − 0.80 ∗ The disadvantages perceived by physicians regarding the new medical technologies − 0.76 ∗ The risks perceived by orthopedic doctors regarding the use of the new medical technolo-gies + 0.584

4. Discussion

The new technologies appearing on the market have greatly improved both the medical and pharmaceutical fields [77]. They facilitated the work carried out by physicians, the rapid identification of diagnoses, the performance of certain medical procedures, and communication with the patients [78]. Some technologies have helped physicians to more easily determine the most suitable treatment, perform surgical interventions as precisely as possible, and monitor permanent patients [79]. Their role is to quickly search databases and provide quick answers to certain problems that would normally take a very long time. These medical technologies have the role of reducing human error and limiting problems that may arise due to mistakes made by physicians or nurses [80]. The emergence of IoT, artificial intelligence, 3D technologies [81], or robots has revolutionized medical activities, with these technologies having the role not to replace the medical personnel, but to support their activity. The current capabilities of automatic and deep learning are not yet ready for a fully autonomous surgical intervention, as they are highly dependent on the human resource performing a real-time task on the patient. Those who support the use of robots on an increasingly large scale appreciate the benefits of robotic systems in performing minimally invasive surgical interventions, although they are aware of the costs and the lack of clear benefits that they bring.

The lack of awareness of the capability of computing power as well as the complex nature of interaction with human tissue has led to delays in the penetration of AI in orthopedic surgery. However, artificial intelligence is advancing at a rapid pace, its role being to support medical practice and not to remove specialists from this field. The benefits of implementing robots in orthopedics cannot be guaranteed, as in-depth studies need to be conducted to analyze in detail the connection between intelligent computers, the patient, and the doctor. Future robots could provide a degree of precision that would not be possible to achieve by human specialists [82]. The environment could also be controlled with AI, such as table tilt, temperature, and lights.

In this paper, quantitative research was carried out that aimed to identify the intention of orthopedic doctors to use the new technologies. The results illustrated that orthopedic doctors consider the new technologies in the medical field to be of major importance in the activities that they carry out, gathering information about them both from internships abroad as well as from specialized publications or websites. In the future, they would like to use advanced devices based on artificial intelligence, robots, or 3D printing technology. Regarding the linear multiple regression model, it was noticed that the intention of orthopedic doctors to use the new medical technologies in this field of activity is influenced in a high proportion by the advantages perceived by orthopedic doctors, by their experience regarding the use of the new technologies, by their receptivity regarding their use, the quality of the medical technologies existing on the market, the disadvantages perceived by orthopedic doctors, but also the risks perceived by them.

Regarding the limits of this quantitative study, it must be stated that it was carried out on a number of 145 respondents, which does not allow us to generalize the results to the entire researched community. Moreover, at the level of quantitative research, only the impact that 10 independent variables have on the dependent variable (the intention of orthopedic doctors to use the new medical technologies in the pandemic era) was studied. In the future, these studies should be carried out starting with certain in-depth interviews to be carried out with several experts in the field of orthopedics. These interviews can provide detailed information regarding the opinion of physicians regarding the possibility of using new medical technologies in this sector of activity. In addition, they can be used to identify other independent variables that can be considered at the level of the linear multiple regression model. Moreover, in the future, other studies should be carried out both among hospital managers and among those who coordinate the activity carried out within private clinics. Their aim should be to identify the barriers they encounter in acquiring the new technologies as well as how the acquisition process of new technologies can be facilitated so that orthopedic doctors have the opportunity to work with such medical tools in the future.

5. Conclusions

The use of new medical technologies in the field of orthopedics is not limited only to ML, DL, NLP, and computer vision, researchers in this field aim to achieve completely autonomous medical actions. Even if they are being carried out to a certain extent at the moment, it is desired to apply them on a much wider scale. Orthopedic doctors should be prepared for the use of the new technologies, there should be specialized training to show them how they can be implemented in the operating room or even in the practice. In the future, it is considered that they will be used more and more efficiently in the decision-making process and human risks and errors will be eliminated. Orthopedic doctors can help integrate new technologies into modern medical practice, and because of this, they should constantly collaborate with scientists, providing them with the data they need to implement them in various applications. The new technologies can revolutionize the field of orthopedics and have the ability to provide optimized patient care in the near future. In the future, these technologies are expected to reduce physician burnout as well as the time required to analyze a particular case or perform a surgical intervention, thus allowing for an increase in the number of appointments or surgeries performed per day.

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The Usage of Digital Health Mobile-Based Applications among Saudi Population

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Abstract: This study aimed at assessing the extent to which the general Saudi population has embraced digital health medical applications to meet their health-related needs so that the Saudi Ministry of Health and government can appropriately be guided on scaling up digital health across the country. As such, this study was guided by the question of to what extent the Saudi people use digital health mobile-based applications. This was a cross-sectional study utilizing snowballing sampling approach. Frequencies, Chi-square, and Spearman rank correlation statistics were used to offer descriptive and inferential analysis of the variables. The majority of the participants were economically able to afford smart devices that have medical apps, had at least an app on such devices, and highly regarded the benefits of the apps. Unfortunately, their understanding of how to use such apps was limited, and this posed a barrier to embracing digital health alongside difficulty downloading apps and medical ethical concerns. Although there is a willingness, extra effort is needed from the Saudi Ministry of Health and the government to promote the uptake of digital health in Saudi Arabia.

Keywords: digital health; mobile; mobile-based applications; medical apps; Saudi Arabia

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1. Introduction

The use of digital information electronically transmitted, stored, and obtained to promote health-related activities and services has been encouraged by the world health organization [1]. As such, novel approaches have been proposed to increase the quality of care and enhance outcomes due to an increased incidence of chronic disorders and difficulties in maintaining adequate screening and follow-up measures [2,3]. Digital health and telemedicine can perform various healthcare procedures [4]. These approaches can significantly enhance the quality of long-distance care, provide patients with suitable preventive and educational options about their disorders, and keep them in touch with their healthcare team in addition to maintaining adequate levels of data privacy [5,6]. Digital health can be used for many purposes, including educational campaigns and research to further enhance the quality of care.

Moreover, properly applying the approaches of digital health and medical applications can also improve access to high-quality and costly approaches that can improve outcomes [7,8]. Mobile and Internet healthcare applications and websites have increased recently [9]. This might be due to increased awareness of the benefits that they offer, including easy monitoring of health [10]. Similar modalities have been reported in developed countries, including online systems and databases that monitor patients with chronic diseases while also offering emergency care [11]. However, the concept of digital healthcare and medical applications within developing countries is still poor [12,13]. For instance, an investigation from Libya estimated that 12% of healthcare workers were not familiar with telemedicine, and only 39% had an adequate understanding of digital healthcare modalities [14].

Attitudes toward the use of digital healthcare and medical applications are markedly affected by individuals' knowledge and awareness [14]. There are many reasons for this, including the fact that applying these approaches is challenging for individuals in developing countries. These people may have poor training in these modalities and require an introduction to new technologies [15]. Accordingly, adequate assessment of knowledge and awareness is essential to determine the appropriate plan before planning any interventions. However, there is a dearth of evidence in Saudi Arabia exploring the extent to which the general population has embraced medical apps. There was a need to conduct a study to understand the usage of digital health mobile-based applications by the people living in Saudi Arabia. The purpose of this research, therefore, was to explore the usage of digital mobile-health-based applications among Saudis with the aim of suggesting ways in which it can be enhanced.

2. Methods

2.1. Study Design and Setting

An analytical cross-sectional study was conducted between October and December 2021 in Saudi Arabia.

2.2. Study Population and Sampling

All people in Saudi Arabia aged at least 15 years old and having a smart device at the time of data collection were eligible to participate in this study. A snowball approach of sampling was used to identify participants. Any person with a link was urged to send it to a friend(s). Opening the link and filling in the questions in the link implied informed consent to all participants.

2.3. Data Collection and Tool

Data were collected using a researcher-designed survey. A link to the survey was shared by the researchers to all their friends, and they were encouraged to share it with as many people as possible across the country. The sharing of the link was through Facebook, Twitter, Instagram, LinkedIn, and WhatsApp. A pre-coded pre-tested questionnaire done specifically for this study contains background questions in addition to other close-ended questions that can investigate awareness and attitudes toward digital health and medical applications. The participants had to answer multiple questions, including demographic factors and questions related to the study objectives. Five different items on the questionnaire measured the knowledge and awareness of the participants. Questions developed regarding knowledge include (1) the number of medical applications that have been downloaded on the mobile device, (2) how much the participant knows about medical applications, (3) the number of official Saudi authorities' applications that have been used, (4) and whether they faced any difficulties while completing the data in the application. Awareness questions included (1) whether the subjects had heard of digital health, (2) the number of medical applications on the device, (3) how much they know about smart devices' medical applications, (4) whether they have benefited from those applications in medical uses and situations, (5) and whether they agree that using medical applications on a smart device is necessary.

2.4. Data Analysis

Data were entered, coded, and processed using Microsoft Excel and the software Statistical Package for Social Science (SPSS) (Version 23). Descriptive statistics were generated for all variables. A correlation was computed to investigate if there was a statistically significant association between participants' educational level, number of apps on their devices, and knowledge of smart devices medical apps. All the data were ordinal; thus, Spearman rank correlation statistic was calculated. A Chi-square test was run to determine whether there was a significant difference in using medical apps among participants of differing characteristics. All statistical tests were considered significant at $p < 0.05$.

2.5. Ethical Approval

Ethical approval was obtained from Almaarefa University, Riyadh, Saudi Arabia. Confidentiality and anonymity were maintained throughout the study, and the collected data were only used for the purposes described in the study objectives.

3. Results

As indicated in Table 1, the majority of the participants were females (67.1%), aged 31 years and above, and Saudi nationals (90.9%). Most of these participants had completed a college level of education (70.5%) and were residing in villa residence type (70.4%) and had owned residence status (71.9%). Most of the participants also had a monthly income of between 6000 and 10,000 (64.9%), did not report having any chronic illnesses (56.5%), were not taking regular medicines (59.1%), and had never faced any medical condition requiring urgent intervention (69.8%).

Table 1. Socio-demographic characteristics of study participants.

Characteristic		Frequency	Percent
Gender			
	Female	494	67.1
	Male	242	32.9
Age			
	15–22 years	110	14.9
	23–30 years	135	18.3
	31–38 years	115	15.6
	39–46 years	138	18.8
	47 or older	238	32.3
Education Level			
	High school	175	23.8
	College	519	70.5
	Elementary	36	4.9
	Primary	6	0.8
Nationality			
	Saudi	669	90.9
	Non-Saudi	67	9.1
Residence type			
	Villa	518	70.4
	Apartment	150	20.4
	A floor of three	68	9.2
Residence Status			
	Owned	529	71.9
	Rented	207	28.1

Table 1. *Cont.*

Characteristic		Frequency	Percent
Monthly Income			
	Less 2000	60	11.3
	2000–5000	127	23.8
	6000–10,000	346	64.9
Suffer from any chronic diseases or allergies			
	Yes	320	43.5
	No	416	56.5
Using regular medications			
	Yes	301	40.9
	No	435	59.1
Faced a medical condition requiring urgent intervention			
	Yes	222	30.2
	No	514	69.8

Table 2 shows the participants' responses about using medical applications on their smart devices. The majority of the participants had heard of digital health (53.4%) from internet advertisements (24.6%), healthcare workers (15.2%), and family/friends (22.1%). The majority of the participants had at least two medical apps on their smart devices (63.7%). Unfortunately, most (63.5%) of these participants had little knowledge about medical apps on smart devices. Eighty-eight percent (88%) of the participants believed that medical apps positively affect the quality of provided health care and that using medical apps to access personal medical data was appropriate (89.5%). Most (89%) of the participants have never been in a situation of using medical applications to know the medical history to save an injured person. Participants who believed medical data and medical history were not private information were as many as those who believed it was private information.

Table 2. Participants' responses to questions about medical apps usage.

	Usage of Medical Apps	Count	Percentage (%)
Heard of digital health			
	Yes	393	53.4
	No	343	46.6
Source of information for digital health			
	Internet Advertisement	181	24.6
	Do not know about it	280	38.0
	Healthcare worker	112	15.2
	Family and Friends	163	22.1
Number of medical applications on device			
	One	185	36.3
	Two	141	27.7
	Three or more	183	36.0

Table 2. *Cont.*

	Usage of Medical Apps	Count	Percentage (%)
Knowledge about smart devices in medical applications			
	Little	467	63.5
	A lot	110	14.9
	Nothing	159	21.6
How applications affect the quality of provided healthcare			
	Positively	648	88.0
	No effect	81	11.0
	Negatively	7	1.0
Using smart devices medical application to access personal medical data is an appropriate way			
	Yes	659	89.5
	No	77	10.5
Completed filling up the required data related to history of illnesses in the applications			
	Yes	247	33.6
	No	489	66.4
Ever been in a situation of using medical applications to know the medical history to save an injured person			
	Yes	81	11
	No	655	89
Medical history in applications useful to any of the medical teams in a previous emergency			
	Yes	48	6.5
	No	130	17.7
	Never been in a situation where it was needed	558	75.8
Some medical applications are part of the operating system of smart devices which does not require downloading.			
	Yes	250	34.0
	No	486	66.0
Medical data and history of illness are private information that you do not prefer to share			
	Yes	368	50.0
	No	368	50.0

Table 3 shows that one of the pairs of the variable (number of medical apps on the device and knowledge about smart devices medical applications) was significantly correlated, r (507) = 0.178, p = 0.000. The direction of the correlation was positive, meaning that highly educated participants tend to have more knowledge about smart devices and medical applications and vice versa.

Table 3. Intercorrelations, Means, and Standard Deviation for three variables (N = 509).

Variable	1	2	3	M	SD
1. Education Level	---	−0.002	0.057	1.83	0.54
2. Number of medical apps on device	---	---	*0.178* *	2.00	0.85
3. Knowledge about smart devices' medical applications	---	---	---	1.58	0.82

* Italic and asterisk values indicate statistical significant (i.e., $p < 0.05$).

Table 4 shows that being in a situation of using medical applications to know the medical history for the sake of saving an injured person was statistically significant. The participants who had never been in a situation of using medical applications to know the medical history for the sake of saving an injured person used the medical apps on their smart devices less than their counterparts who had been in such a situation ($X^2 = 4.97$, $df = 1$, $N = 736$, $p = 0.026$).

Table 4. Chi-square statistic to determine difference for use of medical apps among participants of selected characteristics.

		Used Any of the Saudi Authorized Medical Apps			
Variable	***n***	**Yes**	**No**	**X^2**	***p***
Monthly Income:					
Less 2000	60	12	48	1.44	0.488
2000–5000	127	18	109		
6000–10,000	346	49	297		
Suffers from chronic illnesses or allergies:					
Yes	320	58	262	0.14	0.708
No	416	71	345		
Using regular medication:					
Yes	301	55	246	0.20	0.658
No	435	74	361		
Been in a situation of using medical applications to know the medical history for the sake of saving an injured person:				4.97	*0.026* *
Yes	81	7	74		
No	655	122	533		

* Italic and asterisk values indicate statistically significant (i.e., $p < 0.05$).

Figure 1 shows medical apps that are commonly used in Saudi Arabia to provide healthcare to the people. As shown in Figure 1, the majority of the participants had "Tawakkalna" application on their smart devices (27%), followed by "Sehha" (21%).

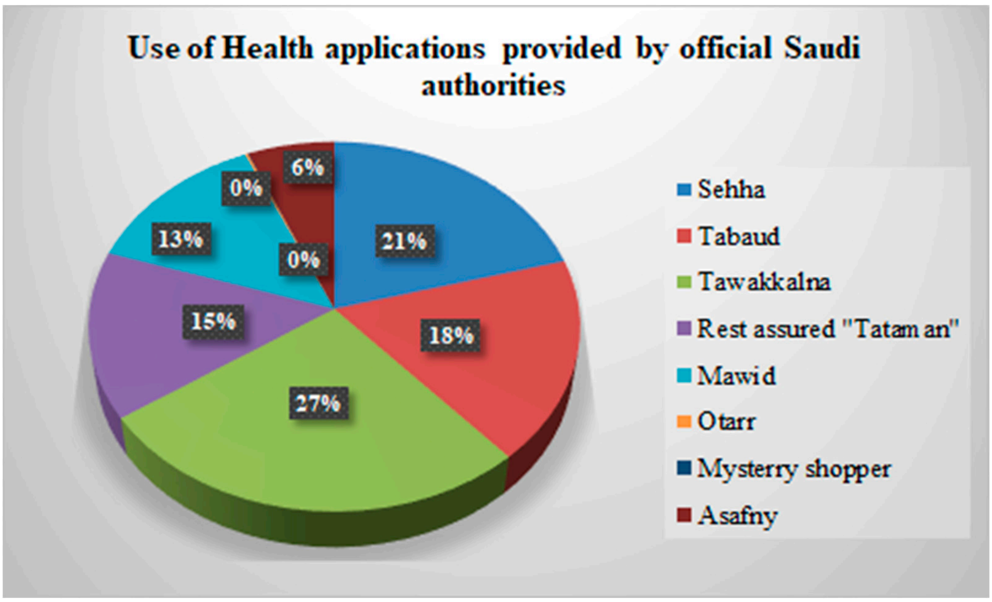

Figure 1. The use of health applications provided by official Saudi authorities.

As far as the benefits of using medical applications are concerned (Figure 2), most of the participants reported improving the process of making the right decision, followed by providing faster medical intervention and enhancing communication between different healthcare teams.

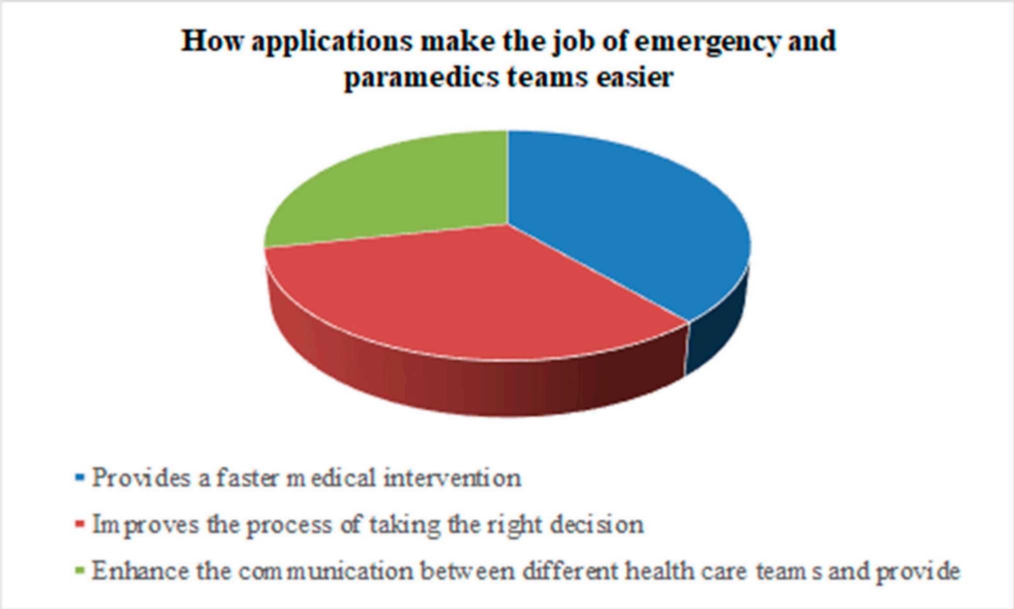

Figure 2. How applications make the job of emergency and paramedics teams easier.

While the majority of the participants reported having no barrier to the use of medical applications on their smart devices (Figure 3), the three common barriers reported by participants were minimal knowledge about the application, difficulty in downloading the application and using it as well as privacy related to medical data.

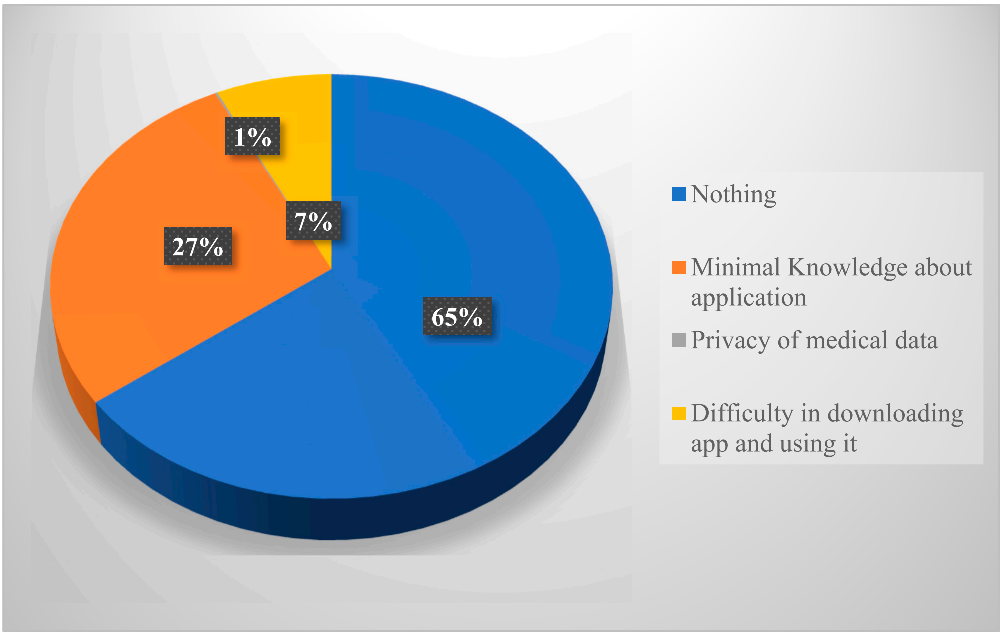

Figure 3. Barriers to use of medical applications on devices.

4. Discussion

As electronic health records gradually replace paper-based methods in healthcare, the manifestation of such changes needs to be assessed in Saudi Arabia. While evidence shows that Saudi Arabia has adopted electronic health records [16–18], the usability of such records has not been widely studied. Yet, electronic health records have been found to increase healthcare quality and patient safety by making patient medical information readily available and accessible to any authorized user. While electronic(e) health, digital health, and mobile (m) health can be used interchangeably [18], this manuscript sticks to the use of "digital health in mobile" apps. Digital health is the application of information technology in healthcare by either the health workers through systems or patients through mobile applications [19]. The systems used by health workers in hospitals and clinics largely take on electronic health records that are not the focus of this manuscript, and the mobile applications that create communication between patients and health workers are the focus of this manuscript. Other studies that have studied the usability of medical apps have looked at it through the lens of education/learning apps that have medical information and are not for communication between patients and health workers. For example, Al-ghamdi found increased use of Medscape, Gray's Anatomy, UpToDate, and Oxford mobile dictionary medical apps in Saudi Arabia relating to where one can find any needed medical information [20]. This study therefore aimed at exploring the extent to which people in Saudi Arabia use medical apps while highlighting the barriers and facilitators to that usability.

In this study, most participants had at least a medical app on their smart devices. In a previous study, Atallah et al. reported similar findings about mentally challenged people [21]; each of them had between one and two applications on their phones. For some reason, people with health concerns in countries where digital health is promoted have been found to have medical apps mostly on their phones [22]. This study finding implies that a reasonable number of Saudis have embraced the government's call to the utilization of electronic health. In 2018, the Saudi government launched digital health in the country and urged all healthcare facilities and practitioners to embrace the new technology-oriented care [23]. While huge strides have been observed in this regard, the progress warrants the local people to also embrace the move.

The majority of the participants in this study largely believed that the medical apps were good. However, they reported having little knowledge about the use of these medical apps. The knowledge of medical applications was affected by the education level of the participants. The study findings show that the participants who were more educated were more likely to understand medical apps compared to those who were less educated. On the contrary, the majority of the participants were above college-level education, yet, with little knowledge. Implying that other factors could have been responsible for this observation that the study did not explore well.

It is important to note that most of the participants had never suffered from any chronic illnesses, were not taking regular medicines, never faced a medical condition requiring urgent intervention, and had never been in a situation of using medical applications to know the medical history for the sake of saving an injured person. Subsequently, the correlation statistic indicated that the participants who had never been in a situation of using medical applications to know the medical history for the sake of saving an injured person used the medical apps on their smart devices less than their counterparts who had been in such a situation. As such, while it was important to understand digital health considering the general population, it is also important to note that some of the questions asked created a limitation to this study. The respondents had not much knowledge of the asked subject areas. While the majority of the participants had never heard about digital health, their major source of information was the Internet, and less health worker communication. Similarly, other studies have indicated that even among health workers, medical app utilization is low due to personal reasons [24]. Some health workers are still locked up in the traditional life of no smart devices, and even when they obtain smart devices, they are not interested in the functioning of the medical apps on such devices. Given the fact that the Saudi government has intentionally financed the implementation of e-health [25], it should as well widen the health communication to the population (specifically to non-health workers) so that people are aware of the importance and the use of digital health as well. Because evidence also shows that the knowledge of digital health among health workers is lacking [25], wholistic equipping of Saudi people, including health workers on digital health is important and urgently needed. Digital uptake among health workers should be enforced first before scaling it up across the general population.

Digital health education can be emphasized and enforced at the medical/health students' training level. Or short courses can be developed to be occasionally provided to the health workers in practice. In a different way, Brown and Bewick propose engaging the end users (health workers and people) throughout the process of developing an app or before the formal rolling out of the app [26]. The authors also suggest introducing digital health and electronic health records contained in the curriculum to students so that students can start learning how to support themselves over minor illnesses. This engagement would help minimize the challenges that come with using such apps following their formal release to the public.

This study showed that the participants were financially stable enough to own smart devices that could accommodate medical applications. The majority of the participants were residing in owned apartments and of Villa type, and their monthly income level was between SAR 6000 and SAR 10,000. As such, one would be moved to conclude that they can afford smart devices and the costs involved with the digital health approach.

The importance of digital health records has been demonstrated by many participants. Participants indicated that digital health improves the process of making the right decision, provides a faster medical intervention, and enhances communication between different healthcare teams. Similarly, studies elsewhere have pointed to digital health being of benefit to both patients and healthcare workers [20,27,28]. Al-ghamdi asserts that medical apps on smart devices increase physicians' accuracy, efficiency, and productivity [20].

For the Saudi Arabia government, this current understanding is good and shows an upward trend toward the desired full penetration of digital health in the country, which was shown to be very low in 2019 [28]. As full medical application penetration is realized, Saudi Arabia will be just like other developed countries that largely rely on digital health implementation for quick interactions between health workers and patients or even in emergency situations where urgent help is needed, and the doctor or physician might not be close. In some instances, patients' conditions are not so critical to attract physical movement to a health facility. For example, patients with chronic conditions can be supported electronically from their places of residence through their phones.

The following applications have been provided by the Saudi Ministry of Health and can freely be downloaded on any device; Sehhaty, Tawakkalna, Tabaud, Seha, Mawid, and Tataman [29]. Most participants had Tawakkalna and Sehha medical apps on their digital devices. The high use of these two apps is linked to the availability of several services it provides and their mandatory use to obtain services from private and public organizations [22]. Additionally, the high use could be linked to the fact that the Sehha app was the seminal application in 2018 as the Saudi government was launching telemedicine [23]. The Tawakkalna app was later introduced in 2020 as the main contact tracing app for COVID-19-related cases. Contrastingly, in a very recent study, these two apps received the least usability ratings regarding COVID-19 [16]. The respondents reported facing several barriers ranging from increased battery drain and lack of privacy to technical issues [16]. Nevertheless, it is important to observe that the use of medical apps in Saudi Arabia is on the rise and requires slight enforcement.

The commonly reported barriers to digital health were knowledge about application use, the privacy of medical data, and difficulty downloading the apps. The same barriers have been reported previously in Saudi Arabia. Aljohani and Chandra assert that for Saudi Arabia to succeed fully in digital health, the apps should be reliable enough to provide accurate and up-to-date data [28]. Additionally, Aljohani and Chandra put forward social influence as a barrier to digital health; the authors asserted that some health workers and the Saudi population exhibit a culture of boredom pertaining to digital health [28], hence, a need to address it for the success of digital health promotion in the country. An additional barrier that could be worth paying attention to is the language in which most apps have been introduced. While Arabic is largely spoken in Saudi, evidence shows that most of the apps have been introduced in English [30], creating a language barrier for would-be users. It is, therefore, a mandate of the Saudi government to address the barriers above if digital health is to blossom in Saudi Arabia.

The World Health Organization asserts that embracing digital health at both local and distant levels would tremendously address and enhance the struggling healthcare systems in developing countries that have trained doctors, clinicians, equipment, and infrastructure constraints [1]. It is believed that digital health closes the rural–urban divide in many countries [31]. In addition to the recommendations provided throughout this discussion, the following are further provided: (1) A clear policy focus by the Saudi Arabia government is needed to amalgamate the hospital and clinic digital health systems with the way the public ought to fit in. (2) Investment in cross-border health data security in all management systems. This will give confidence to people/patients to freely share their information for the sake of its use in apps. (3) Identifying the best medical apps. Given the fact that some medical apps have received negative reviews from users [20], it is imperative for the Ministry of Health of Saudi Arabia to invest in understanding the best apps and advocate for any required financing for their upscaling.

This study obtains its strength in the snowballing sampling method that was able to reach many people with relevant information and the expert review of the proposal by the institutional review board. Unfortunately, it is limited by the lack of generalization due to the non-randomness of the sampling process and the subjective nature of the questions that would attract responses as understood by the participants. Furthermore, this research does not distinguish between respondents from urban and rural settings. Maybe such a distinction would create different findings.

5. Conclusions

This study has shown that digital health among Saudis has several benefits that are on both the side of healthcare and personal health. While many participants already have medical apps on their smart devices, the current study findings indicate that there is a knowledge gap pertaining to their use. Other non-knowledge-related barriers to medical app utilization exist that make people hesitant to both have apps on their smart devices and uncomfortable using them. Given the fact that the Saudi government was at the center of the initiation of digital health in Saudi Arabia, it has an additional role in addressing the barriers hindering the understanding and use of medical apps. This study had several limitations, as indicated throughout the discussion, that make it inappropriate to generalize the results to other study settings. Additionally, further research is needed to fully evaluate the progress on digital health uptake among healthcare workers and how the healthcare workers are motivating the patients or potential patients to embrace it.

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Institutional Review Board Statement: This study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures involving research participants were reviewed and approved by the Local Research and Ethical Committee of AlMaarefa University numbered (3/211) with (approval number: ECM#2023-803).

Informed Consent Statement: Written informed consent was obtained from all subjects.

Data Availability Statement: Data used in this analysis can be obtained by contacting the corresponding author.

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Effect of Mobile Health Interventions on Lifestyle and Anthropometric Characteristics of Uncontrolled Hypertensive Participants: Secondary Analyses of a Randomized Controlled Trial

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Abstract: Our objective was to evaluate the effect of a mobile health (mHealth) intervention on lifestyle adherence and anthropometric characteristics among individuals with uncontrolled hypertension. We performed a randomized controlled trial (ClinicalTrials.gov NCT03005470) where all participants received lifestyle counseling at baseline and were randomly allocated to receive (1) an automatic oscillometric device to measure and register blood pressure (BP) via a mobile application, (2) personalized text messages to stimulate lifestyle changes, (3) both mHealth interventions, or (4) usual clinical treatment (UCT) without technology (control). The outcomes were achieved for at least four of five lifestyle goals (weight loss, not smoking, physical activity, moderate or stopping alcohol consumption, and improving diet quality) and improved anthropometric characteristics at six months. mHealth groups were pooled for the analysis. Among 231 randomized participants (187 in the mHealth group and 45 in the control group), the mean age was 55.4 ± 9.5 years, and 51.9% were men. At six months, achieving at least four of five lifestyle goals was 2.51 times more likely (95% CI: 1.26; 5.00, p = 0.009) to be achieved among participants receiving mHealth interventions. The between-group difference reached clinically relevant, but marginally significant, reduction in body fat (−4.05 kg 95% CI: −8.14; 0.03, p = 0.052), segmental trunk fat (−1.69 kg 95% CI: −3.50; 0.12, p = 0.067), and WC (−4.36 cm 95% CI: −8.81; 0.082, p = 0.054), favoring the intervention group. In conclusion, a six-month lifestyle intervention supported by application-based BP monitoring and text messages significantly improves adherence to lifestyle goals and is likely to reduce some anthropometric characteristics in comparison with the control without technology support.

Keywords: hypertension; lifestyle; physical activity; diet; body fat; digital health; mHealth

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1. Introduction

High blood pressure (BP) is a primary cause of cardiovascular diseases [1]. The prevalence of individuals with BP of 140/90 mmHg or higher has doubled since 1990, reaching 626 million women and 652 million men in 2019, and less than half on treatment had controlled hypertension [2]. However, a healthy lifestyle and BP-lowering medication can avert BP elevation [3], leading to reduced mortality rates, years lived with disability, and years of life lost [4].

A healthy lifestyle can aid in controlling hypertension. This includes maintaining a normal weight, following a healthy low-sodium diet, increasing physical activity, quitting smoking, and limiting alcohol consumption [3,5]. Additionally, a healthy lifestyle can prevent excess body fat accumulation and its associated risk of uncontrolled hypertension [6–8]. Despite a diagnosis of hypertension, few patients tend to modify their lifestyle or sustain adherence to lifestyle recommendations [9–11].

Health technology has opened up new opportunities for enhancing care for chronic conditions, such as hypertension [12,13]. This is particularly relevant after the COVID-19 pandemic. Given the ever-increasing number of smartphone users worldwide [14], mHealth interventions have the potential to not only control BP, but also foster significant lifestyle modifications [15]. Despite numerous randomized controlled trials evaluating the effectiveness of mHealth for promoting smoking cessation, physical activity, dietary improvement, alcohol consumption reduction, and weight loss, the findings have been inconclusive. The results are influenced by various factors, including population characteristics, type of technology, lifestyle intervention, follow-up duration, health professional involvement, and comparator utilized [12,16,17]. Therefore, further studies are required to assess the effectiveness of diverse mHealth strategies in enhancing risk factor management and overall lifestyle.

We evaluated two mHealth interventions and their effectiveness compared to the usual standard of care in outpatient clinics. Specifically, we examined their impact on risk factors for hypertension. If the results were significant, it may be feasible to apply these interventions to outpatients of public health. This analysis aims to determine whether a six-month lifestyle intervention, supported by mHealth, can improve the lifestyle and reduce anthropometric indices of individuals with uncontrolled hypertension who are taking BP-lowering medications.

2. Materials and Methods

2.1. Design

This factorial randomized controlled trial was designed to evaluate Technologies for Innovative Monitoring (the TIM Study) to reduce BP (primary endpoint) and change lifestyle (secondary endpoint). Participants were randomly assigned to one of four groups: (1) telemonitoring home BP (TELEM), (2) text messages for lifestyle (TELEMEV), (3) telemonitoring home BP, and text messages for lifestyle (TELEM-TELEMEV), or (4) control (usual clinical treatment [UCT]). The purpose of TIM Study was to explore potential interventions for promoting lifestyle changes, body fat and/or reducing blood pressure. While the specific method used may not be critical for public health purposes, the intervention must be effective. To that end, we combined the three intervention groups into a pooled mHealth intervention for analysis, while also presenting effect sizes and confidence intervals for each intervention arm separately. The TIM study is registered at www.clinicaltrials.gov with the ID number: NCT03005470 and details have been published [18].

2.2. Participants

Participants were recruited from primary care clinics or online advertising. The trial enrolled individuals aged 30 to 75 years, with hypertension diagnosis, taking one or two BP-lowering medications, and uncontrolled BP. Participants must have a smartphone and internet access. To determine eligibility for the study, we conducted face-to-face consultations with participants and evaluated their blood pressure using standard protocols. To be eligible, participants had to meet two criteria: first, their office blood pressure had to be uncontrolled, which was defined as a systolic blood pressure of 135 mmHg or higher or a diastolic blood pressure of 85 mmHg or higher. Second, their ambulatory blood pressure monitoring had to be uncontrolled, which was defined as a 24 h systolic blood pressure of 130 mmHg or higher or a diastolic blood pressure of 80 mmHg or higher.

We excluded participants with severe hypertension (systolic BP $\geq$ 180 mmHg or diastolic BP $\geq$ 110 mm Hg), a major cardiovascular event in the previous six months, other indications for the use of antihypertensive medication, diagnosis of secondary hypertension, pregnancy or lactation, or inability to tolerate the interventions. In three consecutive morning office visits, potentially eligible participants were evaluated to confirm BP eligibility criteria. The study was conducted in the Clinical Research Center of the Hospital de Clínicas de Porto Alegre. The institution's institutional review board approved the study (GPPG number 16-0187/CAAE 31423214.0.0000.5327), and written informed consent was obtained from all participants according to the principles expressed in the Declaration of Helsinki.

2.3. Interventions and Control

All participants received an individual personalized lifestyle session at baseline. The lifestyle session was performed by a certified researcher with the support of an illustrated colorful booklet, where we presented specific recommendations for living a better lifestyle to control their BP. The instructions included maintaining a normal weight, following the dietary approach to stop hypertension (DASH-type diet) with low sodium intake, performing regular physical activity, stopping smoking or maintaining a habit of not smoking, and no drinking or moderate consumption of alcohol. The study arms are described below.

2.3.1. TELEM Intervention

Participants received an automatic oscillometric device to measure BP five days per week and one day on the weekend. Participants were trained to use the monitor and instructed to perform four daily measurements (two in the morning and two in the evening). The monitor sent BP values to the data center through an application. Participants could also enter BP data manually in the application. After sending BP measurements, participants received a prompt on the mobile phone with feedback about their BP control based on the value entered.

2.3.2. TELEMEV Intervention

Participants received personalized, standardized unidirectional text messages via an application developed for the study to stimulate lifestyle changes. Experts developed messages based on guidelines that emphasized the adoption of a DASH-type diet, reducing sodium intake, reducing alcohol consumption, increasing physical activity, managing weight loss, and taking medications to lower blood pressure regularly. These messages were inserted into software which sent messages automatically, four days a week, during random business hours, without another cell phone contact. Examples of text messages can be found in the Supplementary Materials (Table S1).

2.3.3. TELEM-TELEMEV Intervention

Participants received both mHealth interventions: telemonitoring of BP plus text messages via a mobile application.

2.3.4. UCT

The control group received the healthy lifestyle intervention using the information presented in the booklet in a guided session. Participants did not receive any technological tools or additional BP control.

We combined the three intervention groups into a pooled mHealth intervention for this analysis. Considering that the effectiveness of any intervention would allow for achieving the objective of the study, the lack of interaction between the intervention arms and the outcomes as well as the limited power to assess the individual arm's effect on lifestyle support this approach.

From randomization, follow-ups were scheduled for 7, 30, 90, and 180 days. Participants were asked about adherence to lifestyle recommendations during all visits and were allowed to clarify doubts with the researchers.

2.4. Measurements

Demographic and socioeconomic characteristics were collected at baseline, including age, sex, reported skin color, education level, and work status. All measurements taken during the study were performed on calibrated equipment. At baseline and six-month follow-up, standardized anthropometric measurements of waist circumference (WC), at the midpoint between the lower costal margin and the iliac crest, body weight (kg), and height (cm), to calculate the body mass index (BMI, in kg/m^2), were collected at the clinic by certified healthcare professionals. The bioelectrical impedance analysis InBody 230 (Biospace Co., Ltd., Des Moines, IA, USA) estimated total and segmental trunk body fat. Physical activity level was evaluated using the short-form International Physical Activity Questionnaire [19] for the seven days prior to the randomization, as well as dietary consumption using a validated Food Frequency Questionnaire [20]. Alcohol consumption and smoking status were evaluated using standardized questionnaires. This data collection was repeated in the follow-up.

2.5. Outcomes

The lifestyle change was operationalized by achieving four out of five goals in the follow-up without medication titration. The five lifestyle goals were as follows: lose at least 3 kg or maintain normal BMI; refrain from smoking; engage in regular physical activity for at least 150 min/week; consume no alcohol or drink moderately ($\leq$100 g and $\leq$200 g of alcohol/week for women and men, respectively); achieve at least two of six dietary recommendations: reach or maintain at least 21 servings/week of fruits and vegetables, 14 servings/week of whole grains, seven servings/week of low-fat dairy; consume only one serving/week of sodium-rich foods, <1 serving/week of fast foods or fried foods, and <1 serving/week) of fried or fatty meats. The reduction of at least one anthropometric characteristic was considered a successful outcome (i.e., body fat mass [kg], percentage of body fat [%], segmental trunk fat [kg], percentage of segmental trunk fat [%], BMI [kg/m^2], or WC [cm]).

2.6. Randomization

A computer-generated sequence was created using random allocation software [21] to assign participants to groups using permuted random block sizes of four and eight. An investigator not involved in the participants' enrollment generated the randomization sequence before the trial began. The sequence list was kept in Research Electronic Data Capture software [22], preventing the research team from anticipating to which arm the next participant would be allocated. Data were released after the baseline data collection was completed. Due to the nature of the study, subjects could not be blinded to the intervention; however, the investigator who performed the data analysis was blinded.

2.7. Statistical Methods

TIM Study sample size was calculated to detect a reduction of systolic BP assessed by 24 h ABPM (primary endpoint), and the results were previously presented [23]. This analysis presented data from the secondary endpoint defined a priori. The recruitment of 231 subjects (with 186 in one of the mHealth interventions groups and 45 in control) had sufficient statistical power (85%) to detect a statistically significant difference in 25% achievement of the four of five lifestyle goals between groups with a significance level of 0.05 using a two-sided test. The effectiveness of the pooled mHealth intervention (TELEM + TELEMEV + TELEM-TELEMEV groups) was compared to the control group, which did not receive mHealth intervention (UCT group). Independent samples *t*-test for continuous and chi-square for categorical variables were used to describe the baseline characteristics. A generalized Poisson mixed model was used for binary outcomes of achieving lifestyle goals between mHealth and control groups, adjusting for baseline values, with relative risks and 95% confidence intervals (CIs). General Linear models (GLMs) were used to calculate weight and food groups consumption mean difference between-groups, adjusted for baseline value. Poisson and GLM analysis were performed using complete cases at 6 months. Generalized Estimating Equations (GEE) were used to analyze measurements taken over time on the same individuals. The response variable was the pooled mHealth intervention effect, which has a normal distribution. The identity link function was used. This assumption implies that the data points are not independent, and the GEE model takes this into account while analyzing the data. Additionally, the GEE model accounted for correlated data using an unstructured correlation matrix and adjusted for this correlation using robust covariance estimation. In the GEE, differences between the two groups at six months were evaluated using the adjustment of Bonferroni. These analyses were performed using the intention-to-treat approach in SPSS version 21.0; a two-sided $p < 0.05$ was considered statistically significant.

3. Results

From July 2016 to July 2018, 7750 potential participants were identified at the primary care facilities and the media announcements were screened; 1536 were checked to confirm eligibility at the research clinic. Of these, 467 had BP eligibility criteria assessed by ABPM, 231 met both office BP and ABPM criteria and were randomized. Participants were allocated to the pooled mHealth intervention or UCT control group at a ratio of 186 to 45 (Figure 1).

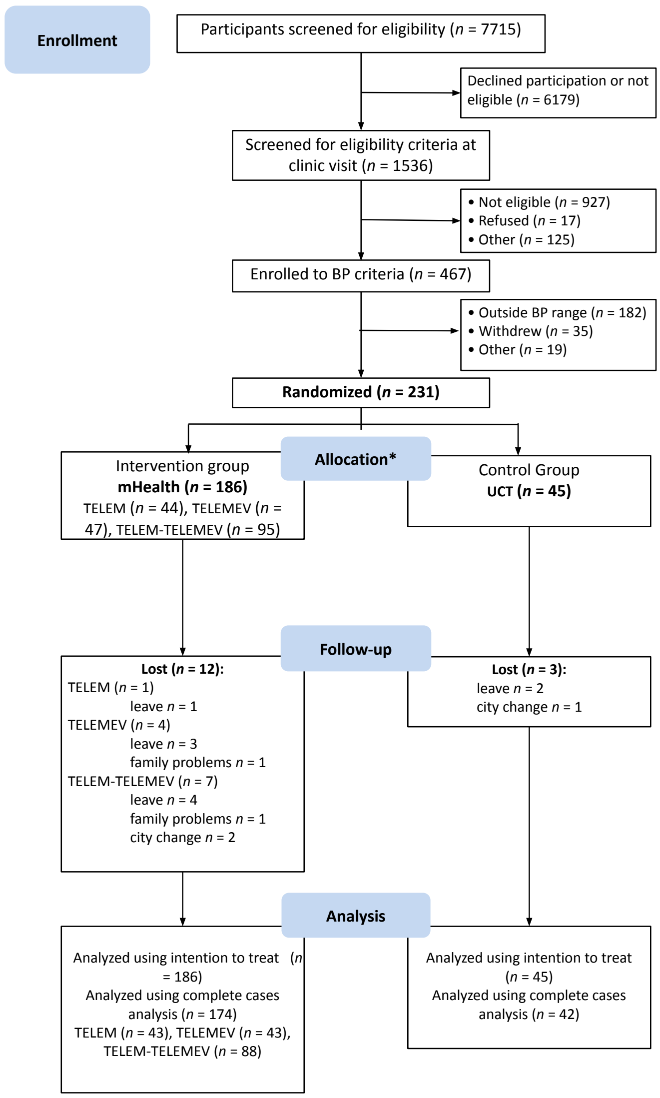

Figure 1. Study flowchart describing selection, randomization, and follow-up process. BP indicates blood pressure. * All participants received the allocated intervention.

At the six-month follow-up, 174 participants in the intervention and 42 in the control group were evaluated for lifestyle characteristics. During follow-up, two participants in the pooled mHealth group discontinued the intervention (one from TELEM and one from TELEM-TELEMEV group) informing unavailability of time to perform the BP check as requested by the protocol. However, they followed up at the study visits. No adverse events were reported during the study follow-up. Table 1 shows that baseline characteristics were similar between groups. Participants were 55.4 ± 9.5 years (mean ± SD), 51.9% were men, and 64.9% were white, with mean education years of 11.1 ± 3.9, and 31% had not completed high school. The mean BMI was 30.5 ± 5.1 kg/m^2, and the mean systolic and diastolic BP were 143.7 ± 11.4 mmHg and 89.6 ± 8.1 mm Hg, respectively.

Table 1. Baseline characteristics, mean ± SD or n (%).

Characteristics	All Participants (*n* = 231)	Pooled mHealth Group (*n* = 186)	UCT Group (*n* = 45)
Age (years)	55.4 ± 9.5	55.5 ± 9.7	55.0 ± 8.7
Male	120 (51.9)	94 (50.5)	26 (57.8)
White skin color	150 (64.9)	120 (64.5)	30 (66.7)
Education (years)	11.1 ± 3.9	11.1 ± 4.0	11.1 ± 3.9
Currently working	154 (66.7)	124 (66.7)	30 (66.7)
Smoking status			
Never	111 (48.1)	90 (48.4)	21 (46.7)
Former	86 (37.2)	70 (37.6)	16 (35.6)
Current	34 (14.7)	26 (14.0)	8 (17.8)
BMI (kg/m^2)	30.0 ± 5.1	29.5 ± 4.9	31.3 ± 6.0
Diabetes mellitus	47 (20.3)	37 (19.9)	10 (22.2)
Systolic blood pressure (mmHg)	143.7 ± 11.4	143.5 ± 11.4	144.5 (11.3)
Diastolic blood pressure (mmHg)	89.6 ± 8.1	89.2 ± 8.0	91.3 ± 8.1

Data from independent samples *t*-test for continuous and chi-square for categorical variables; mHealth = mobile health; UCT = usual care treatment; SD = standard deviation.

3.1. Lifestyle Goals

Table 2 describes baseline and six-month lifestyle characteristics by intervention groups, as well as the relative risk (95% CI) at the end of the trial, adjusted for baseline values. At 6 months, participants in the pooled mHealth group were 1.2 (95% CI: 1.03; 1.42) times more likely to practice at least 150 min/week of physical activity at the end of the trial compared to the control group. In addition, the pooled mHealth group was 1.12 (95% CI: 1.00; 1.25) and 1.22 (95% CI: 1.04; 1.42) times more likely to moderate or no alcohol intake and improve diet quality at the end of the trial compared to the control group, respectively. Among participants in the pooled mHealth group, 11% met the recommendation to eat more than 7 servings/week of low-fat dairy at the end of the trial. Between-groups difference in mean food groups consumption did not vary markedly between intervention groups, reaching statistical significance only for vegetables and low-fat dairy, although the amount was not clinically relevant (Supplementary Materials, Table S2).

Figure 2 presents the relative risk for achieving the goals adjusted for baseline values. Although the loss of at least 3 kg and refrain from smoking were not individually effective, achievement of four of five lifestyle goals more than doubled among participants receiving the pooled mHealth intervention (Figure 2). At six months, 70 (41.9%) participants in the mHealth intervention achieved four of five lifestyle goals, while only seven (16.7%) achieved the goal in the control, resulting in an absolute risk reduction of 24.9% (4.7; 45.1) favoring the intervention group.

Table 2. Relative risk (95% CI) for achieving the lifestyle goals at the end of the trial by intervention groups, adjusted for baseline values.

	Pooled mHealth Group *n* = 174		UCT Group *n* = 42		RR (95% CI) *
	Baseline	**6 Months**	**Baseline**	**6 Months**	
Weight (kg)	82.7 ± 17.2	81.7 ± 17.2	88.4 ± 21.37	87.6 ± 21.5	−0.39 (−1.49; 0.70) [a]
No smoking	148 (86.5)	149 (87.1)	34 (81.0)	35 (83.3)	0.99 (0.92; 1.07)
Physical activity ≥ 150 min/week	112 (64.0)	116 (67.1)	21 (50.0)	18 (42.9)	1.21 (1.03; 1.42)
Moderate or no alcohol intake ≤100 g (women)/≤200 g (men)/week	143 (82.7)	158 (91.3)	38 (90.5)	35 (83.3)	1.12 (1.00; 1.25)
Following ≥ two of six dietary recommendations	45 (26.3)	97 (56.7)	13 (31.0)	16 (38.1)	1.22 (1.04; 1.42)
Fruits and vegetables ≥21 servings/week	55 (32.0)	95 (55.2)	13 (31.0)	18 (42.9)	1.12 (0.97; 1.30)
Whole grains ≥14 servings/week	23 (13.4)	47 (27.3)	4 (9.5)	7 (16.7)	1.10 (0.97; 1.24)
Low-fat dairy ≥7 servings/week	14 (8.0)	39 (22.3)	4 (9.5)	5 (11.9)	1.11 (1.00; 1.24)
Sodium-rich foods ≤1 serving/week	19 (11.1)	38 (22.2)	2 (4.8)	7 (16.7)	1.05 (0.92; 1.20)
Fast or fried food <1 serving/week	34 (19.9)	61 (35.7)	10 (23.8)	14 (33.3)	1.03 (0.88; 1.20)
Fried or fatty meats <1 serving/week	19 (11.0)	51 (29.7)	7 (16.7)	11 (26.2)	1.05 (0.90; 1.22)

* Data from the Generalized Poisson mixed adjusted for baseline values; [a] Generalized linear models adjusted for baseline value were used for between-groups difference (95% CI) at 6 months; mHealth = mobile health; UCT = usual care treatment.

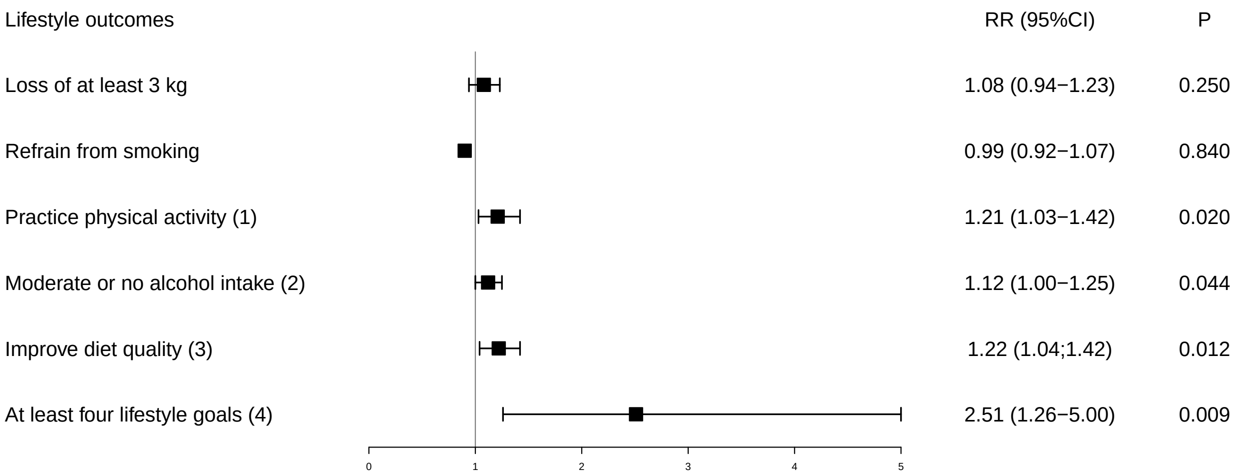

Figure 2. Relative risk of lifestyle goals at the end of the trial adjusted for baseline values. The control group is the reference. (1) Physical activity ≥ 150 min/week; (2) Moderate or no alcohol intake: 100 g (women)/200 g (men)/week; (3) Following two of six dietary recommendations (fruits and vegetables ≥ 21 servings/week; whole grains ≥ 14 servings/week; low-fat dairy ≥ 7 servings/week; sodium-rich foods ≤ 1 serving/week; fast or fried food < 1 serving/week; fried or fatty meats < 1 serving/week); (4) Achieving four out of five lifestyle goals in the follow-up; RR = relative risk.

The Supplementary Materials (Table S3) indicates that none of the individual interventions (TELEM, TELEMEV, and TELEM-TELEMEV) had a statistically significant impact on achieving a weight loss of at least 3 kg or on quitting smoking. However, the other recommendations, such as increasing physical activity, moderating alcohol consumption, and improving diet quality, showed some positive effects. The TELEM and TELEM-TELEMEV interventions were successful in achieving the goal of changing at least four lifestyle habits, but for the TELEMEV intervention, the association was barely borderline. Therefore, the results seemed homogeneous enough to pool the intervention groups. The Supplementary Materials (Table S4) shows that the pooled mHealth had a quite similar effect with statistically significant associations for practice of physical activity, moderate or no alcohol intake, and improved diet quality. Overall, achieving at least four lifestyle goals was 2.5 times more likely for participants in the pooled mHealth group.

3.2. Anthropometric Characteristics

Table 3 shows baseline and follow-up anthropometric characteristics and between-groups difference at 6 months. The between-group difference at 6 months reached clinically relevant reduction, but was marginally significant, favoring the pooled mHealth group for body fat (−4.05 kg 95% CI: −8.14; 0.03, $p = 0.052$), segmental trunk fat (−1.69 kg 95% CI: −3.50; 0.12, $p = 0.067$), and WC (−4.36 cm 95% CI: −8.81; 0.082, $p = 0.054$).

Table 3. Baseline and follow-up anthropometric characteristics and between-groups difference at 6 months [mean (95% CI)].

	Pooled mHealth Group *n* = 186		UCT Group *n* = 45		Between-Groups Difference (95% CI) at 6 Months *	*p* for Between-Groups Difference at 6 Months **
Body Fat Outcomes	**Baseline**	**6 Months**	**Baseline**	**6 Months**		
Body fat mass (kg)	28.8 (27.5; 30.2)	28.1 (26.7; 29.5)	31.8 (28.3; 35.4)	32.3 (28.3; 36.3)	−4.05 (−8.14; 0.03)	0.052
Percentage of body fat (%)	34.8 (33.6; 36.1)	34.3 (33.0; 35.5)	36.0 (33.8; 38.2)	36.4 (34.0; 38.7)	−2.11 (−4.80; 0.56)	0.122
Segmental trunk fat (kg)	15.2 (14.5; 15.9)	14.8 (14.1; 15.5)	16.6 (14.9; 18.2)	16.5 (14.9; 18.2)	−1.69 (−3.50; 0.12)	0.067
Segmental trunk fat (%)	36.1 (35.0; 37.2)	35.6 (34.5; 36.7)	37.3 (35.4; 39.1)	37.9 (35.5; 39.5)	−1.91 (−4.18; 0.35)	0.098
BMI (kg/m^2)	29.9 (29.2; 30.6)	29.5 (28.8; 30.2)	31.3 (29.6; 33.1)	31.1 (29.2; 32.9)	−1.56 (−3.49; 0.37)	0.113
Waist circumference (cm)	102.7 (100.9; 104.5)	101.1 (99.4; 102.9)	105.6 (101.7; 109.4)	105.5 (101.7; 110.3)	−4.36 (−8.81; 0.082)	0.054

Data are expressed as mean (95% CI); mHealth = mobile health; UCT = usual care treatment; * Between-groups difference estimated by generalized estimating equation. ** *p*-value for between-groups difference at 6 months, adjusted for Bonferroni.

4. Discussion

This study showed that a lifestyle program with reinforcement using mHealth interventions based on BP monitoring and text messages promoted a statistically significant and clinically relevant greater adherence to achieving at least four lifestyle goals than the UCT alone. Participants who received the mHealth intervention more than double the likelihood of achieving the lifestyle goals. More significant adherence to lifestyle changes in the mHealth group produced a marginally significant but clinically relevant reduction of more than 4 kg in total body fat, 1.7 in segmental trunk fat, and 4 cm in WC.

Several randomized controlled trials in different populations investigated lifestyle changes using mHealth strategies to prevent and control chronic diseases [24–27]. A lifestyle-focused text messaging program promoted risk factor modification among patients with coronary heart disease [28]. In a cluster-randomized trial where tailored lifestyle text messages were sent for 18 months, Poggio et al. found results somewhat similar to the present study, showing effectiveness for increasing fruit and vegetable intake and physical activity with no effect on alcohol consumption, smoking, or weight loss [29]. Although the intervention group showed greater adherence to lifestyle changes, there was no significant reduction in weight observed in this study. However, there was a marginally significant, but clinically relevant reduction in body fat, segmental trunk fat, and WC. The substitution of certain dietary components, such as increasing the consumption of vegetables and low-fat dairy products while reducing intake of higher-fat foods, has been found to result in decreased anthropometric measurements. It is important to note that this effect does not necessarily promote weight loss.

A similar study used text messages and lifestyle educational sessions versus educational sessions alone in a weight loss program and did not show between-group differences in weight or body fat percentage [30]. The use of mHealth to promote weight loss has been studied with different types of interventions and control groups [31]. Meaningful results in weight loss were seen for interventions compared to nonactive control groups, such as being on the waitlist [31].

With or without mHealth support, BP self-monitoring has effectively promoted BP control, at the expense of medication titration or increased adherence to BP-lowering medications [15,32,33]. However, its effect has never been explored regarding adherence to lifestyle change. This study aimed to improve the lifestyle by adding different approaches. McManus et al. evaluated weight loss in a self-monitoring BP with a digital intervention versus usual care [34]. They also did not observe a difference in the weight measurement (mean difference −0.36 kg, 95% CI: −1.10 to 0.38 kg).

This study shows that, in addition to face-to-face lifestyle intervention, an application based on BP monitoring with a simple text message system is feasible and yields higher lifestyle adherence in patients with uncontrolled hypertension. Current care demands for lifestyle promotion and disease prevention require a long time from health professionals, compromising feasibility in clinical practice. In this scenario, mHealth programs can be an essential ally [35].

To our knowledge, this is the first trial evaluating a lifestyle intervention supported by mHealth to promote BP control and change of lifestyle (without drug titration) in a population of participants with uncontrolled hypertension. We hypothesized that incorporating mHealth into outpatient clinics would lead to shorter consultation times, longer intervals between consultations, and greater adherence to a healthy lifestyle if it proves to be effective. Patients came from primary care clinics, and the findings show the potential of large-scale technology use in public health programs in developing countries.

This study has limitations that should be taken into account when interpreting the results. Our hypothesis was that both mHealth approaches would be more effective than UCT, and the high retention rate of over 90% provided sufficient statistical power to test this. The study was designed to provide insights applicable to patients in public health facilities, and the use of mHealth resources could be a promising alternative to improve adherence to lifestyle changes. However, we lacked the statistical power to determine which mHealth intervention yielded better results, and the availability of such resources may vary. Self-reported information was obtained using validated questionnaires applied by certified researchers, which should minimize potential information biases. The six-month follow-up is relatively long among controlled trials evaluating the effectiveness of mHealth technology. This follow-up period captures the highest level of adherence and effect of the intervention; nevertheless, longer-term studies are necessary to assess sustained interventions.

5. Conclusions

A six-month lifestyle intervention supported by application-based BP monitoring and text messages significantly improves adherence to lifestyle goals and is likely to reduce some anthropometric characteristics in comparison with the control without technology support.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/healthcare11081069/s1, Table S1: Examples of text messages; Table S2: Consumption of each food group per week at baseline and follow-up (mean ± SD) and between-groups difference (95% CI) at 6 months; Table S3: Relative risk for achieving the lifestyle goals at the end of the trial by individual randomization group, adjusted for baseline values; Table S4: Baseline and 6-month lifestyle goals and relative risk (95% CI) for reaching that goal at the end of the trial, adjusted for baseline values.

Author Contributions: C.N.D.: formal analysis, investigation, data curation, writing—original draft, visualization, supervision; C.I.: software, writing—review and editing; E.H.: validation, resources, writing—review and editing; G.P.S.: investigation, supervision, writing—review and editing; M.R.G.: validation, resources, writing—review and editing, funding acquisition; L.B.M.: conceptualization, validation, writing—review and editing; F.D.F.: conceptualization, methodology, validation, data curation, writing—review and editing; S.C.F.: conceptualization, methodology, validation, formal analysis, data curation, writing—review and editing, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Hospital de Clinicas de Porto Alegre (GPPG code 16-0187/CAAE 31423214.0.0000.5327, 8 August 2016).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author, C.N.D., upon reasonable request.

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