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Special Issue Reprint

New Insights into Physical Therapy

Edited by
Patsaki Irini and George A. Koumantakis

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Preface

Physical therapy is a continuously evolving scientific and clinical field, shaped by advances in research, innovative therapeutic approaches, and the rapid development of technology. The increasing prevalence of chronic conditions, musculoskeletal and neurological disorders, disabilities, and age-related functional limitations has highlighted the need for more effective, accessible, and individualized rehabilitation strategies. Beyond restoring function following injury or disease, contemporary physical therapy increasingly contributes to disease prevention, healthy aging, and the preservation of functional independence and quality of life.

The emergence of novel therapeutic approaches and technological innovations and other technology-assisted interventions, has expanded the possibilities of rehabilitation. These developments offer new perspectives for improving functional outcomes, enhancing patient engagement, and overcoming traditional barriers to rehabilitation access. However, their clinical application requires continued investigation, robust scientific evidence, and a better understanding of their effectiveness across different populations and healthcare settings.

The purpose of this Special Issue, entitled "New Insights into Physical Therapy," is to present contemporary scientific developments and explore the potential of innovative techniques and emerging technologies to advance physical therapy practice. Particular emphasis is placed on the translation of scientific advances into clinical practice and their contribution to improving rehabilitation outcomes and accessibility.

This Special Issue has been developed in response to the growing need to explore new directions in physical therapy. By bringing together original research and comprehensive literature reviews, we aim to provide a platform for knowledge exchange, encourage interdisciplinary collaboration, identify emerging research priorities, and strengthen evidence-based clinical practice.

Ultimately, we hope that this collection will contribute to advancing the science of physical therapy, supporting innovation in rehabilitation, and promoting better functional outcomes and quality of life for individuals across the lifespan.

Patsaki Irini and George A. Koumantakis
Guest Editors

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Editorial

New Insights into Physical Therapy: Advancing Rehabilitation Through Innovation, Technology, and Evidence-Based Practice

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1. Introduction

The evolution of physical therapy over the years reflects the entire transformation of healthcare itself. Especially after the world wars and the polio pandemic, physical therapy has transformed into a recognized profession that aims to enhance patients' independence and quality of life [1]. Over the recent years, it embraced evidence-based practice and continued to evolve in response to increasing life expectancy and the prevalence of chronic illnesses. Through advanced technologies and the integration of new knowledge from biology and physiology, physical therapy can provide patient-centered care. This approach encompasses disease prevention and health promotion strategies, extending to the long-term management of chronic diseases [2].

The advancement of physical therapy, which emphasizes and supports the implementation of patient-centered and evidence-based practices, served as the foundation for creating this special issue, "New Insights into Physical Therapy". The nine contributions to this special issue demonstrate how physical therapy continues to develop and expand beyond traditional therapeutic practices by incorporating technological innovations, novel exercise and rehabilitation interventions, advanced outcome measures, and multidisciplinary approaches. Although the studies reflect diverse clinical populations that could benefit from physical therapy and utilize various methodological approaches, some common themes can be further explored.

2. Optimizing Assessment and Clinical Decision-Making

The effectiveness of physical therapy is fundamentally dependent on accurate and holistic assessment that promotes informed clinical decision-making [3]. As the field of physical therapy increasingly adopts personalized care strategies, the selection of reliable, valid, and clinically meaningful outcome measures has become critically important [4]. In addition to documenting a program's effectiveness, ongoing comprehensive assessments guide the evolution of interventions, track recovery trajectories, and enhance communication among healthcare professionals, facilitating a multidisciplinary approach. The studies presented in this special issue clearly indicate that advancements in our measurement capabilities could significantly impact our practices and improve patient outcomes.

Pepera et al. (2026, contribution 1) focused on optimizing of functional capacity assessment by exploring alternative protocols for the Six-Minute Walk Test (6MWT) in people with arterial hypertension, a widely used outcome measure in cardiopulmonary rehabilitation. Although the 6MWT is considered a robust indicator of exercise capacity across diverse patient populations [5], practical constraints often hinder its implementation. Their investigation of modified testing protocols demonstrates how standardized assessments can be adapted to enhance feasibility. The authors noted that the presence of systematic

differences and variability between measurements indicates that the two protocols do not yield interchangeable results, despite showing a moderate level of agreement. Nevertheless, they recommended the 15 m protocol as a practical alternative. Fell et al. [6] also have recommended that for low-resources settings could be implemented. Yet, they underlined that both clinicians and researchers should carefully consider any adaptations made to the 6MWT, as these may influence the interpretation of test results, prognostic assessment, and subsequent exercise prescription.

There is an increased focus on the cardiovascular population due to its high global mortality rates, prevention potential and widespread economic impact [7]. Silva et al. (2025, contribution 2) directed their research toward the cardiorespiratory optimal point (COP) which is a submaximal parameter capable of providing insights into the optimal balance between cardiac workload and pulmonary ventilation. The authors conducted a comprehensive review of the literature, highlighting the role of COP as a prognostic and clinical marker in the heart failure population, as it provides valuable information regarding a patient's cardiorespiratory health. Furthermore, they underlined that the submaximal nature of this test confers substantial clinical value in assessing individuals who are unable to perform maximal exercise testing.

Another important theme emerging from this special issue is the use of assessment to support prognostic evaluation and clinical planning. Pennestri et al. (2025, contribution 3) emphasize that perioperative variables in patients undergoing hip and knee arthroplasty can inform individualized treatment pathways and optimize resource management throughout the recovery process. Rather than serving solely as retrospective indicators of treatment success, the authors noted that age, caregiver support, the presence of comorbidities, sex, BMI pre-operative patient-reported outcome measures (PROMs-such as SF-36) and a Clinician-Reported Outcome Measure (CROMs-such as manual muscle strength examination) along with post-operative Barthel index could contribute to predicting recovery trajectories, identifying patients who may require additional support, and facilitating timely adjustments to rehabilitation programs. There is a growing interest in predictive factors as modifiable are fundamental in implementing preoperative optimization protocols and nonmodifiable should be taken under consideration by the surgeon in order to creat correct expectations in patients [8]. Taking into consideration the advantages offered by the evolution of artificial intelligence, the use of Proms and Croms could allow us to predict the success of rehabilitation program and the need to alter it in any patients' population [9].

Optimizing assessment, in addition to ensuring the most effective rehabilitation strategies, can also play a crucial role in prevention. Particularly in populations at an increased risk of injury, such as athletes, a versatile approach is necessary to address barriers related to sophisticated and expensive equipment. We should keep in mind, that many athletes, particularly those in team academies, do not have access to such equipment. Under this perspective the study of Stojiljkovic et al. (2025, contribution 4) tried to investigate the relationship between physical fitness attributes and dynamic knee valgus in adolescent basketball athletes. As dynamic knee valgus is considered a common biomechanical risk factor for knee injuries in this population, the identification of factors that could influence it could enhance a personalized training approach aimed at reducing the risk of injury. The authors identified that lower limb muscle power and cardiorespiratory fitness play a role in controlling knee valgus. Therefore, athletes who demonstrate deficiencies in VO_2 max and lower limb muscle power may benefit the most from targeted training programs.

3. From Digital Innovation to Personalized Rehabilitation

Reliable outcome measures are fundamental for precision rehabilitation. As mentioned above, refining assessment tools can support prevention, improve treatment monitoring,

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and contribute to individualized exercise prescription. The digital revolution has rapidly transformed conventional physical therapy beyond traditional clinical environments. Notably, during the COVID-19 pandemic, physical therapy adapted to meet the need for remote care [10]. Advances in information technology, data collection, communication technologies, virtual reality (VR), telehealth, mobile applications, and remote monitoring systems are changing how rehabilitation is delivered, monitored, and evaluated [11]. Rather than replacing traditional face-to-face interventions, these technologies complement clinical practice of physical therapy by expanding opportunities for increased accessibility, individualized care, continuous patient engagement, and long-term follow-up [12].

Virtual reality (VR) has emerged as an innovative technology that is revolutionizing rehabilitation. By utilizing computer-generated environments, it transforms how users experience and interact with the world, thereby increasing engagement [13]. Consequently, VR offers a novel, safe and interactive approach to the rehabilitation of various conditions, ranging from musculoskeletal to neurological, as well as chronic and acute care [14,15]. Rogowski et al. (2026, contribution 5) examined the benefits of VR in a unique population, that of dialysis patients, focusing on mood, acceptance of illness, and quality of life. Patients with chronic illnesses often experience a significant psychological burden and a reduced quality of life due to disease symptoms and the need for continuous care. The authors implemented a passive form of VR that utilized realistic scenarios presented through videos, accompanied by relaxation music, and were able to demonstrate improvements in physical functioning, emotional well-being, and energy/fatigue as measured by the SF-36. In the disease targeted section (End-stage renal disease section) of the scale KDQOL-36 scale, significant differences between measurements were observed only in the domains of quality of social interaction, sexual function, and sleep. The authors underlined the need for further investigation but noted that VR relaxation therapy could serve as a complementary component to treatment for the dialysis population. Recent publication has noted that VR relaxation therapy can be conceptualized as a non-pharmacological adjunct for pain management, particularly when pain is strongly influenced by anxiety, stress, attentional processes, and central sensitization [16].

Another aspect of digital innovation is the introduction of mobile applications (m Health) into the care of chronically ill populations. Sapouna et al. (2025, contribution 6) developed a website that offers reliable, accessible, and practical information on medication, physiotherapy, nutrition, exercise, and disease education for children with chronic suppurative lung disease and their caregivers. The authors identified the essential features that a digital health platform should possess to address both clinical priorities and family needs, using a two-phase Delphi process. It is well established that integrating digital interventions into traditional care can improve health outcomes, enhance self-management and facilitate communication between patients, their families and health care providers [17].

4. Emerging Trends and Future Directions in Physical Therapy

As physical therapy continues to evolve beyond traditional intervention-based models, the next generation of rehabilitation will increasingly depend on the integration of scientific innovation, and patient-centered approaches to advance toward precision rehabilitation. The studies included in this special issue reflect this transition by demonstrating the value of individualized exercise prescription, targeted therapeutic approaches, and personalized monitoring of functional outcomes. Studnicki et al. (2026, contribution 7) aimed to examine the immediate effects of a single ankle manipulation on the strength of the peroneal and hip abductor muscles in healthy individuals. This study aimed to assess the application of joint manipulation as a therapeutic strategy for addressing hip abductor muscle imbalances in both athletic populations and patients with degenerative musculoskeletal disorders.

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Their findings indicated that a single superior ankle traction manipulation did not result in significant acute changes, and any neuromuscular influence was likely to be mild and transient.

Targeted exercise prescription was examined by Korda et al. (2025, contribution 8) in the form of lumbar spine stabilization exercises for a sedentary population. Quality of life served as the primary outcome measure, reflecting the broader scope of physical therapy interventions. The four week exercise program (including pelvic tilt, abdominal curl up, side plank, plank, squat etc.) aimed to activate the transversus abdominis muscle through specific breathing techniques. This program demonstrated beneficial effects on dynamic balance and quality of life, particularly in the mental health components. A patient-centered approach is the core of precision health care, even in the aspect of physical therapy. Therapeutic exercises was and continuous to be the cornerstone of physiotherapy. Core stabilization exercise of high importance in populations that need to improve balance. It is well documented that have beneficial effects as they enhance trunk stability, neuromuscular control, and postural regulation [18].

Emerging scientific evidence has the potential to reshape the traditional modalities of general wellness and enhance their role within physical therapy practice. Among these modalities are whole-body heating methods, such as conventional sauna bathing and infrared saunas. The narrative review by Kolber et al. (2026, contribution 9) highlights the benefits of sauna including thermoregulatory, cardiovascular, neuroendocrine, and cytoprotective responses that support homeostasis and adaptive stress tolerance. The authors note that regular sauna use may improve aerobic capacity, and aid in blood pressure regulation. Additionally, sauna use after exercise and during recovery could contribute to tissue repair. Emerging evidence, also suggest the use of it even in mental health recovery [19] and in rheumatic diseases [20].

5. Conclusions

The studies in this special issue collectively (contributions 1–9) illustrate a profession that continues to redefine its role within modern healthcare. Physical therapy now encompasses prevention, acute care, chronic disease management, digital health, and long-term functional optimization. Although the clinical populations and interventions vary significantly, a common principle unites these investigations: rehabilitation is increasingly individualized, multidisciplinary, and focused on outcomes that matter most to patients. This special issue includes contributions covering a diverse range of clinical populations, including some that are more unique, reflecting the evolution of physical therapy practice. Future advances are likely to arise not only from new therapeutic techniques but also from the integration of innovative assessment methods, digital technologies, and patient-centered care models into everyday clinical practice. Future rehabilitation models will likely integrate clinical examination, patient-reported outcomes, biomechanical analysis, wearable sensor data, and machine learning algorithms to generate comprehensive patient profiles that facilitate individualized treatment recommendations.

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Article

Short Versus Standard Corridor Six-Minute Walk Test in Older Adults with Controlled Arterial Hypertension: Clinical Agreement and Determinants of Performance

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Abstract

Arterial hypertension (AH) is strongly associated with reduced functional capacity and elevated cardiovascular risk. The Six-Minute Walk Test (6MWT) assesses submaximal exercise capacity; however, the standard 30 m walkway is often unavailable in clinical settings, necessitating the use of shorter corridors. Evidence regarding the agreement between different walkway lengths in hypertensive populations remains limited. This study investigated the agreement between 15 m and 30 m 6MWT protocols in 23 older adults with medically controlled AH (13 men, 10 women; age 74.04 ± 8.89 years) in randomized order. Anthropometric, cardiovascular, physical activity (IPAQ), and health-related quality of life (SF-36) data were collected. Results showed significantly greater walking distances on the 30 m walkway ($p < 0.001$). Moderate agreement was observed between protocols (ICC = 0.65), with Bland–Altman analysis demonstrating systematically higher distances on the 30 m walkway. Age was negatively correlated with performance, while height and SF-36 physical functioning showed positive correlations ($p < 0.05$). Distinct regression models for each protocol suggest walkway-specific performance determinants. Although the 15 m protocol demonstrated acceptable agreement, it should not be used interchangeably with the standard 30 m protocol in older adults with controlled arterial hypertension. Further research is required to better understand the relationship between the two protocols.

Keywords: 6 min walk test; hypertension; corridor length; track length; agreement; predictors; determinants; functional capacity

1. Introduction

Despite substantial advances in pharmacological management, arterial hypertension (AH) remains a major contributor to cardiovascular morbidity and mortality worldwide. However, less than half of AH cases have been diagnosed and received treatment [1]. Similarly, in Greece, epidemiological data highlight the severity of the disease, as it is estimated that four out of 10 adults suffer from AH, with only one-third of the diagnosed hypertensive patients being able to regulate and control their blood pressure (BP) through treatment [2].

Uncontrolled AH can lead to severe complications, including atherosclerotic disease, angina, myocardial infarction, arrhythmias, and sudden cardiac death. Furthermore, elevated pressure can be a risk factor for strokes and renal failure [1]. In light of these risks, AH necessitates consistent monitoring and appropriate management. A key requirement for effective treatment is a thorough patient assessment, which—particularly in elderly populations—should also incorporate an evaluation of their functional status [3].

The assessment of elderly hypertensive patients should be multidimensional, addressing several factors such as their medical and lifestyle history, physical examination, laboratory testing and functional ability. Unfortunately, issues such as time constraints or high costs may hinder the aforementioned procedures; thus, highlighting the need for simple, rapid, and easily accessible methods for functional assessment. Examples of tools suitable for use in individuals with hypertension include the Duke Activity Status Index (DASI) [4], the Incremental Shuttle Walking Test (ISWT) [5] and the Six-Minute Walk Test (6MWT) [6].

Among the field-based tests used to evaluate functional exercise capacity, the 6MWT test is one of the most widely adopted. It reflects activities performed in daily life while requiring minimal equipment and personnel, and can be readily administered across a range of clinical and research settings [7,8]. Data from a recent meta-analysis further support the validity and reliability of the 6MWT compared to cardiopulmonary exercise testing in individuals with heart failure [9].

Despite the wide acceptability of the 6MWT as a practical measure of functional capacity, its implementation may be restrained by factors such as limited indoor space, time restrictions, and differences in clinical infrastructure. In order to address the aforementioned challenges, alternative configurations are proposed, such as the three-minute walk test (3MWT) and the 6MWT on 10, 15, or 20 m walkways [10–12]; abbreviated walking tests; treadmill-based protocols [13]; and remotely administered assessments [14]. Although these adaptations may act as an adjunct to a conventional 6MWT, the modifications that they apply to test procedures can influence performance outcomes and alter the measurement properties of the test, thus making an evaluation of each modified protocol within the specific population target a prerequisite. Despite the widespread prevalence of arterial hypertension, evidence regarding the validity and comparability of shorter corridor 6MWT protocols in this population remains scarce.

In addition to psychometric properties, it is equally important to identify factors that may influence test outcomes. Previous investigations conducted in cardiovascular and pulmonary populations have demonstrated that demographic characteristics, anthropometric measurements, and patient-reported outcomes may substantially influence walking distance [15,16]. Despite differences in study samples and underlying pathologies, variables such as body mass index (BMI) and age emerge as determinant factors that can affect performance in the 6MWT over a 30 m corridor. However, most available data come from studies employing the standard 30 m walkway, whereas little is known about whether similar results will be derived when shorter corridors are used. This distinction is clinically relevant because shorter walkways require more frequent turns and may introduce additional biomechanical and balance-related demands. Thus, the main aim of this study was (a) to compare the distance covered during the Six-Minute Walk Test (6MWT) on two different walkway lengths (15 m and 30 m), (b) to evaluate the level of agreement between the two protocols, and (c) to explore factors associated with performance in patients with diagnosed and medically controlled arterial hypertension.

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2. Materials and Methods

2.1. Study Design

This study employed a randomized crossover design and was conducted at the Department of Physiotherapy, University of Thessaly, over a three-month period (February–April 2025). The study protocol was approved by the Ethics Committee of the Department of Physiotherapy, University of Thessaly (Approval No. 22513/25/21-07-25), and was conducted in accordance with the Declaration of Helsinki.

2.2. Participants

Eligibility criteria included: (a) diagnosed and medically controlled arterial hypertension, (b) age $\geq$ 18 years, (c) native Greek speakers (required for questionnaire administration), and (d) absence of cognitive impairment. Although adults aged $\geq$ 18 years were eligible, all participants recruited during the study period were older adults; therefore, the findings primarily apply to this age group.

Exclusion criteria were: (a) implanted cardiac devices (pacemaker/defibrillator), (b) neurological or orthopedic conditions affecting walking ability, (c) uncontrolled hypertension (>160/100 mmHg), (d) severe cardiovascular or respiratory disease (e.g., recent myocardial infarction or unstable angina), and (e) severe psychiatric or other conditions affecting participation.

Participants continued their usual antihypertensive medication regimen during the study.

2.3. Experimental Procedure

Anthropometric measurements (height, body weight, and waist circumference) were recorded during the initial assessment. Height was measured using a SOEHNLE 5003 ultrasonic stadiometer (Soehnle Industrial Solutions GmbH, Backnang, Germany) and body weight using a TANITA BC-418MA electronic scale (Tanita Corporation, Tokyo, Japan). Participants stood barefoot in an upright position during measurements.

Participants performed the 6MWT under two conditions: (a) 15 m corridor and (b) 30 m corridor. Both tests were conducted indoors under controlled environmental conditions. Testing was carried out on indoor walkways with level surfaces and clearly defined turning points to ensure consistency across trials.

The order of the two test conditions was randomized to minimize order effects. Participants performed a brief familiarization trial prior to testing to reduce potential learning effects.

Standardized instructions and verbal feedback were provided according to American Thoracic Society (ATS) guidelines [17], and at predefined time points, ensuring consistency between participants and testing conditions. A minimum recovery period of 10 min was provided between tests, and the second assessment was initiated only after heart rate had returned to within $\pm$10 bpm of the resting heart rate measured prior to testing, ensuring adequate physiological recovery between trials. This recovery criterion was applied to minimize residual fatigue and reduce potential carry-over effects between the two testing conditions.

Vital signs (heart rate, systolic and diastolic blood pressure) and adverse symptoms were monitored before and after each test. Test termination followed ATS recommendations and included chest pain, intolerable dyspnea, dizziness, leg cramps, diaphoresis, or any other safety concern.

The tests were conducted at similar times of day to minimize circadian variability.

Self-reported physical activity was assessed using the Greek version of the International Physical Activity Questionnaire—Short Form (IPAQ-SF), and health-related quality of life was evaluated using the SF-36 questionnaire administered via interview [18–20].

2.4. Outcome Measures

The primary outcome was six-minute walk distance (6MWD), expressed in meters.

Secondary outcomes included demographic and anthropometric variables, hemodynamic responses, physical activity level (IPAQ-SF) [16,17], and health-related quality of life (SF-36) [18].

2.5. Statistical Analysis

Data were analyzed using SPSS version 29. Normality was assessed using the Shapiro–Wilk test. Differences between the two 6MWT conditions were examined using paired *t*-tests. Correlation analyses (Pearson, Spearman, and point-biserial) and linear regression analyses were performed to explore associations between variables and 6MWD. Multicollinearity was assessed using variance inflation factors (VIFs). Agreement between protocols was evaluated using the intraclass correlation coefficient (ICC; two-way mixed, absolute agreement) and Bland–Altman analysis.

A priori sample size calculation was performed using G*Power software (version 3.1.9.7; Heinrich Heine University Düsseldorf, Germany) for a paired-samples *t*-test. Based on previous studies reporting substantial differences between 6MWT corridor lengths, a large effect size (Cohen's d = 0.8) was assumed. A minimum sample of 19 participants was required to achieve 80% statistical power at $\alpha = 0.05$.

Because the primary objective of the study also included assessment of agreement between protocols, intraclass correlation coefficient (ICC) and Bland–Altman analyses were additionally performed. However, the sample size calculation was based on detecting mean differences between protocols rather than achieving a predefined level of precision for agreement statistics. Therefore, the agreement analysis should be considered exploratory and interpreted with appropriate caution.

Statistical significance was set at $p < 0.05$.

3. Results

3.1. Participant Flow

A total of 34 individuals were initially approached, of whom 33 fulfilled the inclusion criteria. Ten participants were excluded due to practical constraints. Consequently, 23 participants provided written informed consent and completed both trials. Following randomization, 14 participants performed the 15 m protocol first, and nine performed the 30 m protocol first (Figure 1).

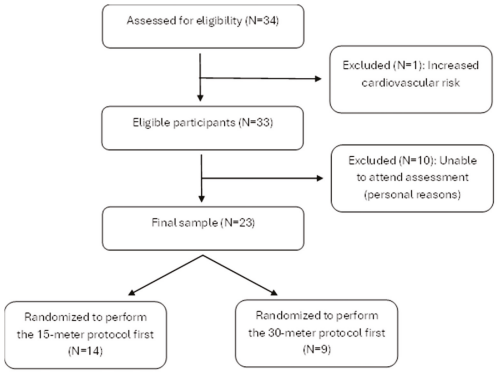

Figure 1. Study flow diagram.

3.2. Baseline Characteristics

Therefore, the study sample predominantly represented older adults with controlled arterial hypertension. Detailed baseline characteristics are presented in Table 1. Physical activity levels (IPAQ-SF) were classified as low (n = 5), moderate (n = 10), and high (n = 8). SF-36 scores indicated higher values in Physical Functioning (PF), Bodily Pain (BP), Role Physical (RP), and Role Emotional (RE), and lower values in General Health (GH), Vitality (VT), and Mental Health (MH). Resting heart rate and blood pressure prior to 6MWT trials were comparable between protocols, with expected post-test increases in heart rate. Hemodynamic responses and 6MWT outcomes are summarized in Table 2.

Table 1. Baseline characteristics of the participants (n = 23).

Variable	Value
Demographic characteristics	
Sex, *n* (%)	
• Male	13 (56.5%)
• Female	10 (43.5%)
Age (years)	74.04 ± 8.89
Anthropometric characteristics	
Weight (kg)	79.78 ± 12.4
Height (cm)	164.65 ± 7.48
Waist circumference (cm)	101.48 ± 13.48
Physical activity (IPAQ-SF), *n* (%)	
• Low	5 (21.7%)
• Moderate	10 (43.5%)
• High	8 (34.8%)
Health-related quality of life (SF-36)	
Physical Functioning (PF)	80.22 ± 18.31
Role Limitations due to Physical Problems (RP)	78.26 ± 31.36
Bodily Pain (BP)	80.87 ± 17.56
Vitality (VT)	62.83 ± 20.5
Social Functioning (SF)	76.63 ± 25.09
Role Limitations due to Emotional Problems (RE)	78.27 ± 34.24
Mental Health (MH)	66.78 ± 18.03
General Health (GH)	59.42 ± 17.55

Data are presented as mean ± standard deviation (SD) or *n* (%).

Table 2. Hemodynamic responses and 6MWT outcomes.

Variable	15 m (Mean ± SD)	30 m (Mean ± SD)
Resting hemodynamics		
Pre-test Heart rate (bpm)	74 ± 13	73 ± 12
Pre-test SBP * (mmHg)	137 ± 12	132 ± 18
Pre-test DBP ** (mmHg)	82 ± 9	84 ± 10
6MWT outcomes		
Post-test Heart rate (bpm)	93 ± 17	99 ± 19
Post-test SBP (mmHg)	142 ± 19	142 ± 18
Post-test DBP (mmHg)	83 ± 11	81 ± 11
Distance (m)	388.05 ± 84.31	451.66 ± 76.26

* SBP—systolic blood pressure; ** DBP—diastolic blood pressure.

3.3. Comparison Between Test Conditions

A paired-samples t-test showed that participants walked a significantly greater distance during the 30 m protocol (451.66 ± 76.26 m) compared to the 15 m protocol

(388.05 ± 84.31 m). The mean difference was 63.61 ± 43.59 m (t = 6.998, $p < 0.001$), with a large effect size (Cohen's d = 1.46) indicating a substantial difference between the protocols.

3.4. Agreement Analysis

Agreement analysis yielded an ICC of 0.653 (95% CI: 0.167 to 0.942). Although the point estimate suggests moderate agreement, the wide confidence interval indicates limited precision and substantial uncertainty regarding the true level of agreement between protocols (ICC = 0.653, 95% CI: −0.167 to 0.942). Bland–Altman analysis demonstrated a mean bias of 63.61 m (solid horizontal line), with wide limits of agreement ranging from −21.83 m to 149.05 m (dashed lines), indicating systematically higher distances during the 30 m protocol and wide inter-individual variability (Figure 2). Additionally, visual inspection of the Bland–Altman plot did not indicate evidence of proportional bias, as the magnitude of disagreement did not appear to systematically increase with higher walking distances.

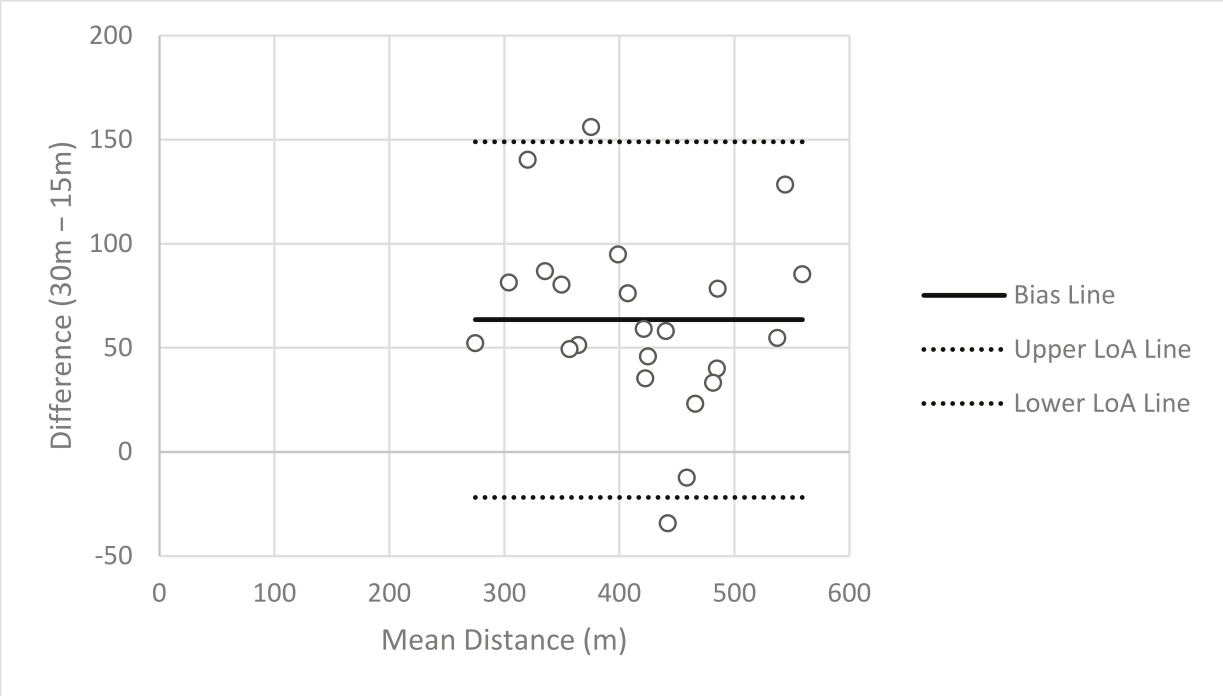

Figure 2. Bland–Altman plot showing agreement between 15 m and 30 m 6MWT protocols. The mean bias was 63.6 m, with limits of agreement ranging from −21.8 m to 149.1 m. The y-axis represents the difference in walking distance between protocols (6MWD30 − 6MWD15), while the x-axis represents the mean distance obtained from the two protocols for each participant. Positive values indicate greater walking distances achieved during the 30 m protocol.

3.5. Correlation and Regression Analysis

Height was significantly correlated with 6MWD on both the 15 m walkway (r = 0.460, $p = 0.027$) and the 30 m walkway (r = 0.413, $p = 0.050$). Age demonstrated a significant negative correlation with 6MWD on both the 15 m (r = −0.439, $p = 0.036$) and 30 m walkways (r = −0.579, $p = 0.004$). Regarding quality-of-life measures, the Physical Functioning (PF) domain of the SF-36 was significantly associated with 6MWD on both walkways, whereas the Role Emotional (RE) domain demonstrated a significant association only with performance on the 15 m walkway (Table 3).

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Table 3. Correlation analysis results.

Variable	$6MWT_{15}$		$6MWT_{30}$	
	p	***r***	***p***	***r***
Age (years)	0.036	−0.439	0.004	−0.579
Height (cm)	0.027	0.460	0.05	0.413
PF	0.031	0.449	0.022	0.474
RE	0.011	0.52	0.067	0.389
Weight	0.211	0.271	0.3	0.226
Waist Circumference	0.617	0.11	0.671	0.094
Sex	0.25	−0.25	0.907	−0.026
IPAQ	0.272	0.239	0.19	0.283

Note: Pearson correlation was used for continuous normally distributed variables, Spearman correlation for non-normally distributed variables, and point–biserial correlation for dichotomous variables.

Multiple linear regression analyses were performed via the enter method to identify independent predictors of 6MWD performance in both corridor lengths. For the 30 m corridor, the regression model explained 55.8% of the variance in walking distance ($R^2 = 0.558$, $p = 0.001$). Age and the Physical Functioning (PF) domain of the SF-36 emerged as significant independent predictors of 6MWD30, whereas height did not retain statistical significance in the final model (Table 4). Multicollinearity diagnostics demonstrated acceptable values, with VIF ranging from 1.02 to 1.18.

Table 4. Multiple linear regression analysis for predictors of 6MWD in the 30 m corridor.

Variable	Unstandardized B	SE	Standardized β	t	*p*	Tolerance	VIF
Constant	264.21	344.5	-	0.77	0.453	-	-
Age (years)	−4.51	1.42	−0.53	−3.17	0.005	0.85	1.18
Height (cm)	2.50	1.69	0.25	1.47	0.156	0.85	1.18
PF *	1.37	0.64	0.33	2.14	0.046	0.98	1.02

* Physical Functioning domain of the SF-36 questionnaire. Note: Dependent variable = $6MWD_{30}$; $R^2 = 0.558$; Adjusted $R^2 = 0.488$; $p = 0.001$.

For the 15 m corridor, the regression model explained 42.1% of the variance in 6MWD performance ($R^2 = 0.421$, $p = 0.035$). In the 15 m corridor model, no independent statistically significant predictors were identified. Although age, height, PF, and the Role Emotional (RE) domain were entered into the model based on their initial correlations with 6MWD15, none of the variables remained statistically significant independent predictors in the final analysis (Table 5). Multicollinearity remained within acceptable limits (VIF = 1.20–1.93).

Table 5. Multiple linear regression analysis for predictors of 6MWD in the 15 m corridor.

Variable	Unstandardized B	SE	Standardized β	t	*p*	Tolerance	VIF
Constant	−187.93	448.09	-	−0.42	0.68	-	-
Age (years)	−2.11	1.91	−0.22	−1.11	0.28	0.80	1.26
Height (cm)	3.92	2.21	0.35	1.77	0.094	0.84	1.20
PF *	0.35	1.11	0.08	0.32	0.757	0.55	1.81
RE **	0.76	0.61	0.31	1.23	0.234	0.52	1.93

* Physical Functioning domain of the SF-36 questionnaire. ** Role limitations due to Emotional Problems domain of the SF-36 questionnaire. Note: Dependent variable = $6MWD_{30}$; $R^2 = 0.421$; Adjusted $R^2 = 0.293$; $p = 0.035$.

4. Discussion

4.1. Principal Findings

The main findings of this study were that performance in the 6MWTwas significantly influenced by the length of the walking corridor, with participants consistently achieving greater distances in the longer (30 m) protocol compared to the shorter (15 m) protocol. Although a moderate level of agreement was observed between the two testing conditions, the presence of systematic differences and variability between measurements indicates that the two protocols do not produce interchangeable results.

Age and aspects of health-related quality of life, particularly physical functioning and role limitations, were consistently associated with walking performance across both protocols. Additionally, regression analyses identified the previous variables as independent predictors of 6MWT performance, highlighting the multifactorial nature of functional capacity in older adults with controlled arterial hypertension.

4.2. Comparison with Previous Literature

4.2.1. Agreement

Agreement between different corridor lengths in the 6 min walk test (6MWT) has been explored in several studies, with findings generally indicating that shorter walking distances tend to produce systematically lower values compared to the standard 30 m protocol, primarily due to the increased number of turns required [21]. Although correlations between protocols are often high—suggesting that individuals maintain their relative performance ranking—agreement analyses frequently reveal important limitations in their interchangeability. Previous studies have primarily reported strong correlations between different 6MWT protocols, indicating consistent ranking of individuals across conditions [22,23]. However, correlation alone does not imply agreement, and studies employing agreement analyses (e.g., Bland–Altman) have demonstrated that substantial absolute differences may exist between protocols, limiting their interchangeability.

However, beyond statistical considerations, the magnitude of the observed difference between protocols also appears to be clinically meaningful. The mean difference in walking distance observed in the present study (63.61 m) exceeded commonly reported minimal clinically important difference (MCID) thresholds for the 6MWT, which range from approximately 25 to 35 m. This suggests that the influence of corridor length is not only statistically significant but also large enough to affect the clinical interpretation of functional capacity. Consequently, results obtained from different corridor lengths should not be considered directly interchangeable, particularly when the 6MWT is used to monitor disease progression or evaluate treatment effects over time.

Discrepancies between corridor lengths are primarily attributed to methodological differences related to the walking environment. Shorter corridors necessitate more frequent turns, which interrupt walking continuity and require repeated deceleration and acceleration phases. This effect has been consistently reported as a key factor reducing total walking distance, as participants spend a proportion of the test time performing non-linear movement rather than forward progression. In contrast, longer corridors allow for more sustained, rhythmic walking, thereby facilitating higher walking speeds and greater total distance covered [17,24,25].

From a biomechanical and physiological standpoint, turning introduces additional demands that extend beyond simple locomotion. Directional changes require increased neuromuscular coordination, balance control, and lower-limb strength, particularly during the phases of braking and re-acceleration. These actions increase the mechanical workload and reduce movement efficiency, especially in populations with impaired motor control or reduced functional reserve [11,26]. Moreover, a factor that needs to be addressed is balance

capacity, since it may potentially influence the observed differences in 6MWD between the different corridor lengths. The 15 m protocol requires substantially more turning maneuvers than the standard 30 m protocol, increasing the demands on dynamic balance, postural control, and movement coordination. Older adults, and particularly those with arterial hypertension, may experience age-related declines in balance and gait stability [27]. Consequently, participants with balance deficits may be disproportionately affected by the increased turns required by the 15 m protocol, which may further reduce walking distance relative to their performance on the 30 m treadmill. Although balance was not directly assessed in the present study, it is possible that some inter-individual differences in postural stability may have contributed to part of the variability observed in the agreement analysis. Moreover, frequent turning has been associated with increased energy expenditure due to the need for repeated force generation and stabilization, which may accelerate fatigue and limit performance. Disruptions to the normal gait pattern, such as those caused by frequent changes in direction and repeated accelerations, further contribute to increased energy expenditure by reducing the efficiency of the energy-conserving mechanisms of walking [28].

4.2.2. Factors Influencing Performance

The agreement observed between different 6 min walk test (6MWT) protocols appears to be influenced by a range of individual-level factors, including demographic, anthropometric, behavioral, and cardiovascular characteristics. Although these factors are well-established determinants of 6MWT performance, their relative contribution may vary depending on corridor length, thereby contributing to differences in agreement between testing conditions.

Age is one of the most consistent predictors of 6MWT performance, with increasing age associated with reduced walking distance across populations. This decline is primarily attributed to reductions in aerobic capacity, muscle strength, and neuromuscular coordination [16,29]. In shorter corridors, the impact of age may be further amplified due to the increased frequency of turns, which require rapid adjustments in balance and motor control. Older individuals often adopt modified movement strategies characterized by slower, multi-step turns instead of efficient pivoting and therefore may experience greater difficulty maintaining walking efficiency under these conditions, leading to disproportionate reductions in performance compared to longer corridors [26].

Anthropometric characteristics, particularly height and body weight (or body mass index), have been widely reported as determinants of 6MWT performance, with greater height facilitating longer stride length and better walking economy, and higher body mass increasing mechanical load and energy expenditure [29,30]. However, in the present study, no significant associations were observed for body weight-related variables. This discrepancy may be attributed to the small sample size and limited variability of the population. Although shorter corridors theoretically increase metabolic cost due to repeated deceleration and re-acceleration [12], this effect was not evident in the current findings.

Sex differences have also been reported in the literature, with males generally demonstrating higher 6MWT performance compared to females, mainly due to differences in muscle mass, stride length, and aerobic capacity [30]. In this study, no significant association was observed between sex and 6MWT performance in either corridor condition, which may be explained by the relatively preserved functional status of the sample and the controlled clinical setting, potentially attenuating sex-related differences.

Physical activity levels represent another factor that has attracted researchers' interest regarding their relationship with the 6MWT, and findings in the literature are inconsistent. Higher levels of habitual physical activity are generally associated with better functional

capacity and increased walking distance [31,32]. However, in some clinical populations, this relationship appears weak or non-significant, potentially due to disease-related limitations and the discrepancy between self-reported physical activity and objective functional capacity [33]. The absence of a significant association between IPAQ and 6MWD in the present study may be partly explained by the distribution of participants across physical activity levels, which may have limited variability within the sample. Additionally, the restricted sample size and the reliance on self-reported physical activity may have reduced the ability to detect meaningful associations between habitual activity and objective functional performance.

Health-related quality of life, particularly domains related to physical functioning, has also been shown to correlate with 6MWT performance [34,35]. These associations suggest that perceived physical limitations are reflected in objective functional capacity. Furthermore, the results of this study suggest that in shorter corridors, additional domains, such as emotional or psychological factors, may play an equally prominent role, as the increased complexity of the task could influence confidence, pacing strategy, and perceived exertion. This may contribute to variability in performance and reduced agreement between protocols.

Finally, cardiovascular parameters, such as heart rate and blood pressure responses, have shown inconsistent associations with 6MWT performance depending on the studied population. Positive relationships have been reported in both hypertensive individuals and healthy older adults, suggesting that even in the absence of severe disease, hemodynamic responses may contribute to functional walking capacity [6,29]. However, in the present context of relatively mild and pharmacologically controlled hypertension, such associations were not evident, indicating a reduced sensitivity of 6MWT performance to acute cardiovascular responses. This pattern suggests that when cardiovascular impairment is limited, performance in the test is more strongly determined by mechanical and neuromotor factors rather than hemodynamic constraints.

The regression analyses suggest that functional capacity during the 6MWT is influenced by a multidimensional interaction of demographic, anthropometric, and health-related quality-of-life factors rather than by physiological characteristics alone. The variation observed between the predictive models of the two walkway configurations indicates that corridor length may influence the determinants of walking performance and that the 15 m and 30 m protocols may not rely entirely on identical underlying mechanisms. In particular, shorter walkways may place greater demands on pacing strategy, balance control, coordination, and repeated acceleration–deceleration during turns, potentially increasing the influence of psychosocial and perceptual factors on test performance [26]. These findings support the notion that functional exercise capacity assessed through the 6MWT is affected not only by cardiovascular and musculoskeletal function but also by the individual's perceived physical and emotional health status. Nevertheless, the absence of statistically significant independent predictors in the 15 m model should be interpreted cautiously. Performance in shorter corridors seems to be influenced by a more complex interaction of factors that could not be fully captured within the present sample. Although the overall model explained a meaningful proportion of variance, the limited sample size may have reduced statistical power, increasing the likelihood of Type II error and limiting the detection of independent associations.

4.3. Clinical Implications

From a clinical perspective, the findings of this study have direct implications for the use of the 6 min walk test (6MWT) in environments with limited space. In small clinics or rehabilitation settings where a standard 30 m corridor is not feasible, the 15 m protocol

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may be a practical alternative for assessing functional capacity. However, its use should be considered a modified version of the test rather than a direct substitute, as corridor length significantly influences performance outcomes.

A key consideration in interpretation is that differences between protocols may exceed the minimal clinically important difference (MCID) reported for the 6MWT (approximately 25–35 m). This indicates that variations due solely to test configuration may be large enough to affect clinical decision-making, particularly when monitoring disease progression or evaluating treatment effects. Therefore, clinicians should avoid a direct comparison of results obtained from different corridor lengths, as this may lead to misinterpretation of functional status.

When implementing the 6MWT in practice, it is recommended that the same corridor length and protocol conditions are used consistently for follow-up assessments within the same patient. If shorter corridors are unavoidable, results should be interpreted with caution and ideally adjusted using population-specific reference values or prediction equations. Standardized reporting of test conditions is also essential to ensure comparability across settings and studies.

4.4. Methodological Considerations

This study presents several methodological strengths that support the interpretation of its findings. The use of a randomized crossover design minimized inter-individual variability and allowed direct within-subject comparison between the 15 m and 30 m 6MWT protocols. Standardized testing procedures were applied across all participants, including consistent instructions and controlled measurement conditions, which enhances internal validity. Additionally, the inclusion of multiple relevant covariates (demographic, anthropometric, behavioral, quality of life, and cardiovascular parameters) provides a comprehensive evaluation of factors influencing performance.

Though it needs to be mentioned that despite the randomization of the order of testing and the provision of a minimum recovery period of 10 min between assessments, both 6MWT protocols were performed on the same day. Consequently, the possibility of an incomplete physiological recovery and the presence of residual fatigue may have affected performance during the second test despite the recovery time applied. Although heart-rate recovery criteria were applied before initiating the second test, the potential influence of same-day repeated testing cannot be completely excluded.

In addition to the potential influence of same-day repeated testing, several other methodological limitations should be acknowledged when interpreting the findings of the present study. First, the restricted sample size (n = 23) reduces statistical power and may limit the generalizability of the findings. Second, the single-center design restricts external validity, as results may reflect specific local characteristics of the studied population and setting. Third, although a randomized crossover design was used to minimize order effects, no formal familiarization trial was performed prior to testing. Consequently, a potential learning effect between the first and second 6MWT administrations cannot be completely excluded, despite the random allocation of protocol order. Additionally, given that balance capacity and postural stability were not formally assessed, any differences in balance performance may have influenced walking efficiency and may have contributed to variability in the distance achieved during the 15 m protocol. Therefore, the potential role of balance as a determinant of performance cannot be excluded. Consequently, the findings cannot be readily generalized to younger adults with arterial hypertension, as variability in disease severity and functional capacity may alter responses to different corridor lengths. Additionally, the study was powered to detect differences in walking distance between protocols rather than to estimate agreement parameters with high precision. Consequently,

the relatively small sample size may have reduced the stability of the regression models and may also have contributed to the wide confidence interval observed for the ICC and the broad limits of agreement in the Bland–Altman analysis. Therefore, the agreement findings should be interpreted cautiously and confirmed in larger studies specifically powered for agreement analyses. Process-related variables such as the exact interval between the two protocols, walking speed, cadence, number of turns, and perceived exertion (RPE) were not recorded. These variables may have provided further insight into the mechanisms underlying performance differences between corridor lengths.

4.5. Future Research

Larger studies specifically designed and powered for agreement analyses are needed to provide more precise estimates of ICC values and Bland–Altman limits of agreement between different 6MWT corridor lengths. In addition, studies should include younger and middle-aged adults with arterial hypertension as well as older populations to determine whether the observed agreement patterns are consistent across age groups. Further validation against established reference standards is also necessary, with particular emphasis on gold-standard assessments of functional capacity, like cardiopulmonary exercise testing (CPET), to determine the extent to which the 15 m 6MWT reflects true or submaximal aerobic capacity. Additionally, multicenter studies would be especially valuable, as they would allow for greater heterogeneity in clinical practice settings and reduce potential site-specific bias.

Finally, future studies should also investigate the contribution of balance and turning efficiency as determinants of 6MWT performance across different corridor lengths in this population. This would provide further insights into the factors leading to the observed discrepancies while enhancing the clinical evaluation of 6MWT results in settings where smaller treadmills are used.

These findings highlight the importance of protocol standardization when interpreting 6MWT results in clinical practice. The 15 m protocol may be useful when space limitations preclude the use of the standard 30 m walkway, but results should not be used interchangeably.

5. Conclusions

In conclusion, the findings of this study demonstrate that corridor length significantly influences performance during the 6 min walk test in older adults with medically controlled arterial hypertension. Therefore, the present findings should primarily be interpreted within the context of older adults with controlled arterial hypertension. Participants achieved consistently greater walking distances on the 30 m corridor compared with the 15 m configuration, while agreement analysis indicated that the two protocols cannot be considered interchangeable. Functional capacity during the 6MWT appears to be influenced by multiple interacting factors, including age, anthropometric characteristics, and aspects of health-related quality of life, with some determinants differing according to walkway length. The shorter corridor likely imposes additional biomechanical and neuromotor demands due to the increased frequency of turns, contributing to reduced walking efficiency and greater variability in performance. Although the 15 m protocol may represent a practical alternative in settings with limited space, clinicians should interpret results cautiously and avoid direct comparison with standard 30 m values. Further research with larger and more heterogeneous populations is required to better clarify the mechanisms underlying performance differences between corridor lengths and to further validate the clinical applicability of shorter 6MWT protocols.

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Data Availability Statement: The data presented in this study are available from the corresponding author upon request. The data are not publicly available due to ethical and privacy concerns.

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Abbreviations

The following abbreviations are used in this manuscript:

AH	Arterial Hypertension
WHO	World Health Organization
BP	Blood Pressure
DASI	Duke Assessment Status Index
ISWT	Incremental Shuttle Walking Test
6MWT	Six-Minute Walk Test
3MWT	Three-Minute Walk Test
6MWD	Six-Minute Walk Distance
COPD	Chronic Obstructive Pulmonary Disease
BMI	Body Mass Index
ATS	American Thoracic Society
IPAQ	International Physical Activity Questionnaire
IPAQ-SF	International Physical Activity Questionnaire—Short Form
SF-36	36—Item Short Form Health Survey
ICC	Intraclass Correlation Coefficient
VIF	Variance Inflation Factor
SBP	Systolic Blood Pressure
DBP	Diastolic Blood Pressure
SD	Standard Deviation
PF	Physical Functioning
RP	Role Limitations due to Physical Problems
VT	Vitality
SF	Social Functioning
RE	Role Limitations due to Emotional Problems
MH	Mental Health
GH	General Health
MCID	Minimal Clinically Important Difference
CPET	Cardiopulmonary Exercise Testing
SPSS	Statistical Package for the Social Sciences

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Article

Assessment of Mood, Acceptance of Illness, and Quality of Life in Dialysis Patients Undergoing Relaxation Therapy Using Virtual Reality

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Abstract

Background/Objectives: Regular dialysis sessions impose a fixed schedule on the patient's days and weeks; this can lead to negative emotions, low mood, helplessness, and a lack of control over their treatment, which significantly reduces the quality of life for these patients. The aim of this study was to assess the mood, level of illness acceptance, and quality of life among dialysis patients undergoing relaxation therapy using virtual reality (VR). **Methods:** Sixty hemodialysis (HD) patients were recruited for a single-arm study. A personal questionnaire as well as the AIS, PHQ-9, and KDQOL-36™ were used. After one month of the control period, 22 patients were analyzed and then continued with one month of VR relaxation therapy consisting of 360° scenarios or 2D landscape movies. Finally, 16 patients were analyzed for the outcomes during dialysis, three times a week. Results: The data analysis showed a small significant increase in AIS scores after the VR therapy. In the PHQ-9, slight significant reductions in scores were observed at the end of VR therapy. Analysis of the Physical Component Summary (PCS), but not for Mental Component Summary (MCS), results showed statistically significant increases after VR therapy. **Conclusions:** The study group of dialysis patients showed small but significant improvements in mood, disease acceptance, and quality of life. The VR therapy intervention may be a useful complementary tool to comprehensive treatment and rehabilitation for hemodialysis patients, but multi-center studies are needed for a larger group of patients.

Keywords: hemodialysis; end-stage renal disease; VR therapy; quality of life; mood; illness acceptance

1. Introduction

End-stage renal disease forces patients to make changes to their lives. Regular dialysis sessions impose a fixed schedule on the patient's days and weeks, interfering with their professional, social, and family lives. This can lead to negative emotions, low mood, helplessness, and a lack of control over their treatment, which significantly reduces the quality of life for these patients.

Besides the psychological burden, their daily routine is limited by symptoms, which typically include fatigue, nausea, frequent muscle cramps, itching, and easy exhaustion. These symptoms reduce their tolerance for social and professional activities and their ability to independently meet basic needs [1,2].

Illness acceptance is a measure of the degree to which a person is able to adapt to a chronic illness while functioning optimally [1]. Research indicates a significant relationship between the level of illness acceptance and mood [3,4].

A patient's level of illness acceptance has a significant impact on their adaptation to the limitations associated with illness and disability, which is associated with numerous clinical and socio-demographic factors [5].

On the one hand, a lack of illness acceptance causes a significant sense of psychological discomfort and hinders adaptation. On the other hand, greater illness acceptance is associated with a reduction in the severity of negative reactions and emotions associated with the illness itself, as well as with the accompanying comprehensive treatment and care.

Painter emphasized that illness acceptance can act as a motivating factor, and maintaining physical activity promotes greater illness acceptance [6].

Improving illness acceptance and mood is essential to help patients better psychologically adapt to the illness and its effects, and even improve the survival rate of patients with chronic diseases [3].

Patients with ESRD undergoing hemodialysis demonstrate varying degrees of illness acceptance when confronted with life changes and the need for adaptation. They may perceive their poorer physical condition as a major factor contributing to their reduced quality of life [1]. Dialysis patients' quality of life is also impaired by general fatigue resulting from low levels of physical activity, decreased physical capacity and muscle strength [7], sleep disturbances [8], cognitive impairment, depression and anxiety [9,10], and dietary restrictions. Patients' health status influences absenteeism from work, which may lead to reduced income [11]. All of these factors may contribute to a reduced quality of life in dialysis patients.

The aim of this study was to assess the mood, level of illness acceptance, and quality of life of dialysis patients undergoing relaxation therapy using virtual reality (VR).

We hypothesized that VR-assisted relaxation during dialysis would be associated with improvements in mood, illness acceptance, and quality of life relative to a preceding control period.

2. Materials and Methods

2.1. Study Design

Patients undergoing hemodialysis (HD) were recruited from the Dialysis Center at St. Luke's Hospital (Bolesławiec, Poland). This pilot study presents findings supported by a grant from the Wroclaw University of Health and Sport Sciences (grant no. Z.23.03). The study protocol received approval from the Ethics Committee of the Wrocław University of Health and Sport Sciences, Poland (approval no. 9/2024). All study procedures complied with the principles of the Declaration of Helsinki. The trial was registered in the Australian and New Zealand Clinical Trials Registry under the identifier ACTRN12626000164392. Written informed consent was obtained from all participants prior to inclusion, following a detailed explanation of the study's purpose and procedures, with assurance of the confidentiality of the collected data, as well as information regarding the voluntary nature of participation and the right to withdraw from the study at any stage of the project. Because of the nature of the intervention, blinding of participants and treating physiotherapists was not possible. To ensure adherence to the study, the patients were informed about the planned VR intervention. The intervention was administered by physiotherapists

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who did not participate in the survey or outcome assessment. All psychometric assessments were conducted at three separate time points within the same patient group: at the start of the study, prior to the one-month control period—timepoint 1 (T1), after the control period—timepoint 2 (T2), and after one month with VR therapy—timepoint 3 (T3) (Figure 1).

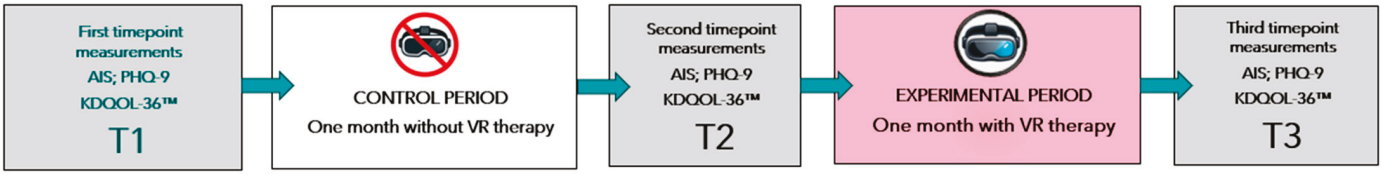

Figure 1. Design of the study.

2.2. Participants

The sample size was estimated for repeated measures ANOVA, assuming a test power of 0.8, alpha = 0.05, three repeated measures, a correlation between repeated measures of 0.7, and an effect size of 0.25. The minimum sample size was set at 17 individuals. Calculations were performed using the G*POwer 3.1 program. All participants were referred to the program by a nephrologist. Eligibility for inclusion in the study required fulfillment of the following criteria:

- Provision of informed consent to participate in the study;
- Diagnosis of chronic kidney disease (CKD);
- Receipt of hemodialysis treatment for a minimum of 3 months prior to study initiation;
- Ability to complete a comprehensive cognitive assessment;
- Preserved cognitive functioning (MMSE score > 23);
- Age between 40 and 70 years.

Participants were excluded if they met any of the following criteria:

- Contraindications to VR-based training, including epilepsy, vertigo, labyrinth disorders, or motion sickness;
- Documented severe psychiatric or neurological conditions (e.g., impaired consciousness or dementia);
- Pharmacological treatment for depression or other psychiatric disorders;
- Concurrent participation in other non-pharmacological support interventions during the study period.

The pilot study began with 25 HD patients; after a month without VR therapy, 22 remained. Sixteen patients completed the VR intervention. Reasons for dropping out included kidney transplant, ophthalmic surgery, lack of interest, and patient death.

Ultimately, the study recruited:

Group I (completers of the VR period)—16 HD patients;

Group II (completers of the control period)—22 HD patients (Table 1, Figure 2).

Given the high dropout rate, we examined the significance of differences between the VR period completers and those who dropped out of the program. The groups did not differ significantly in terms of gender, age, body weight and height, BMI, or years of dialysis (Appendix A, Table A1).

Table 1. Characteristics of the study group. Completers of the VR period and completers of the control period.

		Completers of the Control Period n = 22		Completers of the VR Period n = 16		Test T	
		Mean	**SD**	**Mean**	**SD**	**T**	***p***
Age (years)		63.55	15.07	64.56	15.78	−0.20	0.8415
Body height (m)		1.71	0.10	1.70	0.11	0.19	0.8531
Body mass (kg)		79.30	19.96	76.66	17.95	0.42	0.6768
BMI (kg/m^2)		27.01	6.01	26.21	4.44	0.45	0.6555
Years on dialysis		3.77	2.43	4.00	2.76	−0.27	0.7894
		n	%	*n*	%		*p*
gender	male	12	54.55	9	56.25		
	female	10	45.45	7	43.75		0.6277

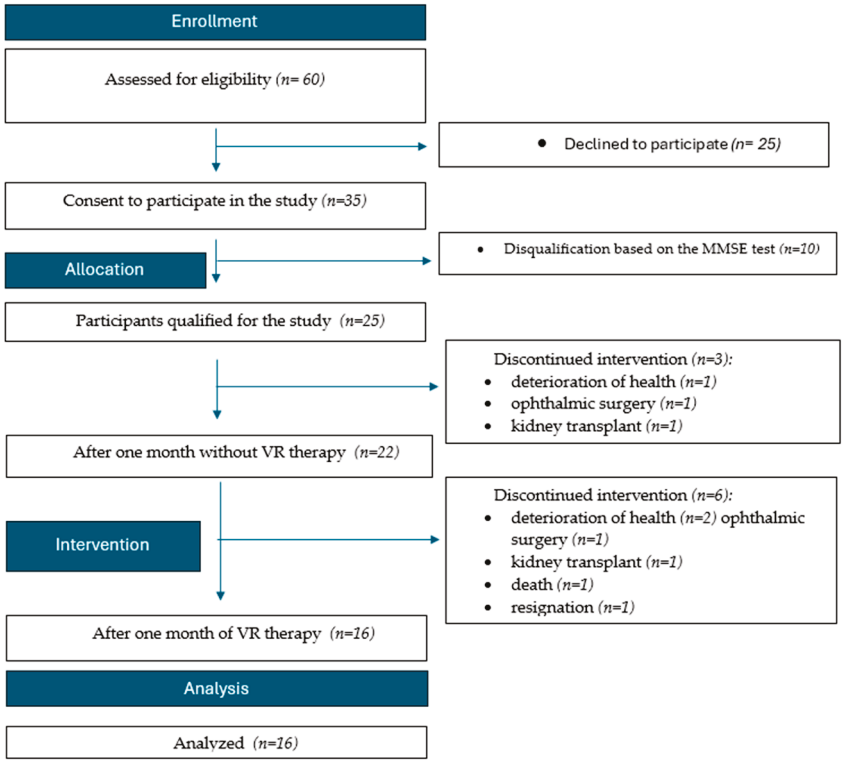

Figure 2. Flow diagram of the study.

2.3. The Intervention

Therapy was conducted under continuous supervision of a nephrologist and a physiotherapist. Relaxation therapy was delivered for one month, using immersive VR goggles (Meta Quest 3; Meta Platforms, Inc., Menlo Park, CA, USA). At the start of the intervention, each patient participated in a brief introductory interview covering preferences, technical aspects of VR goggle use, and safety procedures. Patients were informed that VR therapy could be discontinued at any time in the event of adverse effects (e.g., nausea, dizziness, visual discomfort). Session length depended on the self-selected presentation from the proposed content. The main reasons for shortening or discontinuing a session were fatigue related to the weight of the headset, loss of interest/boredom, or the patient falling asleep. The median number of sessions was 11 (IQR: 9–12), and the median duration of a single session was 30 min (IQR: 10–50). Passive VR therapy was applied using the YouTube platform (https://www.youtube.com). Based on patients' preferences, participants were presented

with realistic scenarios consisting of 360° videos and standard 2D landscape videos, accompanied by relaxation music Active immersive applications that required handheld controllers were excluded due to safety concerns. Following each session, participants completed a brief interview to evaluate any potential adverse reactions. No withdrawals related to serious adverse effects associated with VR therapy were observed. Only three cases of minor complications, i.e., dizziness, were reported during exposure to 360° environments. In these cases, patients independently decided to shorten or discontinue the session, or to change the scenario.

2.4. Measurement Tools

The following scales was used: a personal questionnaire, the Acceptance of Illness Scale (AIS), the Patient Health Questionnaire-9 (PHQ-9), and the Kidney Disease Quality of Life (KDQOL-36™) were used. The questionnaires were assessed by personnel who did not participate in the intervention.

The AIS contains eight questions that assess the degree of acceptance of the illness. The person can get from 8 to 40 points. A low score indicates a lack of acceptance of illness, which means that the patient may have significant emotional distress related to the illness. A high score signifies adaptation to the illness and the associated discomfort. The results below 20 points represent low acceptance of the illness. Scores 20–30 points suggest average acceptance, and scores greater than 30 points indicate a very good acceptance of the illness.

The PHQ-9 is a nine-item questionnaire designed to evaluate the severity of depressive symptoms. The total score ranges from 0 to 27 points. Threshold scores of $\geq$5, $\geq$10, $\geq$15, and $\geq$20 indicate mild, moderate, moderately severe, and severe depression, respectively. Currently, the PHQ-9 is considered one of the most effective screening instruments for identifying depression risk among individuals aged 18–60 years [12].

The KDQoL was used to subjectively assess the quality of life of patients with ESRD. The KDQoL includes questions about kidney disease, quality of life in the disease, and daily functioning. Point values for the entire survey, ranging from 0 to 100, are coded so that higher numbers reflect better health. The resulting total score represents the overall quality of life of the respondent. The higher the total score, the better the subjective quality of life [13,14].

Scores for all subscales were recalculated according to the Validated KDQOL-36™ scoring algorithm [15]. Calculations were performed using the KDQOL-SF™ 1.3 Excel spreadsheet, available online at https://www.rand.org/health/surveys/kdqol.html (accessed 14 May 2026).

2.5. Statistical Analysis

Descriptive statistics were computed for all variables. Given the ordinal scale of the data, results were summarized using the median as a measure of central tendency and the interquartile range (IQR = Q3–Q1) as a measure of variability. The T-test for dependent samples and the Mann–Whitney U test were used to compare the group of completers of the control period and completers of the VR period. The significance of differences between the three repeated measurements was tested using Friedman ANOVA. If the observed differences were significant, the Dunn Benjamini–Hochberg post hoc test was used to indicate which measurements had a significant difference. Analyses of significance of differences included only complete cases (n = 16). Effect size was tested using Kendall's W coefficient. For comparisons indicating the significance of differences, a confidence interval for the difference in medians was calculated.

The analysis was performed using Statistica 14.1.0.4 and PQStat 1.8.4. The level of significance was set at $p < 0.05$.

3. Results

We enrolled 25 patients, of whom 22 finished the control period and started the experimental VR therapy, which was completed by 16 subjects. The data analysis showed a significant increase in Acceptance of Illness Scale scores after the VR therapy (T3) (median 31.5 points) vs. measurement before VR therapy (T2) (median 25.5 points), and measurement at the start of the study (T1) (median 26.5 points), before the control period. There was no significant change in AIS after the control period (T1 to T2) (Table 2).

Table 2. Results of AIS at three timepoints of the study T1, T2 and T3.

				Friedman's ANOVA	Kendall's	Post Hoc 1 vs. 2	Post Hoc 1 vs. 3	Post Hoc 2 vs. 3
	Timepoints	Median	IQR	*p*	W	*p*	*p*	*p*
AIS	T1 T2 T3	26.5 25.5 31.5	11 12 7	<0.0001 *	0.76	0.8597	<0.0001 * CI: −9.0–(−4.0)	0.0001 * CI: −10.0–(−3.0)

AIS—the Acceptance of Illness Scale; IQR—interquartile range; T1—measurement 1; T2—measurement 2; T3—measurement 3; post hoc test—Dunn Benjamini–Hochberg; * $p < 0.05$.

In the Patient Health Questionnaire-9 (PHQ-9), significant reductions in scores were observed at the end of VR therapy (T3) (median 3 points), vs. the measurement point at the start of VR therapy (T2) (median 5.5 points), or before the control period (T1) (median 5 points). There was no significant reduction in PHQ-9 after the control period (T1 to T2) (Table 3).

Table 3. Results of PHQ-9 scale at three timepoints of the study T1, T2, and T3.

				Friedman's ANOVA	Kendall's	Post Hoc 1 vs. 2	Post Hoc 1 vs. 3	Post Hoc 2 vs. 3
	Timepoints	Median	IQR	*p*	W	*p*	*p*	*p*
PHQ-9	T1 T2 T3	5 5.5 3	8 6 6.5	<0.0001 *	0.66	0.6585	0.0006 * CI: 1.0–4.0	0.0001 * CI: 1.0–4.0

PHQ-9—the Patient Health Questionnaire-9; IQR—interquartile range; T1—measurement 1; T2—measurement 2; T3—measurement 3; post hoc test—Dunn Benjamini–Hochberg; CI—95% confidence interval for differences in medians; * $p < 0.05$.

Analysis revealed significant differences in the domain levels included in the SF36. The significance of the differences was primarily observed when comparing timepoint T1 with T3 and T2 with T3. At T3, the greatest improvements were observed in Physical functioning, Emotional well-being, and Energy/fatigue. In the disease targeted section (ESRD section of the scale), significant differences between measurements were observed only for the domains: Quality of social interaction, Sexual function, and Sleep. However, due to low or moderate effect sizes, no significant differences were found between successive timepoints, except for sleep duration, which was significantly longer at T3 compared to T1 (Tables 4 and 5).

Analysis of the Physical Component Summary (PCS) and Mental Component Summary (MCS) results showed statistically significant increases only in PCS scores after VR therapy, i.e., 48.34 points at T3 vs. 34.8 points at T2, and 33.58 points at T1 for PCS (Table 6).

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Table 4. Changes in raw scores of KDQoL at all three timepoints.

	KDQoL	T1		T2		T3	
		Median	IQR	Median	IQR	Median	IQR
ESRD-targeted areas	Symptom/problem list (12)	76.04	13.02	77.09	30.73	89.58	20.83
	Effects of kidney disease (8)	76.57	23.44	59.38	40.62	79.69	23.44
	Burden of kidney disease (4)	40.63	34.38	37.50	28.13	59.38	32.81
	Work status (2)	0.00	50.00	0.00	50.00	25.00	50.00
	Cognitive function (3)	73.33	35.00	80.00	40.00	96.67	20.00
	Quality of social interaction (3)	76.67	35.00	73.33	36.67	86.67	8.33
	Sexual function (2)	100.00	0.00	100.00	56.25	100.00	31.25
	Sleep (4)	57.50	25.00	62.50	21.25	96.67	20.00
	Social support (2)	83.33	5.21	91.67	9.58	86.67	13.33
	Dialysis staff encouragement (2)	100.00	25.00	87.50	25.00	100.00	25.00
	Patient satisfaction (1)	75.00	33.33	100.00	33.33	91.67	33.33
	Physical Component Summary						
36-item health survey (SF36)	Physical functioning 10)	45.00	37.50	87.50	25.00	90.00	21.25
	Role limitations—physical (4)	37.50	81.25	25.00	75.00	100.00	31.25
	Pain (2)	50.00	67.50	56.25	47.50	95.00	32.50
	General health (5)	40.00	25.00	47.50	16.25	50.00	16.25
	Mental Component Summary						
	Emotional well-being (5)	66.00	25.00	60.00	18.00	82.00	26.00
	Role limitations—emotional (3)	66.67	75.00	83.34	66.67	100.00	0.00
	Social function (2)	75.00	37.50	81.25	40.63	93.75	25.00
	Energy/fatigue (4)	50.00	12.50	50.00	42.50	77.50	16.25
	Health in the previous year (question 2)	50.00	50.00	50.00	25.00	75.00	6.25
	Subjective overall health (1) (question 22)	50.00	22.50	50.00	32.50	60.00	30.00

IQR—interquartile range; T1—measurement 1; T2—measurement 2; T3—measurement 3.

Table 5. Significance of differences between KDQoL scores obtained at three time points.

		Friedman's ANOVA	Kendall's	Post hoc Dunn Benjamini–Hochberg		
				1 vs. 2	1 vs. 3	2 vs. 3
		p	W	*p*	*p*	*p*
ESRD-targeted areas	Symptom/problem list (12)	0.0730	0.16			
	Effects of kidney disease (8)	0.1398	0.12			
	Burden of kidney disease (4)	0.0862	0.15			
	Work status (2)	0.2231	0.09			
	Cognitive function (3)	0.1988	0.10			
	Quality of social interaction (3)	0.0318 *	0.21	0.2505	0.2505	0.0647
	Sexual function (2)	0.0176 *	0.25	0.2792	0.3239	0.6585
	Sleep (4)	0.0001 *	0.31	0.4795	0.0001 * CI: −37.5–(−2.5)	0.0012 * CI: −27.5–0.00
	Social support (2)	0.9369	0.01			
	Dialysis staff encouragement (2)	0.3583	0.06			
	Patient satisfaction (1)	0.9131	0.01			

Table 5. *Cont.*

		Friedman's ANOVA	Kendall's	Post hoc Dunn Benjamini–Hochberg		
				1 vs. 2	1 vs. 3	2 vs. 3
		p	W	*p*	*p*	*p*
36-item health survey (SF36)	Physical Component Summary					
	Physical functioning (10)	0.0010 *	0.58	0.0030 * CI: −5.0–15.0	0.0030 * CI: −55.0–(−5.0)	0.8597
	Role limitations—physical (4)	0.0005 *	0.47	0.7909	0.0120 * CI: −100.0–0.0	0.0106 * CI: −75.0–0.0
	Pain (2)	0.0003 *	0.50	0.3768	0.0059 * CI: −35.0–0.0	0.0407 * CI: −35.0–0.0
	General health (5)	0.3556	0.06			
	Mental Component Summary					
	Emotional well-being (5)	0.0003 *	0.51	0.2505	0.0200 * CI: −32.0–0.0	0.0009 * CI: −36.0–(−4.0)
	Role limitations—emotional (3)	0.0354 *	0.21	0.9296	0.1396	0.1396
	Social function (2)	0.0335 *	0.21	0.7909	0.1674	0.1674
	Energy/fatigue (4)	0.0001 *	0.57	0.9296	0.0006 * CI: −35.0–(−10.0)	0.0006 * CI: −55.0–(−5.0)
	Health in the previous year (question 2)	0.0586	0.17			
	Subjective health assessment (question 22)	0.1728	0.11			

CI—95% confidence interval for differences in medians; * $p < 0.05$.

Table 6. Comparison of the Physical Component Summary and Mental Component Summary at three timepoints of the study.

	T1		T2		T3		Friedman's ANOVA	Kendall's W
	Median	IQR	Median	IQR	Median	IQR	*p*	
PCS	33.58	20.55	34.80	16.46	48.34	9.90	0.0171 *	0.25
	Post hoc Dunn Benjamini–Hochberg							
	1 vs. 2		1 vs. 3		2 vs. 3			
	0.5959		0.0508		0.0240 * CI: −16.9–(−4.3)			
	T1		T2		T3		Friedman's ANOVA	Kendall's W
	Median	IQR	Median	IQR	Median	IQR	*p*	
MCS	46.45	14.87	51.83	15.73	55.05	8.12	0.0808	0.16

PCS—the Physical Component Summary score, MCS—the Mental Component Summary score, MCS, 1 vs. 2, 1 vs. 3, and 2 vs. 3—*p*-value post hoc test, CI—95% confidence interval for differences in medians; * $p < 0.05$.

4. Discussion

Previous systematic reviews of studies on the use of VR therapy among patients with chronic diseases, including kidney disease, indicate that these therapies are well-tolerated and promising in improving psychological adjustment [16,17]. Primarily, they lead to

reduced stress and anxiety levels and improved mood [18,19]. However, there are still few studies on the effectiveness of VR in the therapy and treatment of patients with chronic kidney failure requiring dialysis, and those that do exist concern small groups of patients [10]. Mood disorders in a group of HD patients may result from anticipating hypothetical complications of dialysis during a long-term medical process. The observed change in the PHQ-9 score is small, below the minimal clinically important difference (MCID) of 5 points, but it is important to note that this value was determined in a population of patients diagnosed with depression [20]. Research shows that dialysis is an ideal time to utilize various therapies aimed at supporting the treatment process and improving the psychophysical condition and quality of life of these patients [21,22]. The observed improvement in disease acceptance is also important, as it is associated with a better perceived quality of life among these patients [23]. Available research findings indicate that improved mood promotes better disease acceptance by patients and increases their involvement in the treatment and rehabilitation process [24]. The relationship between these two parameters is multifaceted, suggesting that improving the level of disease acceptance may also reduce symptoms of depression in patients [3]. To date, no studies have been found that directly assess the level of disease acceptance following VR use, particularly in dialysis patients [21]. Within the study group, both mood and disease acceptance initially deteriorated during the first month of observation in the absence of intervention, followed by an improvement after the implementation of virtual reality (VR) therapy. Analyzing the underlying causes of these changes is complex and may be partially related to behavioral–psychological factors, which are beyond the scope of the present study and our area of expertise. Nevertheless, patients undergoing dialysis may experience boredom during treatment sessions, potentially contributing to negative emotional states. Therefore, one possible explanation is that the intervention helped diversify patients' activities during dialysis and thereby enriched the overall treatment experience. Importantly, we aimed to evaluate a therapy that did not require continuous specialist supervision and was instead more patient-centered. To date, most VR-based interventions have included a physical exercise component, which makes direct comparison of outcomes across studies difficult. These findings constitute valuable and promising evidence supporting the potential effectiveness of VR-based interventions and underscore the need for further research, particularly studies evaluating the long-term efficacy of VR therapy in this patient population. This may provide a foundation for building or regaining a proactive attitude toward treatment and dialysis, as well as restoring a sense of control and self-confidence (e.g., through engaging in physical activity on non-dialysis days or participating in training during dialysis) [22,25]. Based on the observed improvements in disease acceptance and evidence from current studies, the findings suggest that virtual reality interventions may enhance treatment adherence and patient engagement among haemodialysis patients [26]. Patients with CKD frequently experience impaired quality of life driven by chronic fatigue, emotional distress, and treatment burden associated with long-term dialysis [27]. Non-pharmacological interventions targeting psychological stress are increasingly recognized as essential components of supportive care. Virtual reality relaxation may improve mental health outcomes by promoting attentional distraction, reducing anxiety, and inducing relaxation responses [28–30], which in turn may positively influence perceived physical functioning [26]. Patient rehabilitation is no longer viewed solely as restoring the highest possible level of health and physical fitness; it also seeks to facilitate reintegration into social life and enhance overall quality of life. A subjectively low quality of life, reflected for example by KDQoL questionnaire scores, is associated with an increased risk of more frequent hospitalizations and premature mortality [31]. The present findings indicate that virtual reality-based relaxation therapy was associated with improvements in the Physical Component Summary (PCS) of the KDQoL in patients with

chronic kidney disease. In contrast, although the Mental Component Summary (MCS) demonstrated a favorable tendency, the observed change was not statistically significant. The observed improvements in Physical functioning, Role limitations—physical, Pain, Sleep, and the general PCS are unexpected, particularly because our intervention was intentionally designed to be passive due to safety reasons. At this stage of the pilot study, it is difficult to confirm the mechanism of these changes. The immersive VR relaxation may have reduced those aspects through altered stress or pain perception via autonomic relaxation. Also, reduced depressive symptoms may have indirectly enhanced patients' perception of their physical condition and daily functioning. It should be noted that the interpretation of these findings is highly speculative, as the study did not include physiological or behavioral measures directly testing these pathways [21,25,26]. Collectively, these results suggest that immersive virtual environments may positively influence certain dimensions of health-related quality of life, potentially through interacting physiological and psychological pathways [32]. There are limited reports regarding the influence of immersive VR relaxation therapy on quality of life in hemodialysis patients [26]. In one study with a non-immersive VR game, an improvement in the quality of life of HD patients was observed [33], although most interventions focus on exercise therapies, in the form of VR-supported exercises [34,35] or aerobic or resistance training only [36]. In all these interventions, improvements in both physical and mental quality of life were observed. Positive effects of VR interventions on well-being and quality of life have also been reported in other populations, including older adults [25], patients with chronic pain [37], and individuals with chronic illnesses [38]. Therefore, there is a need to explore therapeutic approaches and their combinations that can be implemented during dialysis to improve the psychophysical functioning and quality of life of patients undergoing dialysis. Virtual reality (VR) appears to be a promising tool in this context; however, further research in this patient population is warranted.

The present study has several limitations. The assessment of mood was based on screening measures and does not constitute a clinical diagnosis. This study was a single-center study with a relatively small sample size, limited by the absence of randomization and a control group. Complete blinding was not feasible, as outcome data were collected by the physiotherapist conducting the study, who was familiar with the study group. Nevertheless, to limit the assessor and detection bias, the intervention was delivered by physiotherapists who were not involved in the administration of questionnaires or outcome assessment. The study was also limited by the absence of long-term follow-up, preventing assessment of the sustained effects of the intervention. It is important to remember that with any intervention, the change in a patient's condition may be related not only to the intervention itself. It is also possible to experience regression to the mean, psychological expectancy bias, or the so-called Hawthorn effect. It should also be noted that Kendall's W coefficient values may be overestimated due to the small sample size.

Additionally, patients who were undergoing pharmacological treatment for depression were excluded from the study to avoid any doubt as to whether any improvement in mood was a result of pharmacological treatment or the introduction of VR therapy.

5. Conclusions

Preliminary findings suggest potential improvements in mood, disease acceptance, and quality of life among patients undergoing hemodialysis, which warrant confirmation in randomized controlled trials. The lack of significant side effects, ease of use, and positive reception of the therapy may constitute an interesting diversification of dialysis. Virtual reality (VR) relaxation therapy may serve as a useful complementary component

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of comprehensive treatment and rehabilitation in hemodialysis patients; however, multicenter studies with larger patient populations are needed.

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Abbreviations

The following abbreviations are used in this manuscript:

HD	Hemodialysis
ESRD	End-Stage Renal Disease
VR	Virtual Reality
EG	Experimental Group
CG	Comparator Group
AIS	Acceptance of Illness Scale
PHQ-9	Patient Health Questionnaire-9
KDQoL	Kidney Disease Quality of Life

Appendix A

Table A1. Comparison of the group of people participating in VR and the group of people who resigned from participating in the program.

		Completers of the VR Period *n* = 16		**Participants Who Withdrew *n* = 6**			
		Median	**IQR**	**Median**	**IQR**	**U**	***p***
Age (years)		67.50	24.00	65.50	20.00	37.5	0.4610
Body height (m)		1.69	0.16	1.74	0.02	37	0.4389
Body mass (kg)		80.30	30.70	97.50	33.50	31	0.2238
BMI (kg/m^2)		25.75	5.91	32.20	10.57	34	0.3196
Years on dialysis		3.00	2.00	3.00	2.00	42	0.6851
		n	%	*n*	%		*p*
gender	male	9	56.25	8	50		
	female	7	43.75	8	50		0.7232

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The Effect of Lumbar Spine Stabilization Exercises on the Quality of Life, Functional Movement, and Dynamic Balance in a Population with a Sedentary Lifestyle: A Pilot Randomized Controlled Trial

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Abstract

This pilot randomized controlled trial (RCT) aimed to evaluate the effect of a lumbar spine stabilization exercise program (LSSEP) in healthy adults with a sedentary lifestyle. Thirty-eight healthy Greek adults (mean age 40.53 ± 11.91 years) who had been sedentary for at least six months participated in the study. They were randomly assigned to an intervention group (n = 18) and a control group (n = 20). The intervention group followed a supervised progressive four-week LSSEP, while the control group received a booklet with ergonomic and stretching instructions (passive control). The primary outcome was the 12-Item Short Form Health Survey version 2 (SF-12v2), which measures quality of life, and secondary outcomes were the Functional Movement Screen (FMS) and the Y-Balance test (YBT), assessed before and immediately after the intervention period. A repeated-measures 2 × 2 mixed ANOVA revealed significant time × group interactions in favor of the intervention group for the mental component of quality of life and for functional movement and dynamic balance performance ($p < 0.05$), with moderate to large effect sizes. The LSSEP appears to improve specific aspects of quality of life and movement performance in healthy sedentary adults, with potentially clinically meaningful benefits observed even within a short four-week period. Confirmation through larger, longer-term trials is warranted.

Keywords: prevention; back pain; lumbar spine stabilization exercises; sedentary behavior; sedentary work; lack of physical activity

1. Introduction

A significant portion of the global population is increasingly characterized by sedentary behavior due to the rising demand for office work and the utilization of information and communication technologies [1]. This shift towards "technophilic" societies, driven by technological advancement and automation, has been associated with prolonged sitting and reduced habitual physical activity in many occupational settings [2,3], contrasting with the physiological requirement for regular physical activity.

According to recent global estimates published by the World Health Organization in 2024, approximately 31% of adults worldwide (1.8 billion people) did not meet the recom-

mended levels of physical activity in 2022 [4,5]. The increasing prevalence of sedentary behavior has emerged as a significant risk factor for both physical and mental health, including cardiovascular disease, metabolic dysfunction, cancer, and psychological disorders [6–11].

In addition, sedentary behavior is strongly associated with musculoskeletal disorders, particularly low back pain (LBP) and neck pain, regardless of overall levels of physical activity [12]. Adults may spend several hours per day engaged in sedentary activities and sitting time, particularly in occupational settings [2], while sedentary behavior exceeding three hours per day has been associated with reduced mobility of the lumbar spine and muscle imbalances [13–15]. These factors may contribute to the onset and persistence of low back pain and related disability, negatively affecting spinal mechanical stability and functional capacity [16].

Sedentary behavior is acknowledged as a principal modifiable risk factor. Lumbar spine stabilization exercises represent an active intervention aimed at restoring or enhancing the ability of the neuromuscular system to protect the spine from injury or re-injury [17–20]. Such exercise approaches have been shown to improve coordination, balance, and functional performance [21–23].

Prolonged sedentary behavior may negatively affect trunk function, postural control, movement patterns, and muscular endurance, potentially increasing the risk of musculoskeletal dysfunction over time. Previous research has demonstrated associations between core muscle function, postural control, balance, and neuromuscular recruitment patterns [24]. According to Hoffman and Gabel [21], spinal stability is closely related to movement control and neuromuscular coordination, while Akuthota et al. [23] highlighted the role of core stabilization exercises in improving trunk stability and functional movement control. Lumbar stabilization exercises may therefore represent a targeted preventive approach for sedentary individuals by helping maintain functional capacity and potentially reducing the risk of future musculoskeletal dysfunction, even before the onset of clinical symptoms. Such exercises may also improve coordination between the nervous and muscular systems by enhancing trunk stability and postural control, which may facilitate more efficient distal limb movement and functional performance [21]. The importance of trunk stabilization in maintaining spinal integrity and optimizing movement has been widely highlighted in the literature, as effective activation of core musculature contributes to improved neuromuscular control and functional performance [22]. In addition, lumbar stabilization exercise approaches have been associated with enhanced functional capacity and overall physical health, even in non-clinical populations [23,25,26]. However, most existing studies have focused on clinical populations or individuals with established LBP, either in primary or secondary prevention contexts [16,27–30]. Nevertheless, this preventive approach may be particularly relevant in occupational settings characterized by prolonged sedentary exposure, where workplace exercise interventions have demonstrated beneficial effects on employees' physical function and overall health [25,26].

Despite growing recognition of sedentary behavior as a risk factor associated with musculoskeletal dysfunction and low back pain [5,12–16], there is limited evidence regarding the effects of targeted exercise interventions in asymptomatic but sedentary individuals who may be at increased risk of developing musculoskeletal disorders. To date, it remains unclear whether early implementation of a lumbar spine stabilization exercise program (LSSEP) can provide preventive benefits in this population.

The Functional Movement Screen (FMS) and the Y-Balance Test (YBT) are widely used tools for the assessment of functional movement quality, dynamic balance, and neuromuscular control [24,31]. These measures are considered relevant indicators of lumbar stability and overall movement performance and have been shown to be sensitive to changes following exercise interventions, making them appropriate for evaluating

the potential effects of lumbar stabilization exercises in sedentary individuals [24,32,33]. Therefore, the aim of this study was to evaluate the effects of a lumbar spine stabilization exercise program (LSSEP) on quality of life, and to examine whether its implementation could improve functional movement patterns and dynamic balance in sedentary adults.

2. Materials and Methods

2.1. Study Design

The study was designed and reported in accordance with the CONSORT 2025 statement for randomized controlled trials [34]. The study used a randomized controlled trial (RCT) design with parallel groups in a 1:1 allocation ratio. The study was registered at ClinicalTrials.gov (No. NCT07447167) on 25 February 2026, prior to participant recruitment. The sample size was determined based on feasibility considerations, as this study was designed as a pilot randomized trial aiming to provide preliminary estimates rather than confirmatory hypothesis testing. The selected sample size is consistent with recommendations for pilot studies [35], given the pilot nature of the study, all inferential analyses were considered exploratory and intended to provide preliminary estimates of potential intervention effects rather than confirm definitive hypotheses. Therefore, results should be interpreted with caution.

2.2. Ethics

For the implementation of the study, the Ethics Committee of the University of West Attica provided approval (protocol code 124095/01-12-2025). The details of the study protocol were posted on the international database ClinicalTrials.gov (No. NCT07447167).

This research was conducted according to the principles of the Declaration of Helsinki. Specifically, potential participants were initially informed about the purposes and methods of the trial prior to being recruited for the study. They were also informed that their participation was on a voluntary basis and about their right to withdraw from the study at any time. A printed informed consent form was then signed by all recruited participants. A collaboration agreement was obtained from the participating company for the use of facilities and employee participation.

2.3. Participants

All participants were healthy Greek adults aged 18–65 who worked in a corporate environment at the time of the study and met IPAQ-based criteria for low physical activity levels, including prolonged occupational sitting and absence of regular exercise participation for at least six months. A prerequisite for participation in the study was the ability to follow a moderate-intensity exercise program, to understand the instructions, and to be able to complete the assessment questionnaires.

Exclusion criteria included recent musculoskeletal injury, neurological or rheumatic disorders, recent surgery, contraindications to exercise, pregnancy, and use of medications affecting performance or balance.

2.4. Procedures

The principal investigator (D.K.) sent an electronic invitation to companies that employ staff with sedentary work. The company Connect Line responded positively to the invitation. The principal investigator then met with HR to present in detail the study's purpose and implementation steps. Following the meeting, the human resources department emailed the invitation to participate in the study to the company's staff. Forty people agreed to participate in the study. After signing the informed consent form, the participants completed:

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- The demographics questionnaire;
- The International Physical Activity Questionnaire—Short Form (IPAQ-SF) for assessing the level of physical activity over the past seven days;
- A questionnaire based on the Physical Activity Readiness Questionnaire (PAR-Q), with the addition of questions regarding overall health, such as musculoskeletal and neurological health, and medication use, as well as the presence of any specific condition (pregnancy or postpartum or any other condition);

Participants then also completed the study outcomes;

- The SF-12v2 Health Survey for the assessment of quality of life;
- The Functional Movement Screen (FMS), assessing functional movement performance;
- The Y-Balance Test (YBT), assessing dynamic balance.

To assess measurement error, the FMS and YBT were performed twice with a three-day interval on all participants prior to randomization.

After the initial assessment, participants were randomly allocated (1:1) using a computer-generated sequence (IBM SPSS Statistics, v.29.02.0) by an independent researcher. Simple randomization without stratification or blocking was applied. Allocation was concealed using sealed opaque envelopes. Outcome assessors were not blinded to group allocation. The groups were formed as follows:

- An intervention group, receiving an LSSEP;
- A control group was included, in which participants were provided with printed brochures containing ergonomic and stretching instructions, representing a minimal intervention. Participants in the control group were asked to record the frequency of leaflet use in a self-reported log; however, this was not used as a formal adherence measure, and no systematic monitoring of compliance was performed.

The intervention lasted four (4) weeks and included two (2) thirty-minute sessions each week. The exercise frequency and duration were selected based on feasibility considerations and to allow the investigation of early neuromuscular adaptations in a sedentary population.

2.5. Interventions

The intervention group was finally formed by eighteen individuals who met the inclusion criteria. Two individuals were excluded based on the IPAQ-SF criteria because they had a high level of exercise, according to the tool's categorization. For more effective guidance, the remaining individuals were randomly divided into two subgroups of five and two subgroups of four. During the sessions, special emphasis was placed on learning to activate the transversus abdominis muscle through breathing techniques, forming the basis for the proper execution of stabilization exercises.

The exercises were performed in different positions, such as standing, supine, side-lying, and quadruped (Figure 1). The level of difficulty increased gradually, following the principle of progressive overload (Table 1). Progression decisions were based on the participants' ability to perform the exercises with proper technique, control, and without compensatory movements. All sessions were supervised by the principal investigator to ensure correct execution and consistency of the intervention protocol. Attendance was recorded throughout the intervention period to monitor participant adherence. Fidelity was monitored through direct observation, verbal feedback, and individualized instructions provided throughout the sessions to facilitate correct technique and appropriate trunk muscle activation according to each participant's capabilities.



Figure 1. The exercises included in the lumbar spine stabilization exercise program (LSSEP).

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Table 1. The exercises included in the lumbar spine stabilization exercise program (LSSEP) and their progressions over the 4 weeks of its duration.

	Week 1	Week 2	Week 3	Week 4
Diaphragmatic breathing	2 × 10 reps	2 × 10 reps	2 × 10 reps	2 × 10 reps
Abdominal drawing-in	2 × 10 (4 s)	2 × 10 (6 s)	2 × 10 (8 s)	2 × 10 (8 s)
Pelvic tilt	2 × 8	2 × 10	2 × 12	2 × 12
Abdominal curl up	1 × 10	2 × 10	2 × 10 single leg stretch	2 × 12 single leg stretch
Heel slides	2 × 10	2 × 10	-	-
Dead bug	2 × 8 (5 s) only leg + only arm	2 × 10 (8 s) leg-arm/opposite leg/arm stable	3 × 10 (10 s)	3 × 12 (15 s) table top
Glute bridge	2 × 10 (5 s)	2 × 10 (8 s)	-	-
Bridge march	-	2 × 10	3 × 10	3 × 12
Single-leg bridge	-	-	3 × 8 (10 s)	3 × 10 (15 s)
Clamshell	2 × 10	2 × 12	2 × 10 raised pelvis	-
Side plank	2 × 8 knees (5 s)	2 × 10 (8 s)	3 × (10 s)	3 × (12 s)
Plank	-	2 × 8 knees	3 × (10 s)	3 × (12 s)
Quadruped arm/leg	1 × 10 only arm + only leg	2 × 8	2 × 10	2 × 12
Squat	-	-	3 × 10	3 × 12
Lunge	-	-	3 × 8	3 × 10
Single-leg balance	-	2 × 20 s	3 × 30 s	3 × 10 s (eyes closed)

2.6. Control Group

In the control group, a pamphlet with ergonomic instructions was given, representing a minimal intervention, which the participants could incorporate into their daily routine in their work environment. Specifically, the instructions given were to sit with the back straight and use lumbar support; to position the screen at eye level (50–70 cm distance); to adjust the chair so that the knees form a 90° angle and the feet are flat on the ground or footrest; and to use the keyboard with elbows at a 90° angle and shoulders relaxed. Finally, the pamphlet instructed participants to take a break every 30–45 min to walk and stretch. No systematic monitoring of adherence to the provided instructions was performed.

2.7. Participants' Demographic Characteristics, Physical Health Assessment for Safety to Exercise, and Self-Reported Level of Current Physical Activity

2.7.1. Demographics Questionnaire

Participant's demographic information, such as age, gender, height, body mass, body mass index, socioeconomic characteristics, smoking, and level of exercise.

2.7.2. Short Form of the International Physical Activity Questionnaire in Greek (IPAQ-SF-GR)

To evaluate the degree of physical activity of the participants, the Greek version of the International Physical Activity Questionnaire—Short Form (IPAQ-SF) was used, which has been documented as a reliable and valid tool internationally [36] as well as in the Greek population [37]. It allows categorization of the level of physical activity into three groups:

low, moderate, and high [36]. Additionally, it served as a criterion for inclusion or exclusion from the study and was completed at the beginning of the trial. Systematic reviews of the IPAQ-SF show reliability of repeated measurements with correlation coefficients ranging from r = 0.66 to 0.88 [38]. Additionally, it demonstrates adequate criterion validity, showing moderate correlations with objective measures of physical activity [36,38]. The tool is considered suitable for detecting clinically significant changes, according to the criteria for evaluating measurement properties [39]. The Greek version of the IPAQ-SF has been validated in terms of criterion validity and construct validity, showing statistically significant correlations with the Godin Leisure-Time Exercise Questionnaire (r = 0.39–0.68, $p < 0.001$) and exhibiting expected variations related to gender, age, BMI, and participation in sports activities [40].

2.7.3. Questionnaire for Assessing Physical Health for the Safe Administration of Therapeutic Exercise

An additional questionnaire was used to assess the overall physical health status of the study participants to confirm the safety of administering therapeutic exercise to them, based on the Physical Activity Readiness Questionnaire (PAR-Q) [41], to provide supplementary documentation of the subjective health parameters that were not adequately covered by the other tools.

2.8. Outcome Measures

2.8.1. The SF-12v2 Health Survey (Greek Version)

Health-related quality of life was assessed using the SF-12v2 Health Survey, a shorter version of the SF-36. It provides two summary scores—the Physical Component Summary (PCS) and Mental Component Summary (MCS)—derived from eight health domains [42].

The reliability of repeated measurements of the SF-12v2 has been evaluated by the creators of the scale, with coefficients of 0.89 for the PCS subscale and 0.76 for the MCS over a two-week period [42]. In long-term reassessment studies, the annual reliability of the SF-12v2, as determined by the intraclass correlation coefficient (ICC), was 0.61 for the PCS and 0.57 for the MCS, indicating a moderate degree of stability over time. The Mosier alpha coefficient indicated that the internal consistency was 0.70 and 0.69, respectively [43]. Additionally, its validity has been documented, and it has a strong correlation with the SF-36, adequately reproducing the physical and mental dimensions of health [42]. The SF-12v2 scale has been translated, adapted, and evaluated in the Greek population [44].

The use of the questionnaire was carried out under a license from QualityMetric (License Number: QUO-10609-Z7Z3H6).

2.8.2. Functional Movement Screen (FMS)

The Functional Movement Screen (FMS) was used to assess the quality of fundamental movement patterns [31]. The FMS was performed using the FMS test kit (Move2Perform, Evansville, IN, USA). The test includes seven assessments that measure symmetry, stability, and motor control. The tests specifically are deep squat, hurdle step, inline lunge, shoulder mobility, active straight leg raise, trunk stability push-up, and rotary stability. The maximum score for all tests is 21 points. A total score below 14 points has been associated with an increased risk of injury primarily in athletic populations [32]. However, it has been emphasized that this threshold should be interpreted in the context of the specific characteristics of the population being examined [45].

The reliability and accuracy of the Functional Movement Screen (FMS) have been extensively examined. A recent study on structural validity in tennis athletes confirmed a satisfactory factor structure through exploration and confirmatory factor analysis, with the final model representing 54.05% of the total variance. The overall reliability of the tool

was high (ICC = 0.91, 95% CI [0.53, 0.92], $p = 0.001$) [46]. The research on adult volunteers showed extremely high reliability among raters (ICC = 0.98) [47] and significant reliability among repeated measurements (ICC = 0.92) for the overall FMS score. Also, a systematic review and meta-analysis found that the reliability coefficients within and between raters were equal to ICC = 0.81 (95% CI 0.69–0.92) and ICC = 0.81 (95% CI 0.70–0.92), respectively, indicating good reliability [32]. The FMS has also been used to effectively monitor changes after exercise interventions [45,48]. The sensitivity of the tool to small changes may be affected by the initial level of motor competence of the participants [49], a factor that should be considered when analyzing the results.

2.8.3. Y-Balance Test

The YBT is a useful tool for assessing dynamic balance and is often used to identify functional asymmetry and potential motor imbalances [50]. To calculate asymmetry, the absolute difference (in cm) between the right and left foot was determined for each direction (ANT, PM, PL). The total score was calculated as a percentage of the lower limb length [51].

Lower composite scores have been associated with reduced dynamic stability and neuromuscular control. On the other hand, greater asymmetry in the anterior direction (ANT) has been associated with a higher risk of injury in the literature [33].

The YBT for the lower limbs demonstrated high reliability (ICC = 0.85–0.91), along with adequate discriminative and predictive validity, thus confirming its usefulness in both clinical practice and research protocols [33,51]. Regarding predictive validity, it has been reported that anterior asymmetry $\geq$4 cm is associated with an increased risk of lower extremity injuries, particularly in athletic populations [50]. Therefore, this threshold should be interpreted in relation to the characteristics of the population being examined.

The YBT was performed using the YBT kit ^{TM} (Move2Perform, Evansville, IN, USA). For the execution of the test, the examinee is asked to stand on one foot, placing the sole on a base located at the center of the device, while keeping the sole that supports the body in constant contact with the base of the device. Then, with the lower limb that is not in contact with the ground, the examinee attempts, while maintaining their balance, to extend the toe of this foot to the maximum distance from the center of the device in three directions: anterior, posteromedial, and posterolateral. The distance is measured in centimeters.

Taken together, the FMS and YBT were selected as outcome measures due to their widespread use in assessing functional movement quality, dynamic balance, and neuromuscular control in both clinical and non-clinical populations [31]. Previous studies have demonstrated that these tools are sensitive to changes following exercise interventions and are associated with core muscle activation and postural control [24]. Although these assessments primarily reflect global movement patterns rather than isolated lumbar spine motor control, they are considered relevant functional indicators of trunk stability and overall motor control, which may be influenced by lumbar spine function.

2.9. Statistical Analysis

All statistical analyses were performed with the IBM Statistical Package for the Social.

Sciences (IBM SPSS Statistics, v.29.02.0). The quantitative variables were presented as mean and standard deviation (SD), while the qualitative/categorical variables (gender, BMI categories, marital status, educational level, income, smoking, and exercise level) were presented as absolute and relative frequencies [*N* (%)]. For the comparison of the baseline measurements of the continuous quantitative variables between the two independent groups, the independent samples t-test was used, while for categorical variables, the x^2 test was applied. All tests were two-tailed, and the significance level was set at $\alpha = 0.05$.

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A per-protocol analysis was performed, as participants who withdrew after randomization were excluded from the final analysis.

Before treatment administration, test–retest reliability of the YBT and FMS was evaluated in the initial sample of 40 participants, with a 3-day interval between measurements, using appropriate indices of relative and absolute reliability. As a measure of relative reliability for the YBT, the intraclass correlation coefficient (ICC) with a two-way mixed-effects model was used, examining the degree of absolute agreement for single measurements (two-way mixed-effects absolute-agreement single-measurements intraclass correlation coefficient—$ICC_{2,1}$) and, for the FMS, the same measure for the average of measurements ($ICC_{2,k}$) [52,53]. As absolute reliability indices, the standard error of the measurement (SEM) and the minimum detectable change ($MDC_{95\%)}$ were used [52]. The two indices of absolute reliability represent the magnitude of the error between measurements, and specifically, the minimum detectable change represents the limits of the error beyond which the difference is due to a true change in the measured variable.

To examine whether the change in SF-12v2, FMS, and YBT from pre-to-post differed between the intervention group and the control group (interaction time $\times$ group), a 2 $\times$ 2 repeated-measures mixed ANOVA was conducted with the within-subjects factor being time (pre/post) and the between-subjects factor being group (intervention/control). For the outcomes that were significantly different between groups at baseline, additional ANCOVA analyses were conducted for the post-intervention scores using baseline outcome values and age as covariates to account for potential baseline imbalances between group effects. Normality assumptions were assessed prior to the application of parametric analyses to ensure the appropriateness of ANOVA procedures. Partial eta squared (η^2_p) values of 0.01, 0.06, and 0.14 were interpreted as small, medium, and large effect sizes, respectively. Given the pilot nature of the study, no formal correction for multiple comparisons was applied, and all inferential analyses were considered exploratory and intended to provide preliminary estimates of potential intervention effects rather than confirm definitive hypotheses. Therefore, statistically significant findings should be interpreted with caution, particularly given the multiple exploratory and secondary analyses performed and the potential for inflated type I error.

3. Results

3.1. Demographics

A total of 40 individuals initially agreed to participate in the study. Participant flow is presented in Figure 2 in accordance with CONSORT recommendations.Following randomization, two participants allocated to the intervention group withdrew prior to the initiation of the intervention because they reported plans to engage in regular exercise, which no longer met the study criteria (Figure 2). Therefore, a total of 38 participants (28 women) with sedentary jobs for at least six months and low to no level of exercise, without musculoskeletal conditions, were included in the study.

The distribution of participants in terms of demographic characteristics in total and across the two groups is presented in Table 2. No significant baseline differences were observed between groups, except for age, with participants in the intervention group being younger on average (36.28 $\pm$ 12.40 years) compared to the control group (44.35 $\pm$ 10.31 years). This difference was considered a potential confounding factor and was accounted for in subsequent analyses.

3.2. Test–Retest Reliability of the ϒBT and FMS

The test–retest reliability of the YBT and FMS demonstrated excellent reliability across all measures (ICC range: 0.95–0.98), with low measurement error (Table 3).

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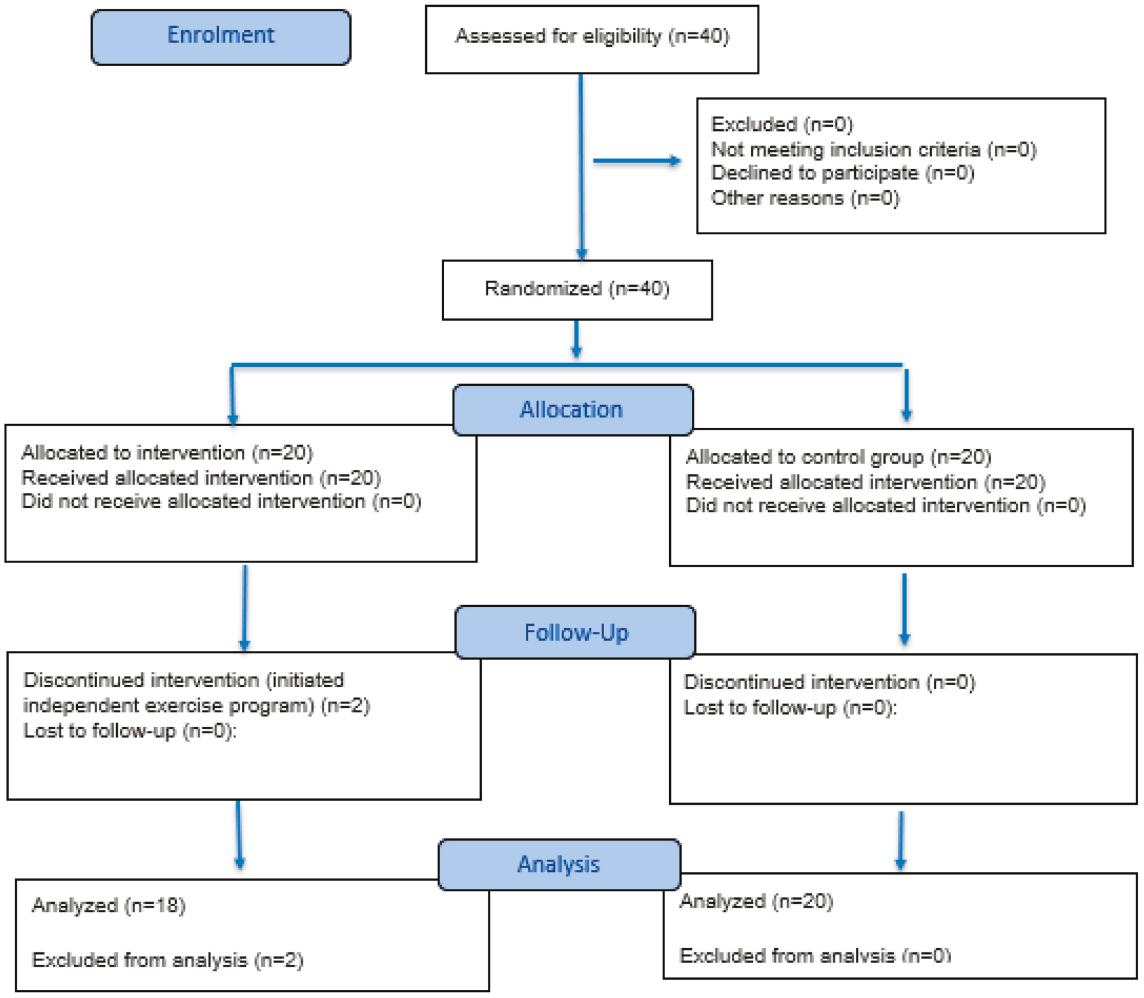

Figure 2. Flow diagram of participants.

Table 2. Characteristics of participants in the overall sample and by study group.

	Total Sample N = 38	**Intervention Group N = 18**	**Control Group N = 20**	**Comparison, *p*-Value**
Age (years), *Mean* ± *SD*	40.53 ± 11.91	36.28 ± 12.40	44.35 ± 10.31	t = 2.19; df = 36; $p = 0.03$
Gender, *N* (%)				
Male	10 (26.3%)	5 (27.8%)	5 (25.0%)	$X^2(1) = 0.04$; $p = 0.85$
Female	28 (73.7%)	13 (72.2%)	15 (75.0%)	
Height (m), *Mean* ± *SD*	1.69 ± 0.09	1.70 ± 0.07	1.67 ± 0.10	$t = 0.82$; $df = 36$; $p = 0.41$
Body Mass (kg), *Mean* ± *SD*	72.32 ± 16.01	71.72 ± 16.03	72.85 ± 16.39	$t = 0.21$; $df = 36$; $p = 0.83$
BMI (Kg/m^2), *Mean* ± *SD*	25.29 ± 4.58	24.63 ± 4.10	25.89 ± 5.00	$t = 0.84$; $df = 36$; $p = 0.40$
BMI Categories, *N* (%)				
Underweight	1 (2.6%)	1 (5.6%)	0 (0.0%)	$X^2(3) = 1.17$; $p = 0.94$ [a]
Normal	20 (52.6%)	9 (50.0%)	11 (55.0%)	
Overweight	13 (34.2%)	6 (33.3%)	7 (35.0%)	
Obese	4 (10.5%)	2 (11.1%)	2 (10.0%)	
Marital Status, *N* (%)				
Single	19 (50.0%)	11 (61.1%)	8 (40.0%)	$X^2(2) = 1.72$; $p = 0.85$ [a]
Married	14 (36.8%)	5 (27.8%)	9 (45.0%)	
Divorced	5 (13.2%)	2 (11.1%)	3 (15.0%)	

Table 2. *Cont.*

	Total Sample N = 38	Intervention Group N = 18	Control Group N = 20	Comparison, *p*-Value
Level of Education, *N* (%)				
High School	1 (2.6%)	1 (5.6%)	0 (0.0%)	$X^2(1) = 1.14$; $p = 0.47$ [b]
University	37 (97.4%)	17 (94.4%)	20 (100.0%)	
Income, *N* (%)				
Low	10 (26.3%)	5 (27.8%)	5 (25.0%)	$X^2(2) = 4.07$; $p = 0.17$ [a]
Average	24 (63.2%)	13 (72.2%)	11 (55.0%)	
High	4 (10.5%)	0 (0.0%)	4 (20.0%)	
Smoking, *N* (%)				
No	26 (68.4%)	13(72.2%)	13 (65.0%)	$X^2(2) = 0.24$; $p > 0.99$ [a]
Sometimes	7 (18.4%)	3 (16.7%)	4 (20.0%)	
Often	5 (13.2%)	2 (11.1%)	3 (15.0%)	
Level of Exercise, *N* (%)				
Low	19 (50.0%)	7 (38.9%)	12 (60.0%)	$X^2(2) = 2.44$; $p = 0.26$ [a]
Average	18 (47.4%)	10 (55.6%)	8 (40.0%)	
High	1 (2.6%)	1 (5.6%)	0 (0.0%)	

BMI: body mass index; SD: standard deviation; [a] *p*-value estimated using Monte Carlo simulation; [b] Exact *p*-value (exact significance).

Table 3. Descriptive statistics (means ± SD) and reliability indices ($ICC_{2,1}$, SEM, $MDC_{95\%}$) of the YBT (best of 3 measurements per movement direction, composite scores, and anterior direction asymmetry) and of the total FMS score (n = 40).

Mean ± SD 1	Mean ± SD 2	$ICC_{2,1}$ (95% CI)	SEM	$MDC_{95\%}$
		YBT—Anterior R lower limb		
74.39 ± 11.47	76.26 ± 11.86	0.97 (0.85–0.99)	1.55	4.29
		YBT—Posteromedial R lower limb		
81.10 ± 12.37	83.51 ± 12.74	0.96 (0.79–0.98)	2.04	5.66
		YBT—Posterolateral R lower limb		
89.58 ± 10.30	91.93 ± 10.56	0.95 (0.61–0.99)	1.51	4.17
		YBT—Composite R lower limb		
81.69 ± 9.19	83.90 ± 9.48	0.96 (0.44–0.99)	1.16	3.22
		YBT—Anterior L lower limb		
76.96 ± 11.72	78.12 ± 11.53	0.98 (0.95–0.99)	1.42	3.93
		YBT—Posteromedial L lower limb		
83.62 ± 12.25	84.97 ± 11.97	0.96 (0.92–0.98)	2.07	5.74
		YBT—Posterolateral L lower limb		
90.28 ± 10.72	91.35 ± 11.48	0.97 (0.94–0.99)	1.55	4.31
		YBT—Composite L lower limb		
83.62 ± 9.27	84.81 ± 9.26	0.98 (0.90–0.99)	1.00	2.77
		Total FMS Score		
14.20 ± 1.90	14.37 ± 2.02	0.98 (0.95–0.99)	0.27	0.75

YBT: Y Balance Test, FMS: Functional Movement Screen, L: left, R: right, CI: confidence interval, SD: standard deviation, LL: leg length; for the YBT data, the Mean, SD, SEM, and $MDC_{95\%}$ values represent % LL; (1,2–Measurement 1 and Measurement 2).

3.3. Between-Group Differences

No statistically significant differences in their clinical baseline characteristics were identified between groups, except for the YBT composite scores for the R and L lower limbs and the FMS total score (Table 4). Therefore, for these outcomes, an ANCOVA analysis was also conducted. Significant time × group interactions were observed for mental health-related quality of life, particularly for the Mental Component Summary (MCS) and related subscales, indicating greater improvements in the intervention group compared to the

control group ($p < 0.05$, Table 4, Figure 3). No significant interactions were observed for the Physical Component Summary (PCS).

Table 4. Descriptive statistics (mean ± SD) and interaction effect (time × group) of the main and the secondary outcomes for pre- and post-intervention time-points per treatment group.

		EG (n = 18)	CG (n = 20)	F (1,36)	*p*	η^2_p
Main Outcome–SF12v2						
PCS (0–100)	Pre	54.61 ± 6.42	51.94 ± 6.39	1.77	0.19	0.05
	Post	57.20 ± 3.20	52.18 ± 6.18			
MCS (0–100)	Pre	44.99 ± 6.52	45.99 ± 6.40	35.38	<0.001	0.50
	Post	52.38 ± 3.73	45.76 ± 6.29			
PF subscale (0–100)	Pre	93.06 ± 16.73	82.50 ± 24.47	0.85	0.36	0.02
	Post	97.22 ± 11.78	83.75 ± 23.33			
RP subscale (0–100)	Pre	75.69 ± 21.64	80.62 ± 20.06	18.95	<0.001	0.34
	Post	92.36 ± 11.45	80.62 ± 19.65			
BP subscale (0–100)	Pre	86.11 ± 15.39	73.75 ± 24.97	3.06	0.09	0.08
	Post	94.44 ± 10.69	75.00 ± 22.94			
GH subscale (0–100)	Pre	61.11 ± 15.39	53.75 ± 20.32	16.16	<0.001	0.31
	Post	75.00 ± 8.57	55.00 ± 19.19			
VT subscale (0–100)	Pre	51.39 ± 15.98	56.25 ± 21.27	31.00	<0.001	0.46
	Post	69.44 ± 10.69	55.00 ± 22.36			
SF subscale (0–100)	Pre	83.33 ± 19.17	82.50 ± 20.03	11.28	0.002	0.24
	Post	94.44 ± 10.69	81.25 ± 21.27			
RE subscale (0–100)	Pre	74.31 ± 18.43	73.12 ± 18.71	21.24	<0.001	0.37
	Post	89.58 ± 13.04	73.75 ± 18.09			
MH subscale (0–100)	Pre	59.03 ± 11.18	59.37 ± 13.97	48.68	<0.001	0.57
	Post	75.00 ± 9.59	60.00 ± 13.81			
Secondary Outcomes						
YBT—Composite R Lower Limb	Pre	87.66 ± 8.06 [a]	80.08 ± 9.58	41.70	<0.001	0.54
	Post	93.50 ± 8.57	78.59 ± 8.72			
YBT—Composite L Lower Limb	Pre	88.86 ± 8.41 [a]	80.98 ± 8.94	5.42	0.03	0.13
	Post	91.78 ± 11.41	79.66 ± 8.79			
YBT—Anterior Direction Asymmetry	Pre	3.61 ± 3.36	3.30 ± 2.62	6.90	0.01	0.16
	Post	2.33 ± 2.47	3.25 ± 2.17			
Total FMS Score	Pre	15.39 ± 1.72 [a]	13.65 ± 1.90	17.98	<0.001	0.33
	Post	16.61 ± 1.88	13.70 ± 1.72			

SF12v2: Short Form 12-item Health Survey version 2, PCS: Physical Component Summary, MCS: Mental Component Summary, PF: physical functioning, RP: role physical, BP: bodily pain, GH: general health, VT: vitality, SF: social functioning, RE: role emotional, MH: mental health, YBT: Y Balance Test, FMS: Functional Movement Screen, L: left, R: right, CI: confidence interval, SD: standard deviation, LL: leg length; for the YBT data, the Mean and SD values represent % LL, [a]: significantly different between-group baseline value.

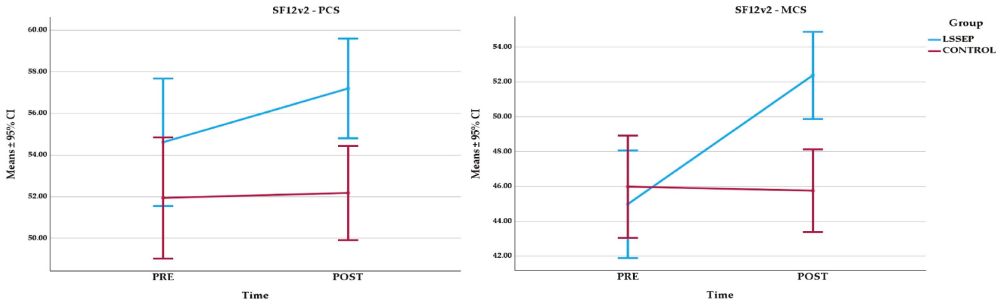

Figure 3. Change over time of the estimated marginal means (±95% CI) for the Physical Component Summary (PCS) and the Mental Component Summary (MCS) of the SF12v2 for the two groups.

For the secondary outcomes, significant improvements were observed in dynamic balance (YBT composite scores) and functional movement performance (FMS total score) in the intervention group compared to the control group ($p < 0.05$, Table 4, Figure 4).

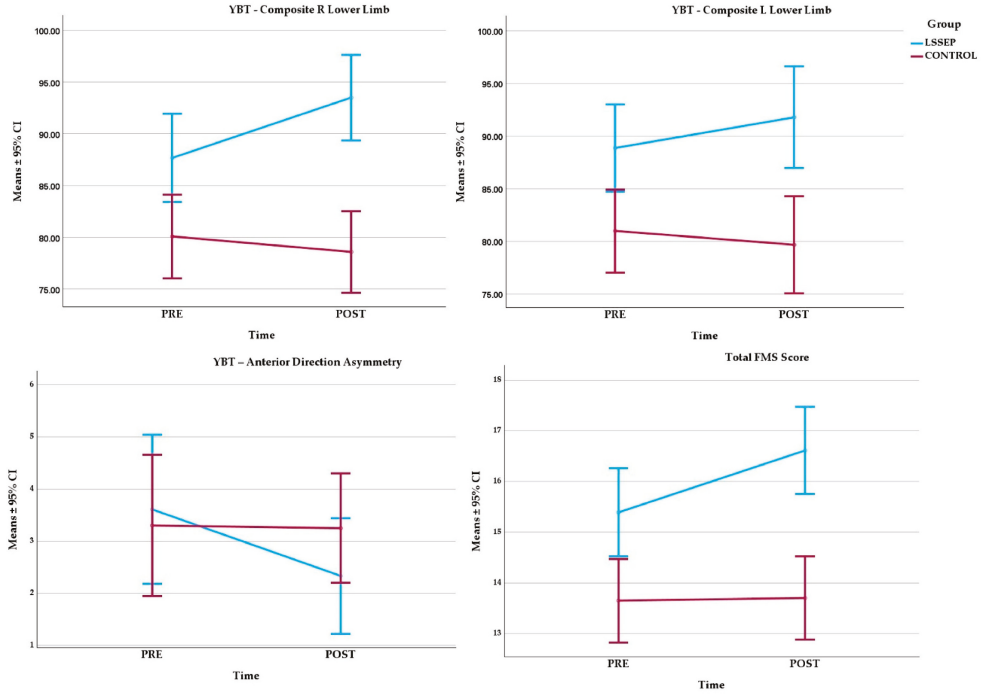

Figure 4. Change over time of the estimated marginal means (±95% CI) for the right (R) and left (L) lower limb composite scores and the anterior direction asymmetry of the Y Balance Test (YBT) and of the total FMS score for the two groups.

For the secondary outcomes, significant time × group interactions were observed for YBT composite right lower limb ($F(1,36) = 41.70$, $p < 0.001$, $\eta^2_p = 0.54$), YBT composite left lower limb ($F(1,36) = 5.42$, $p = 0.03$, $\eta^2_p = 0.13$), and YBT anterior direction asymmetry ($F(1,36) = 6.90$, $p = 0.01$, $\eta^2_p = 0.16$), indicating improvements in dynamic balance performance in the experimental group (Figure 4). All YBT composite scores reported in the analyses were normalized to leg length.

Additionally, a significant interaction effect was found for the total FMS score ($F(1,36) = 17.98$, $p < 0.001$, $\eta^2_p = 0.33$) (Figure 4). In all three ANCOVA analyses conducted, the group effect remained statistically significant, indicating that the initial result could not be attributed solely to baseline differences between the groups. The consistency of the findings between the repeated-measures ANOVA (time × group interaction) and the ANCOVA (baseline-adjusted difference at post) enhances the reliability of the intervention results.

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Moreover, ANCOVA analyses adjusting for baseline scores and age demonstrated that the intervention effects for FMS and YBT outcomes remained statistically significant after controlling for age differences between groups. Specifically, significant adjusted group effects were observed for FMS total score ($F(1,34) = 23.78$, $p < 0.001$, $\eta^2_p = 0.412$), YBT right composite score ($F(1,34) = 39.34$, $p < 0.001$, $\eta^2_p = 0.536$), YBT left composite score ($F(1,34) = 4.81$, $p = 0.035$, $\eta^2_p = 0.124$), and asymmetry score ($F(1,34) = 8.34$, $p = 0.007$, $\eta^2_p = 0.197$). Age was not a significant covariate in any of the adjusted models.

Overall, the intervention resulted in moderate-to-large effect sizes in mental health and functional performance outcomes, while physical health domains showed no significant changes.

Finally, with regard to the control group, insufficient information was gathered regarding adherence to the brochure-based instructions, as no systematic monitoring of compliance was performed. This limitation may have introduced performance bias and affected internal validity, as differences between groups could partly reflect variations in engagement rather than the intervention itself. Therefore, the control condition can be considered a minimal intervention comparator.

4. Discussion

The present study investigated the effects of a four-week LSSEP in sedentary adults and demonstrated improvements in quality of life, functional movement performance, and dynamic balance, suggesting a potential role for targeted exercise as a strategy for promoting movement quality and well-being in sedentary adults. While most exercise programs focus on individuals with existing musculoskeletal conditions [28,54], fewer studies have examined physically inactive but otherwise healthy populations [25,26,55]. Accordingly, the current study focused on sedentary but otherwise healthy individuals at increased risk, addressing an area requiring further investigation. These findings may inform the development of workplace-based exercise programs aimed at improving employee well-being and potentially supporting long-term musculoskeletal health.

Minor logistical challenges were encountered during recruitment due to workplace constraints.

No significant differences were observed between groups in most baseline characteristics, including gender, BMI, and lifestyle factors. However, a significant difference in age was identified, with participants in the intervention group being younger on average than those in the control group. This difference may have influenced the results, particularly in outcomes related to motor learning and balance, as younger individuals tend to demonstrate greater neuromuscular adaptability and responsiveness [56,57]. Future studies could consider age-matched groups to minimize this potential confounding effect.

The use of the IPAQ-SF contributed to the selection of a relatively homogeneous sedentary sample, reducing the potential influence of baseline physical activity levels on the results.

The SF-12v2 questionnaire was used to assess quality of life as the primary outcome. The observed improvement in the Mental Component Summary (MCS) exceeded the minimum clinically important difference (MCID), suggesting a clinically meaningful enhancement in psychological well-being [43,58,59]. However, these MCID thresholds have not been specifically validated in healthy sedentary adult populations and should therefore be interpreted with caution. These findings are consistent with previous research indicating that sedentary behavior is associated with poorer mental health and reduced quality of life, while increased physical activity is linked to improvements in these domains [60–66].

In contrast, no significant changes were observed in the Physical Component Summary (PCS), suggesting that the intervention may have had a greater impact on the mental rather

than the physical dimension of perceived health. This may be partly explained by the short duration of the intervention and the relatively high baseline functional status of participants. However, these findings should be interpreted with caution, as the SF-12v2 is a self-report instrument and may be influenced by subjective perceptions or participant expectations.

These findings suggest that the intervention had a greater effect on the mental rather than the physical dimension of perceived health. However, the results should be interpreted with caution, as the SF-12v2 is a self-report instrument and may be influenced by factors such as participants' subjective perception of health or their attitude toward the intervention. Furthermore, participants exhibited limited functional limitations at baseline, a fact that likely limited the potential for improvement in the physical domains.

The observed improvements in the Mental Component Summary suggest a clinically meaningful enhancement in psychological well-being, consistent with previous research linking sedentary behavior with poorer mental health and reduced quality of life, and physical activity with improvements in these domains [60–66].

Improvements were also observed across several subscales, including general health, vitality, emotional role, and mental health, suggesting an overall positive effect on psychological well-being. These findings may be related to increased physical activity, improved functional capacity, and enhanced perception of health, as well as previously reported benefits of exercise on mood regulation and emotional well-being [63,67,68]. However, alternative explanations such as increased daily activity, improved sleep quality, social interaction, the novelty of structured group participation, or placebo effects cannot be excluded.

In contrast, no significant changes were observed in the Physical Component Summary or in several physical-related subscales, which may be explained by the short duration of the intervention and the relatively high baseline functional status of participants. Similar findings have been reported in previous studies, where improvements in physical domains were less pronounced in asymptomatic populations. Although the present intervention was relatively short, previous studies suggest that short-term stabilization programs may induce early neuromuscular adaptations, particularly in previously inactive individuals. However, longer intervention durations are likely required to achieve more substantial and sustained improvements [69–71].

The potential role of diaphragmatic breathing and exercise-induced physiological adaptations may also contribute to these findings, including mechanisms related to autonomic regulation and inflammatory processes [68,72–78]. However, these mechanisms were not directly assessed in the present study and should therefore be interpreted with caution. Additionally, emerging evidence suggests that factors such as stress-related biological responses and gut microbiota may also be involved in the relationship between physical activity, mental health, and musculoskeletal function [76–80].

For dynamic balance (YBT), a time $\times$ group interaction was observed, indicating improvements in the intervention group. Reduced asymmetry may suggest improvements in movement coordination and more symmetrical load distribution between the limbs, potentially associated with enhanced trunk stability and lumbopelvic control [24].

The reduction in anterior asymmetry may also be of clinical relevance, as greater asymmetries have been associated with increased injury risk [50]. However, the literature shows heterogeneity regarding the predictive value of asymmetry indices [33]. Additionally, it should be noted that the YBT may be influenced by learning effects and may present variability in asymptomatic populations, which should be considered when interpreting the findings.

The results of the FMS indicated an improvement in total score in the intervention group, suggesting improvements in movement quality and neuromuscular coordination. Although no significant changes were observed in most individual tests, small

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improvements across specific movement patterns may have contributed cumulatively to the overall score.

The observed improvement in the 'Inline Lunge' test may reflect enhanced dynamic stability and lumbopelvic control, findings that are consistent with previous research on trunk stabilization interventions [31,49]. In contrast, the absence of changes in other tests may be explained by the relatively high baseline functional status of participants. Additionally, potential ceiling effects and learning effects associated with repeated testing should be considered when interpreting these findings.

The observed improvement in the total FMS score exceeded the corresponding $MDC_{95\%}$ value, supporting that this change likely reflects a true change beyond measurement error. Similar trends exceeding the corresponding $MDC_{95\%}$ values were observed for specific YBT outcomes, although interpretation should be made with caution due to variability across movement directions and limbs. Although statistically significant improvements were observed in the FMS and YBT outcomes, the clinical relevance of these changes should be interpreted with caution. In asymptomatic populations, even small improvements in movement quality and dynamic balance may reflect enhanced neuromuscular control; however, it remains unclear whether these changes translate into meaningful functional benefits or reduced injury risk. Further research is required to determine the clinical significance of such changes.

Although the intervention was designed as a lumbar spine stabilization exercise program, several exercises incorporated functional and balance-related movement components. Nevertheless, previous evidence suggests that trunk stabilization and lumbopelvic neuromuscular control are closely associated with postural stability, balance performance, and movement efficiency. Therefore, the observed improvements in FMS and YBT outcomes may reflect the integrated effect of lumbar stabilization within functional movement tasks rather than isolated balance-training adaptations alone.

Several limitations should be considered when interpreting the findings, including the use of a minimal control condition without systematic monitoring of adherence to the ergonomic and stretching instructions, which may have introduced performance bias. In addition, the relatively small sample size may have limited the statistical power of the study, particularly in the analysis of individual FMS components. Furthermore, the relatively short duration of the intervention (four weeks), combined with the absence of a follow-up assessment, does not allow conclusions regarding the long-term sustainability of the observed effects and may have limited the extent of neuromuscular adaptations observed. Although short-term stabilization programs have demonstrated measurable improvements in motor control, longer interventions may be required to achieve more substantial and sustained changes.

Repeated testing procedures may have also introduced learning effects, particularly in functional assessments such as the FMS. In addition, the presence of a baseline age difference between groups may also have influenced outcomes, especially in relation to motor learning and adaptability, although ANCOVA analysis revealed that age did not account for any additional variance in the outcomes tested. Although standardized scoring procedures were used, the lack of blinding of the principal investigator may have increased the potential for assessment bias, particularly in functional assessments such as the FMS that include observational scoring components. Participants were recruited from a single workplace setting, which may have introduced selection bias and limited the generalizability of the findings to broader sedentary populations.

Finally, the findings cannot be generalized to clinical populations, older adults, or highly trained individuals, as functional capacity and neuromuscular control mechanisms differ across populations.

5. Conclusions

Overall, the results of this study suggest that a structured four-week lumbar stabilization exercise program may have beneficial effects on movement quality, dynamic balance, and certain aspects of quality of life in healthy adults who do not exercise regularly. Improvements were primarily observed in mental health-related outcomes, highlighting the potential multidimensional effects of targeted lumbar stabilization exercises. Additionally, improvements in movement quality and dynamic stability may indicate enhanced neuromuscular function in sedentary individuals potentially susceptible to movement-related dysfunction associated with prolonged sedentary behavior.

These findings highlight the potential value of early intervention strategies for sedentary but otherwise healthy adults, a population that remains underrepresented in the literature. The incorporation of brief, structured lumbar stabilization programs may represent a promising approach for promoting health within workplace settings. However, these findings should be considered preliminary, and further research with larger sample sizes and longer follow-up periods is required to confirm and extend these results.

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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 upon request from the corresponding author. The data are not publicly available due to the applicable data protection law in Greece (Law 4624/2019).

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Abbreviations

The following abbreviations are used in this manuscript:

ANOVA	Analysis of Variance
ANT	Anterior Direction
BP	Bodily Pain
CSE	Core Stability Exercises
FMS	Functional Movement Screen
GH	General Health
HRQoL	Health-Related Quality of Life
IPAQ-SF	International Physical Activity Questionnaire—Short Form
LBP	Low-Back Pain
MCS	Mental Component Summary
MCID	Minimal Clinically Important Difference
MET	Metabolic Equivalent
MH	Mental Health

PCS	Physical Component Summary
PF	Physical Functioning
PL	Posterolateral Direction
PM	Posteromedial Direction
QOL	Quality of Life
RE	Role Emotional
RP	Role Physical
SD	Standard Deviation
SF-12v2	Short Form Health Survey, Version 2
SF	Social Functioning
YBT	Y-Balance Test
VT	Vitality
η^2_p	Partial Eta Squared

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Article

Assessment of Immediate Traction Manipulation of the Ankle Joint on the Peroneus Longus, Gluteus Medius and Tensor Fascia Lata Muscles in Healthy People: A Randomized Double-Blind Study

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Abstract

Objectives: This study aimed to evaluate the effect of a superior ankle traction manipulation on the strength and electrical activity (surface EMG) of the peroneus longus, gluteus medius, and tensor fasciae latae muscles in healthy young adults. Methods: In total, 30 healthy participants (26 men and 4 women) were enrolled in a prospective, randomized, double-blind, controlled study. Participants were randomly assigned to a Manipulation or Sham group. Muscle activity was recorded using surface EMG, and isometric strength was assessed with a Biodex dynamometer. EMG signals were normalized to session-specific maximal voluntary isometric contractions (MVIC) and expressed as %MVIC for amplitude and median frequency. Baseline differences were examined with Welch's *t*-tests. The primary analysis used analysis of covariance (ANCOVA) on POST values adjusted for PRE, with partial eta squared (η^2_p) as an effect size. Change-score comparisons (Δ = POST − PRE) and Hedges-corrected Cohen's d were reported as sensitivity analyses. False discovery rate (FDR) correction was applied across outcomes. Results: No significant between-group differences were observed after adjustment for baseline in any %MVIC amplitude or median frequency outcome ($p > 0.05$, all FDR-adjusted $q > 0.05$). Within-group analyses showed small, nonsignificant changes in both groups, with the Manipulation group tending toward slightly greater increases in peroneus longus %MVIC amplitude (Δ = +3.1%, $p = 0.033$, $d = 0.79$, not significant after FDR correction). Descriptive data indicated similar PRE and POST values across groups for all muscles. Conclusions: When EMG activity is expressed relative to MVIC and baseline differences are controlled, a single superior ankle traction manipulation does not produce statistically significant acute changes in peroneus longus, gluteus medius, or tensor fasciae latae activity compared with a sham procedure. These findings suggest that previously reported differences may have reflected unadjusted baseline variability rather than true intervention effects.

Keywords: ankle manipulation; muscle strength; regional interdependence; hip abductors; peroneal muscles

1. Introduction

Correct biomechanics of the ankle joint is crucial for normal everyday activities and sports activities. And the resulting limitation may affect climbing and descending stairs, crouching, jumping or running [1]. The resulting biomechanical disorders may change the input signals to the central nervous system and, consequently, affect neuromuscular control not only of the ankle joint, but also of other knee and hip joints [2]. The correct positioning of the talus in the ankle joint creates a mechanism that connects the upper subtalar joint with external rotation in the hip joint [3]. This may have a significant impact on the correct posture [4], leading to balance disorders or impaired coordination between the ankle and hip joints [5]. Limitations in proper neuromuscular control in the ankle joint may be caused by reduced activity of the peroneal muscles [6] and in the hip joint of the abductors, in particular, the gluteus medius muscle [7,8].

Mobilization and manipulation involve applying a high velocity, low amplitude (HVLA) force to the joint and surrounding structures, which can reduce pain [9] and modulate neuromechanical responses believed to underlie various physiological and clinical effects [10]. Ankle manipulation, in particular, has shown potential in enhancing hip abductor strength in individuals with ankle sprains, although it may simultaneously result in weakening of the tensor fascia lata (TFL) muscle, as reported by [11]. Additionally, ankle manipulation has demonstrated benefits in improving dorsiflexion range of motion and treating conditions such as ankle equinus [1,2]. However, the inconsistency in findings across studies highlights the need for more standardized research protocols to better evaluate its efficacy and guide clinical applications [3]. While HVLA manipulation has shown potential for pain reduction and functional improvement, the results remain variable. For instance, Fryer et al. [4] found no significant increase in dorsiflexion range of motion in asymptomatic individuals following a single HVLA thrust to the talocrural joint. In contrast, Weerasekara et al. [5] reported immediate improvements in dynamic balance and short-term dorsiflexion range in individuals with chronic ankle sprains. Notably, a manual manipulation approach for treating ankle equinus produced substantial immediate increases in dorsiflexion, outperforming a six-month daily stretching program [1].

Synergetic muscles cooperate with each other and influence each other, which is why their joint assessment in electromyographic tests is so important [12]. This repetitive function requires precisely coordinated activity of both muscles, resulting in a heterogeneous surface EMG (sEMG) signal [13]. Electromyography is often used to assess muscle activity occurring during movement or exercise to determine the potential for muscle-strengthening effects [14]. On ankle joint, studies have shown that ankle positioning can significantly influence quadriceps activation and torque output during isometric tasks, with dorsiflexion being particularly effective for enhancing strength [6]. Additionally, muscle activity has been observed to increase proportionally with walking speed and manual resistance, highlighting the importance of neuromuscular demand in functional tasks [7]. Analyzing the interaction between synergistic muscles allows for the detection of compensatory patterns and imbalances, guiding rehabilitation and performance strategies. This is especially relevant when assessing the impact of therapeutic interventions, such as joint manipulation, which may induce both local and systemic neuromuscular adaptations [8].

Although multiple-session manipulation protocols are often used clinically, the acute single-dose approach adopted in this study was deliberately chosen to investigate the immediate neuromechanical and neurophysiological responses to a standardized high-velocity, low-amplitude (HVLA) ankle traction. Examining a single manipulation allows for isolation of the direct, short-term neural and muscular effects without the confounding influence of cumulative treatment exposure or adaptation. Previous research has demonstrated that even a single HVLA manipulation can transiently increase muscle

strength and corticospinal or corticomotor drive in lower-limb muscles of healthy or athlete populations [9,10].

The potential clinical implications of these findings include enhanced stability of the ankle and hip joints during locomotion, which may help prevent the development of osteoarthritis. Additionally, they may support improved hip joint function in postoperative rehabilitation and promote a better understanding of the biomechanical relationship between the ankle and hip joints and the activation of associated muscles. The primary objective of this study was to examine the immediate effects of a single ankle manipulation on the strength of the peroneal and hip abductor muscles in healthy individuals. The outcomes of this analysis may support the use of joint manipulation as a therapeutic approach in conditions involving hip abductor muscle imbalance, whether in athletic populations or in the context of degenerative musculoskeletal disorders.

2. Materials and Methods

2.1. Participants

Thirty-one healthy volunteers were recruited. The study group consisted of 26 men and 4 women. Basic anthropometric characteristics and division for the groups are shown in Table 1. Volunteers were qualified on the basis of inclusion criteria: (i) healthy person aged 19–26. The exclusion criteria included: (i) surgery of the lower limb and lumbar spine, lower limb injury within the last 6 months, (ii) pain in the ankle, knee or hip joint, (iii) hypermobility of the ankle joint, (iv) rheumatic diseases, (v) neurological diseases, (vi) neoplastic diseases, (vii) connective tissue diseases, (viii) symptoms of spinal root compression, sciatica, spinal canal stenosis, (ix) manipulation in the past, (x) manipulation in the history of treatment (Figure 1). This study was approved by the Independent Bioethics Committee for Scientific Research at the Medical University of Gdańsk (Resolution No. NKBBN/866/2022-2023). The content of this study was explained in detail to the participants with an easy-to-understand description of the study protocol, and written informed consent was obtained from the volunteer before entering this study. Participants were asked to limit their physical activity to usual activities before this study.

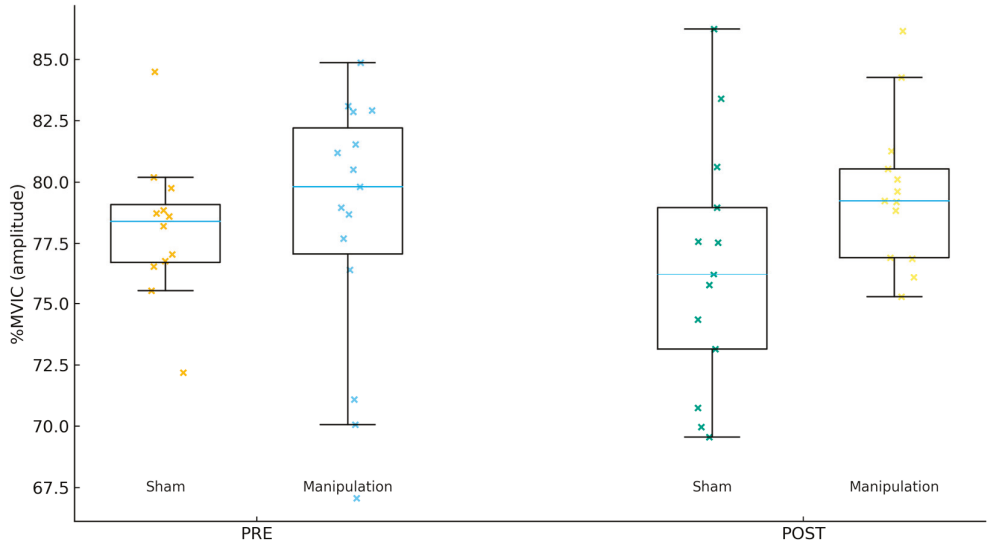

Figure 1. Gluteus medius (Gmed) %MVIC by group and time.

Table 1. Mean and standard deviation regarding anthropometric characteristics of the experimental and placebo groups.

Group	Age (Years)	Height (cm)	Body Mass (kg)	Muscle Mass (kg)	Fat Mass (%)
Experimental (n = 15)	21.73 ± 1.67	176.93 ± 9.68	80.53 ± 12.59	39.37 ± 7.75	14.28 ± 6.88
Placebo (n = 15)	22.27 ± 1.71	182.67 ± 9.21	75.93 ± 18.03	37.35 ± 8.81	14.19 ± 7.28

2.2. Study Design

A prospective, randomized, double-blind study design was used to evaluate the effects of traction manipulation of the upper ankle joint on the peroneus longus (PL), gluteus medius (Gmed), and tensor fascia lata (TFL) muscles. This research was carried out at the Department of Biomechanics and Sports Engineering, AWFiS in Gdańsk, in the Physical Exercise Laboratory. Before this study, participants were asked to limit their physical activity to usual activities. The selected limb was selected by a random "coin toss" method. The volunteers were assessed for muscle activity using surface EMG.

2.3. Assessment of Muscle Strength

The strength of the peroneus longus (PL) and hip abductors (gluteus medius–Gmed, and tensor fasciae latae–TFL) muscles was assessed using the Biodex System 4 device (Biodex Medical Systems Inc., Shirley, NY, USA). All muscles were assessed according to the manufacturer's recommendations. PL strength assessment was performed in a seated position on an adjustable dynamometer seat and the test leg was raised using a support arm below the knee. The foot was placed on the footrest and secured with two Velcro straps. All subjects completed the test barefoot. The subtalar joint was placed in a neutral position by setting the axis of the dynamometer to intersect the sagittal axis of the joint. Additionally, standard diagonal Velcro straps were used to keep the torso stable, and a single strap secured the hip. The arms were crossed over the chest and the opposite leg was rested on a support arm attached to the chair. PL strength was measured in volunteers using sEMG. For the abductor examination, the volunteers lay on their sides. The lower limb being examined was attached to the arm of the device using leather straps, and the rotating shaft of the device was aligned with the anatomical axis of the hip joint to allow for movement in the frontal plane. The participants' pelvis was stabilized using leather straps.

Each time during the PL, GMed, and TFL testing, each participant performed three 5 s maximum voluntary isometric contractions (MVIC). There was a 30 s break between each repetition, and during the performance, participants were verbally encouraged to maximize their effort. The highest peak torque (Nm) of the three tests was taken for further analyses. Peak torque was also normalized to individual body weight (Nm $\times$ kg^{-1}) [15].

2.4. Assessment of Surface EMG

Surface EMG data were recorded for the peroneus longus (Per) during maximal voluntary isometric contraction (MVIC) inversion and for the tensor fasciae latae (TFL) and gluteus medius (GMed) during hip-abduction MVIC. The middle three seconds of each five-second MVIC were analyzed to minimize transient onset and offset effects. Signals were collected and differentially amplified at a gain of 500 using a TeleMyo DTS system (Noraxon, Scottsdale, AZ, USA) and disposable Ag/AgCl surface electrodes (1 cm^2; Sorimex, Toruń, Poland). The raw sEMG signals were band-pass filtered between 15 and 500 Hz and sampled at 1500 Hz (16-bit resolution) using an analogue-to-digital converter. All recordings were archived and processed in MyoResearch 2.8 software (Noraxon).

Electrode placement and skin preparation followed the SENIAM protocol [11], with precise anatomical reference points to ensure inter-subject consistency. For the Per, elec-

trodes were positioned along the line from the fibular head to the lateral malleolus at the proximal one-third of this distance, parallel to the muscle fibers, with a reference electrode over the fibular head. For the GMed, electrodes were centered midway between the iliac crest and the greater trochanter, aligned with the fiber orientation, with a reference on the iliac crest. For the TFL, electrodes were placed one-quarter of the distance from the anterior superior iliac spine (ASIS) to the lateral femoral condyle, with a reference electrode on the ASIS. Before electrode application, the skin was shaved, lightly abraded, and cleaned with 70% isopropyl alcohol to achieve an impedance below 5 kΩ. Inter-electrode distance was kept constant at 20 mm (center-to-center).

To minimize artifacts and noise, all EMG traces were visually inspected prior to analysis. Recordings with visible baseline drift, motion artifacts, or cable disturbances were discarded. When minor 50 Hz interference was observed, a narrow notch filter was applied. The system's common-mode rejection ratio exceeded 100 dB, ensuring high signal quality. Signals were full-wave rectified and smoothed by the root-mean-square (RMS) method using a 300 ms moving window. The mean RMS amplitude (EMG_{RMS}, μV) and the median frequency of the raw power spectrum (EMG_{MED}, Hz) were extracted for each muscle as outcome measures.

To ensure reproducibility, all measurements were performed by the same examiner under identical environmental conditions. Electrode positions were marked on the skin to allow for accurate replacement between PRE and POST sessions. Each participant performed three five-second MVICs separated by 30 s of rest, and the highest RMS amplitude was used for normalization. In the lower limb, published MVIC sEMG protocols using similar processing (band-pass 15–500 Hz, RMS windows, frequency-domain analysis) show good–excellent repeatability for amplitude and spectral measures (commonly ICC > 0.80, often approaching $\geq$0.90 for some muscles/metrics), though exact values depend on muscle and feature [12]. Normalized EMG values were expressed as a percentage of the session-specific MVIC (%MVIC) for both amplitude and median frequency to enable comparisons across participants and sessions.

2.5. Intervention and Blinding Procedures

Participants were randomly allocated to either the Manipulation or Sham (placebo) group using a computer-generated random sequence (Microsoft Excel, simple randomization). Randomization was performed by an independent researcher not involved in data collection or analysis. Allocation codes were placed in sequentially numbered, opaque, sealed envelopes that were opened only after completion of all baseline measurements. Because of the small number of female volunteers (n = 4), randomization was not stratified by sex; however, women were evenly distributed between groups (two per group).

2.5.1. Blinding

Both participants and the researcher responsible for EMG and strength measurements were blinded to group allocation. Only the treating therapist knew the assignment in order to perform the appropriate technique; this therapist had no role in outcome recording or analysis. All participants received identical explanations ("You will feel a quick pulling motion around your ankle") and identical body positioning, contact, and session duration to preserve blinding.

2.5.2. Manipulation Group (Experimental)

All participants were placed in a supine position with the upper and lower limbs aligned along the torso and the ankle joint just beyond the edge of the plinth. Participants received the intervention using a high-speed, low-amplitude, short-duration traction manipulation. Participants were informed about how the intervention would be carried out.

The volunteer was in a supine position with the upper and lower limbs placed along the torso. The therapist, positioned on the foot side, wraps both hands around the neck of the talus bone and extends the ankle joint. Manipulation of the ankle joint was performed, moving it parallel to the lower limb in the lower limb axis with the maximum range of tissue tension. Reaching the maximum tissue tension, the therapist made sure that the volunteer did not feel any discomfort by stopping at the maximum capsular tension and then performed manipulations increasing the tissue tension. The technique was performed only once for each subject. Participants who received the placebo intervention were also informed about how the intervention would be performed. The volunteer was in a supine position with the upper and lower limbs placed along the torso. The therapist, positioned on the foot side, covers the distal part of the lower leg above the ankles with both hands, thus bypassing the upper ankle joint, while extending the ankle joint. Manipulation of the ankle joint was performed, moving it parallel to the lower limb in the lower limb axis with the maximum range of tissue tension. Reaching the maximum tissue tension, the therapist made sure that the volunteer did not feel any discomfort by stopping at the maximum capsular tension and then performed manipulations increasing the tissue tension. The technique was performed only once for each subject [16].

2.5.3. Sham Group (Placebo)

For the placebo condition, all preparatory steps were identical—participant position, hand contact, ankle extension, and verbal instruction. However, to ensure the procedure was non-therapeutic, the therapist placed both hands over the distal lower leg just above the malleoli, deliberately bypassing the talocrural joint and avoiding joint play engagement. Gentle, steady traction was applied for approximately 2–3 s and then slowly released without thrust, acceleration, or cavitation. The total contact time, positioning, and verbal cues were identical to those in the manipulation group to preserve participant blinding and expectation. The sham method thus replicated the tactile and kinesthetic sensations of the intervention while withholding the critical HVLA mechanical component.

2.5.4. Timeline of Assessments

The experimental session followed a consistent timeline for all participants. After arrival, participants rested for 10 min and underwent baseline (PRE) measurements of EMG and maximal voluntary isometric contraction (MVIC). The assigned intervention (manipulation or sham) was then performed immediately afterward. Within 2 min post-intervention (POST), all EMG and MVIC tests were repeated in the same sequence as baseline to capture the immediate neuromuscular responses while minimizing fatigue or recovery effects.

2.5.5. Therapist Standardization

All procedures were delivered by licensed physiotherapists with postgraduate manual-therapy training. Before the experiment, therapists attended a two-hour calibration session to standardize both the HVLA and sham techniques, ensuring identical hand placement, verbal instructions, and timing between groups.

2.5.6. Manipulation-Check

Immediately after the post-intervention measurements, participants answered a brief question: "Do you believe you received the real joint manipulation or a simulated one?" (options: real, simulated, unsure). The proportion of correct guesses did not differ from chance (53%, $\chi^2 = 0.27$, $p = 0.60$), confirming that participant blinding was effective.

2.6. Sample Size

The planned sample size was established a priori on the basis of published recommendations for pilot and mechanistic studies in the absence of reliable variance estimates for EMG outcomes. Following Julious [13] and Eldridge et al. [14], a minimum of 12 participants per arm is typically sufficient to estimate the standard deviation and feasibility parameters for a future definitive trial. We therefore targeted 30 participants (15 per group) to provide stable variance estimates while maintaining logistical feasibility for the intensive EMG protocol.

To quantify the magnitude of effects detectable with reasonable power, we conducted an a priori analysis in G*Power 3 for a two-tailed independent-samples *t* test ($\alpha = 0.05$, $1-\beta = 0.80$). With $n_1 = n_2 = 15$, this design has 80% power to detect a standardized mean difference in $d \approx 1.06$ (large effect), as obtained from G*Power's two-sample mean comparison module [15]. When baseline values are included as a covariate in an ANCOVA, statistical efficiency improves in proportion to the squared correlation between baseline and follow-up; specifically, the residual variance is reduced by approximately 1, so that if the pre–post correlation is $r \approx 0.70$, the variance reduction is ≈ 0.51 and the detectable standardized difference improves to about $d \approx 0.75$. This efficiency result and its use in planning are standard for ANCOVA [17]. These calculations indicate the present study was adequately powered for large acute effects, but underpowered for small-to-moderate effects; accordingly, the absence of significant between-group differences supports the interpretation of no large immediate neuromuscular changes, rather than evidence of no effect. For planning a confirmatory trial targeting a moderate effect ($d = 0.50$) at $\alpha = 0.05$ and $1-\beta = 0.80$, approximately 64 participants per group are required using the same two-sample framework in G*Power [15].

2.7. Statistical Procedures

Data were analyzed using IBM SPSS Statistics for Windows, version 29.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics (mean and standard deviation) were computed for each variable. The normality of the data distribution was assessed using the Shapiro–Wilk test. Levene's test was applied to verify the homogeneity of variances between groups.

Before analysis, all electromyographic (EMG) signals were normalized to session-specific maximal voluntary isometric contractions (MVIC). Each EMG outcome was expressed as a percentage of MVIC (%MVIC), computed for amplitude and median frequency measures separately. This normalization procedure allowed for comparisons between participants and across sessions while minimizing inter-individual variability in raw signal amplitude.

Baseline (PRE) differences between groups were tested using Welch's *t*-tests, which do not assume equal variances. When significant or relevant baseline differences were identified, the main analyses of intervention effects were performed using an analysis of covariance (ANCOVA) model, with the POST value as the dependent variable, group (Manipulation vs. Sham) as the fixed factor, and the corresponding PRE value as a covariate. This model provides adjusted group effects accounting for baseline variability, as recommended for pre–post experimental designs.

As a sensitivity analysis, unadjusted between-group differences in change ($\Delta = \text{POST} - \text{PRE}$) were also evaluated using Welch's *t*-tests. For each test, Cohen's d (Hedges-corrected for small samples) was computed as an effect-size estimate, and 95% confidence intervals (CIs) were reported for within- and between-group changes [17]. In the ANCOVA models, partial eta squared (η^2_p) was reported to quantify the magnitude of the adjusted group effect.

To control for inflation of Type I error due to multiple outcomes, *p*-values from the ANCOVA family were adjusted using the Benjamini–Hochberg false discovery rate (FDR) procedure. Both raw and adjusted (q) values are presented.

Descriptive statistics are reported as mean ± standard deviation (SD) for each group at PRE and POST. Distribution plots were produced to visualize data spread. All results are accompanied by exact *p*-values, confidence intervals, and effect sizes to allow for full interpretation of both statistical and practical significance.

3. Results

For Gmed %MVIC (amplitude, Figure 1), the PRE mean ± SD was 80.22 ± 6.67 in Sham and 77.53 ± 6.24 in Manipulation ($p = 0.267$). For TFL %MVIC (amplitude, Figure 2), the PRE mean ± SD was 81.38 ± 5.75 in Sham and 80.97 ± 6.53 in Manipulation ($p = 0.856$). For Per %MVIC (amplitude, Figure 3), the PRE mean ± SD was 81.39 ± 14.64 in Sham and 73.53 ± 12.18 in Manipulation ($p = 0.125$). Table 2 shows the descriptive statistics of study variables by experimental and control groups at pre- and post-intervention.

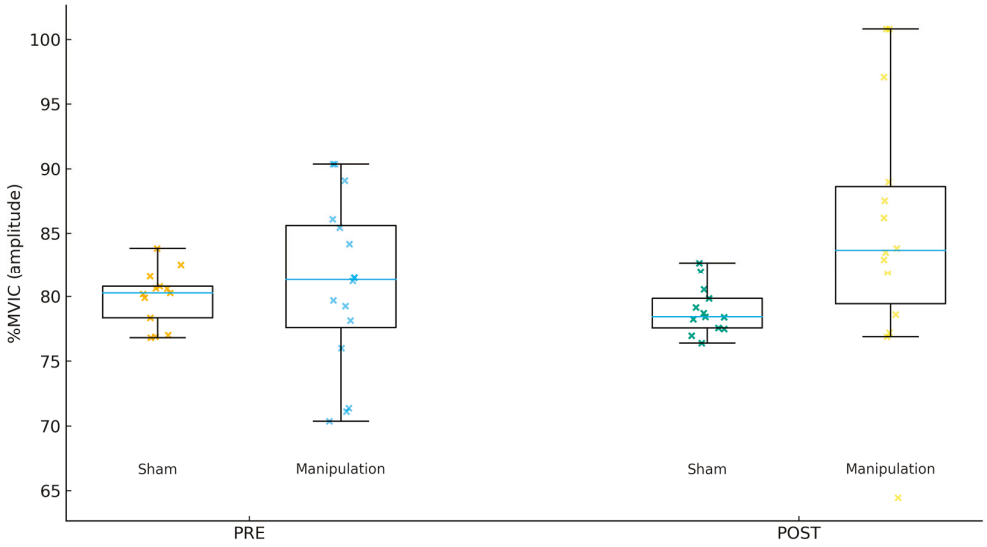

Figure 2. Tensor fasciae latae (TFL) %MVIC by group and time.

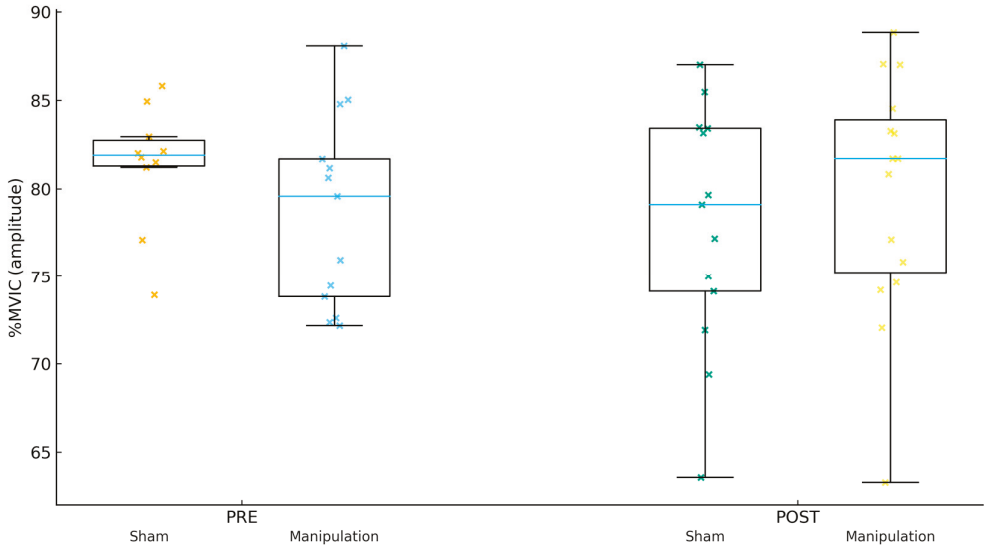

Figure 3. Peroneus longus (Per) %MVIC by group and time.

Table 2. Descriptive statistics (means and standard deviations) of study variables by experimental and control groups at pre- and post-intervention.

Muscle	Outcome	Manipulation PRE (Mean ± SD)	Manipulation POST (Mean ± SD)	Sham PRE (Mean ± SD)	Sham POST (Mean ± SD)
Gmed	%MVIC (amplitude)	77.53 ± 6.24	116.24 ± 98.98	80.22 ± 6.67	116.56 ± 150.13
TFL	%MVIC (amplitude)	80.97 ± 6.53	94.87 ± 28.59	81.38 ± 5.75	79.38 ± 2.43
Per	%MVIC (amplitude)	73.53 ± 12.18	81.59 ± 10.08	81.39 ± 14.64	75.09 ± 12.37
Gmed	%MVIC (median frequency)	36.18 ± 29.52	37.12 ± 31.70	26.49 ± 19.92	62.42 ± 73.05
TFL	%MVIC (median frequency)	25.32 ± 13.71	24.92 ± 10.87	18.54 ± 10.20	20.09 ± 14.14
Per	%MVIC (median frequency)	44.71 ± 30.22	36.25 ± 16.44	29.12 ± 9.23	45.67 ± 52.65

GMed: gluteus medius; TFL: tensor fasciae latae; Per: peroneus longus.

For Gmed %MVIC (median frequency), the PRE mean ± SD was 26.49 ± 19.92 in Sham and 36.18 ± 29.52 in Manipulation ($p = 0.297$). For TFL %MVIC (median frequency), the PRE mean ± SD was 18.54 ± 10.20 in Sham and 25.32 ± 13.71 in Manipulation ($p = 0.133$). For Per %MVIC (median frequency), the PRE mean ± SD was 29.12 ± 9.23 in Sham and 44.71 ± 30.22 in Manipulation ($p = 0.065$).

For Gmed %MVIC (amplitude), the adjusted group effect was not significant ($p = 0.907$; q = 0.907; partial $\eta^2 = 0.001$; $R^2 = 0.013$). For TFL %MVIC (amplitude), the adjusted group effect was not significant ($p = 0.059$; q = 0.176; partial $\eta^2 = 0.126$; $R^2 = 0.128$). For Per %MVIC (amplitude), the adjusted group effect was not significant ($p = 0.159$; q = 0.239; partial $\eta^2 = 0.072$; $R^2 = 0.083$).

For Gmed %MVIC (median frequency), the adjusted group effect was not significant ($p = 0.118$; q = 0.354; partial $\eta^2 = 0.088$; $R^2 = 0.149$). For TFL %MVIC (median frequency), the adjusted group effect was not significant ($p = 0.659$; q = 0.659; partial $\eta^2 = 0.007$; $R^2 = 0.742$). For Per %MVIC (median frequency), the adjusted group effect was not significant ($p = 0.366$; q = 0.549; partial $\eta^2 = 0.030$; $R^2 = 0.042$).

For Gmed %MVIC (amplitude), the within-group change was 36.34 [−50.69, 123.38] in Sham and 38.71 [−12.88, 90.29] in Manipulation. The between-group difference in change was 2.36 with a 95% CI of [−95.20, 99.93] ($p = 0.960$; d = 0.02). For TFL %MVIC (amplitude), the within-group change was −2.00 [−5.05, 1.06] in Sham and 13.90 [−1.95, 29.75] in Manipulation. The between-group difference in change was 15.90 with a 95% CI of [−0.15, 31.94] ($p = 0.052$; d = 0.70). For Per %MVIC (amplitude), the within-group change was −6.30 [−15.81, 3.21] in Sham and 8.06 [−1.90, 18.01] in Manipulation. The between-group difference in change was 14.36 with a 95% CI of [1.21, 27.51] ($p = 0.033$; d = 0.79).

For Gmed %MVIC (median frequency), the within-group change was 35.92 [−7.82, 79.66] in Sham and 0.94 [−6.77, 8.65] in Manipulation. The between-group difference in change was −34.98 with a 95% CI of [−79.15, 9.18] ($p = 0.111$; d = −0.65). For TFL %MVIC (median frequency), the within-group change was 1.56 [−1.80, 4.91] in Sham and −0.41 [−4.29, 3.48] in Manipulation. The between-group difference in change was −1.96 with a 95% CI of [−6.87, 2.94] ($p = 0.419$; d = −0.29). For Per %MVIC (median frequency), the within-group change was 16.55 [−14.56, 47.67] in Sham and −8.46 [−21.72, 4.80] in Manipulation. The between-group difference in change was −25.01 with a 95% CI of [−58.00, 7.98] ($p = 0.129$; d = −0.59).

4. Discussion

The present study aimed to examine the immediate effects of a single superior ankle traction manipulation on the strength and electrical activity of the peroneus longus, gluteus medius, and tensor fasciae latae muscles in healthy individuals. Contrary to our initial expectations, did not reveal any statistically significant between-group differences following the manipulation. Both amplitude and median frequency expressed as %MVIC showed no significant group effect after adjustment, indicating that a single manipulation

did not acutely alter neuromuscular activation in the assessed muscles compared with the sham procedure.

Although no adjusted group differences emerged, descriptive and exploratory analyses revealed small, non-significant increases in peroneus longus %MVIC amplitude in the Manipulation group (Δ = +3.1%), while the Sham group remained stable or slightly decreased. This pattern, although not statistically significant after false-discovery-rate (FDR) correction, may suggest a subtle tendency toward enhanced recruitment or sustained activation of the peroneal musculature immediately after manipulation. Such a response could reflect transient changes in proprioceptive input or spinal excitability rather than robust strength adaptations. However, given the small magnitude and lack of significance after correction, these findings should be interpreted cautiously and regarded as preliminary.

Our adjusted analyses do not support an acute increase in GMed activation after a single ankle-region manipulation in healthy participants. By comparison, Lawrence and colleagues [18] reported increased hip abductor force and immediate increases in GMed activation following a series of high-velocity, low-amplitude manipulations applied to the talocrural/subtalar/proximal-distal tibiofibular complex, but in individuals with prior ankle sprain and unilateral TFL weakness rather than a healthy, unselected sample. The discrepancy likely reflects differences in population (clinical deficits vs. healthy volunteers), manipulation dosage (multiple ankle-region thrusts in the involved limb), and analysis approach; in impaired cohorts, greater neuromuscular plasticity or baseline inhibition may permit larger post-manipulation effects that are not observed in healthy controls. A plausible neurophysiological mechanism for remote muscle facilitation is transient modulation of central drive and reflex pathways after manipulation, as seen in studies where spinal manipulation increased strength and corticospinal excitability of ankle plantar flexors in elite athletes [9] and altered motor unit behavior acutely [19]. Within the broader framework of regional interdependence, remote joint interventions may influence neuromuscular output via neurophysiological rather than purely biomechanical routes, although effects can be subtle and context-dependent [20].

We observed small, non-significant increases in PL %MVIC amplitude in the manipulation group that did not survive correction, suggesting at most a modest and transient tendency toward enhanced peroneal activation in healthy participants. In contrast, tibiofibular joint manipulation has been shown to acutely facilitate fibularis (peroneus) longus and soleus activation in individuals with chronic ankle instability (CAI), a population with known arthrokinematic and neuromuscular impairments [21]. Over multi-week periods, proximal or distal tibiofibular manipulation has also been associated with improvements in ankle dorsiflexion range and function in CAI, implying that repeated dosing and clinical deficits may be important moderators of response [22]. Altered PL activation patterns have been documented in individuals with functional ankle instability during gait, underscoring the role of peroneal muscles in dynamic stability and the potential headroom for change in impaired populations that is absent in healthy participants [23]. Transient increases in corticospinal excitability and voluntary activation after spinal manipulation provide a biologically plausible pathway for short-term facilitation of distal muscles, although effects may be task-, muscle-, and population-specific [10].

The TFL showed no significant between-group differences in %MVIC amplitude or median frequency after adjustment. Prior work that reported hip abductor facilitation after ankle-region manipulation targeted participants with unilateral TFL weakness during muscle testing and prior ankle sprain, again pointing to the importance of baseline impairment and targeted selection for observing clinically meaningful effects [18]. Given TFL's role in frontal-plane control and its interplay with GMed, the absence of an effect in our healthy

participants is consistent with a ceiling effect and with evidence that manipulation-induced changes in muscle output are more detectable when pre-existing inhibition or motor control deficits are present [19].

This study presents several limitations that should be considered when interpreting the findings. First, the relatively small sample size of healthy participants may have limited statistical power to detect subtle differences between groups, particularly after applying false-discovery-rate corrections. The inclusion of predominantly male participants (26 men and 4 women) also restricts the generalizability of the results, as sex-related differences in hip and ankle neuromuscular control have been widely documented in previous research. Women tend to demonstrate distinct lower-limb kinematics, neuromuscular recruitment patterns, and proprioceptive responses compared with men, which may influence the effects of manipulative interventions. Consequently, the current results should primarily be interpreted as representative of young, healthy males. A covariate analysis including sex was considered but not performed due to the small and unbalanced female subsample (n = 4), which would produce unstable estimates and violate the assumptions of ANCOVA. Instead, we acknowledge this imbalance as a limitation and recommend that future studies ensure adequate female representation or stratify randomization by sex to permit meaningful between-sex comparisons.

Moreover, the experimental design assessed only the immediate post-manipulation effects, precluding conclusions about the persistence or cumulative nature of potential neuromuscular adaptations over time. The use of a single manipulation session may have been insufficient to elicit measurable central or peripheral adaptations, as repeated high-velocity, low-amplitude (HVLA) manipulations are more likely to produce detectable neuroplastic effects [10].

An additional limitation concerns the fixed order of intervention administration, as the ankle manipulation was consistently performed after the baseline measurements. This introduces the potential for order or learning effects, in which repeated maximal voluntary contractions could produce mild neuromuscular adaptation or fatigue, possibly influencing post-test EMG amplitudes or torque values independent of the manipulation itself. However, several methodological aspects likely minimized this risk. All participants performed identical testing sequences under the same conditions, with fixed 30 s rest intervals between MVICs, and the order was the same for both groups; thus, any non-specific temporal or repetition effects would have influenced both groups equally, reducing systematic bias. Furthermore, EMG data were normalized to each session's maximal contraction (%MVIC), which helps correct for intra-session recruitment changes related to repetition or familiarization. Nevertheless, we acknowledge that randomizing the order of real and sham manipulations or employing a crossover design with an appropriate washout period would provide stronger control for potential order effects, and this refinement is planned for future research.

Additionally, although EMG normalization to MVIC improves inter-subject comparability, small variations in electrode placement or participant effort may still contribute to measurement variability. The outcomes selected—namely, isometric muscle strength and surface EMG amplitude/frequency—provide precise indicators of neuromuscular activation but do not directly assess the functional or behavioral implications of ankle manipulation. No dynamic or performance-based measures (e.g., balance, gait, or functional reach) were included, limiting the ecological validity of the findings. Future investigations should integrate objective functional tests, such as the Y-Balance Test or single-leg hop assessments, alongside electrophysiological measurements to determine whether acute neuromuscular changes translate into improved dynamic stability, balance control, or performance in daily and athletic tasks. Finally, because this study involved healthy individuals with no underlying dysfunction, ceiling effects may have limited the observable

impact of the manipulation compared with clinical populations where baseline inhibition or instability is present.

From a clinical standpoint, these findings suggest that a single superior ankle traction manipulation does not induce meaningful immediate changes in hip abductor or peroneal muscle activation when assessed under normalized and baseline-adjusted conditions in healthy adults. The lack of significant group differences underscores the importance of cautious interpretation of unadjusted pre–post findings. Clinicians should therefore view ankle manipulation as a potentially complementary, rather than primary, intervention for neuromuscular enhancement in asymptomatic populations. However, subtle trends toward increased peroneal activation in the manipulation group, although not statistically significant, may have clinical relevance in populations with chronic ankle instability, where proprioceptive deficits and motor inhibition are common. Consequently, future clinical applications and research should consider the dosage, population characteristics, and combination with functional rehabilitation exercises when integrating ankle manipulation into therapeutic programs aimed at improving lower-limb stability and neuromuscular performance.

5. Conclusions

When electromyographic activity is normalized to maximal voluntary isometric contraction and baseline differences are statistically controlled, a single superior ankle traction manipulation does not produce significant acute changes in the electrical activity or isometric strength of the peroneus longus, gluteus medius, or tensor fasciae latae muscles in healthy individuals. The minor, non-significant trends toward increased peroneal activation observed in the manipulation group suggest that any neuromuscular influence of a single intervention is likely subtle and transient. These findings emphasize the importance of rigorous normalization, baseline adjustment, and correction for multiple comparisons in studies examining manual therapy–induced neuromuscular effects. Further research should explore repeated interventions, clinical populations, and longer-term outcomes to determine whether ankle manipulation can meaningfully enhance neuromuscular function through regional interdependence mechanisms.

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Institutional Review Board Statement: This study was approved by the Independent Bioethics Committee for Scientific Research at the Medical University of Gdańsk (Resolution No. NKBBN/866/2022-2023), accessed date 17 December 2022. Participants received a detailed explanation of this study, including a simplified description of the protocol. Before participating, they provided written informed consent, confirming their voluntary participation and understanding that they could withdraw from this study at any time without penalty. This study adhered to the ethical principles outlined in the Declaration of Helsinki.

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

Data Availability Statement: The data can be provided upon reasonable request to the corresponding author.

Acknowledgments: The materials obtained during this study are secured and are in the possession of the corresponding author.

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

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Development of a Website for E-Health Use for Children with Chronic Suppurative Lung Diseases: A Delphi Expert Consensus Study

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Abstract

This study aimed to develop a website providing physiotherapy, exercise, and disease knowledge information as a digital tool for use with children with chronic suppurative lung diseases (CSLDs). Data were analyzed using a mixed qualitative and quantitative approach. Initially, a comprehensive list of the website's content and functions was developed through a Focus Group study with healthcare professionals (HCPs) and parents. Afterward, two rounds of an online Delphi survey were conducted with a group of expert HCPs (pediatricians and physiotherapists) who were recruited based on their expertise in the field of pediatric physiotherapy. The Focus Groups established 10 main themes. Two rounds of Delphi questionnaires established the important items of a website, based on expert consensus from HCPs. A Delphi survey containing 36 outcomes was completed by participants from Greece. The findings support the integration of multidisciplinary and user-centered approaches in the design of a pediatric website. This website is expected to enhance disease self-management, improve treatment adherence, and support families in daily care.

Keywords: chronic suppurative lung diseases; Delphi method; e-health; focus groups; website

1. Introduction

Chronic suppurative lung disease (CSLD) is a clinical term for conditions that, in children, are characterized by a persistent or recurrent wet cough, endobronchial infection, and neutrophilic airway inflammation, without radiographic evidence of bronchiectasis on high-resolution CT (HRCT) [1,2]. Conditions under the CSLD umbrella include protracted bacterial bronchitis (PBB), non-cystic fibrosis bronchiectasis (NCFB), primary ciliary dyskinesia (PCD), and immunodeficiency-related lung disease [1–3].

CSLD is increasingly recognized as a major cause of pediatric respiratory morbidity worldwide. It remains prevalent in low and middle income countries, especially among socially disadvantaged and indigenous children, highlighting the need for global action and equitable care strategies [3]. Timely diagnosis and treatment are essential, as CSLDs may be reversible, while delayed management increases the risk of progression to irreversible bronchiectasis [4]. Management includes antibiotics, airway clearance, exercise, and regular monitoring [5]. Optimal care can improve and even normalize lung function in children; however, access to multidisciplinary care, especially paediatric physiotherapy, is limited. Personalized, high-quality care is key to preventing decline and improving quality of life [6].

Several studies have demonstrated the potential of digital health sources (DHSs) to improve clinical outcomes and disease management in children with CSLDs. The use of mobile applications, e-Health exercise programs, serious games, and telehealth tools has been associated with improved treatment adherence, better symptom monitoring, enhanced functional capacity, and increased health knowledge [7]. While many interventions show promise, challenges remain regarding accessibility, cultural relevance, and the need for high-quality evidence to support widespread implementation [8–11]. Healthcare professionals (HCPs) and parents of children with CSLDs may play a central role in the development and implementation of digital health solutions, as their perspectives on barriers and enablers are crucial for their successful adoption. Considering the vast technological advancements and recognizing the importance of digital health in shaping the future of medical advances is key for the optimization of current and new DHSs [12].

It is essential to acknowledge that a significant gap remains in educational and informational materials specifically designed for children with CSLDs. Families and pediatric patients often have limited access to structured, evidence-based resources related to the disease itself, as well as its pharmacological and non-pharmacological management, including airway clearance techniques, physical activity, and nutrition. The aim of this study was to develop a website that provides reliable, accessible, and practical information on medication, physiotherapy, nutrition, exercise, and disease education for children with CSLDs and their caregivers.

2. Materials and Methods

2.1. Study Design

This research was conducted in two sequential stages: Focus Group discussions, followed by two rounds of Delphi consensus questionnaires. The Committee for Research Ethics of the Physiotherapy Department of the University of Thessaly approved all the study procedures (protocol number: 14892/12-07-24). Prior to commencing the online survey, participants were provided with an information sheet and consent form. Consent was confirmed via a checkbox before participation.

2.2. Research Questions

The research questions were as follows: (a) What are the content and functions of a website for use in children with CSLDs? (b) Do you believe that the following items related to content and functions could be incorporated in a website for children with CSLDs?

2.3. Scope

This study aimed to develop a website to inform users regarding disease symptomatology management. It targets children aged 6–12 years, whose main symptoms are a productive cough and abnormal sputum.

2.4. Stage 1: Focus Group

Focus Groups are a cost-effective, quick, and more efficient alternative to one-on-one interviews for gathering data from multiple participants [13].

2.4.1. Participants

Purposive sampling was used. Two groups were invited to participate in this study, Group A (pediatricians and physiotherapists) and Group B (parents). Consequently, Group A consisted of professionals who (a) had more than 5 years of clinical experience, (b) were specialized in pediatrics, and (c) were working with children with CSLDs. Members of Group

B were (a) parents of a child diagnosed with CSLD, and (b) parents who had a child receiving regular treatment at a pediatric clinic in a public hospital or a private clinic in Greece.

Recruitment was through an email invitation sent to public hospitals and private clinics across Greece, aiming to include HCPs actively involved in managing children with CSLDs. Parents were approached through the same clinical settings where the participating HCPs practiced; in most cases, they were first informed about the study directly by their child's clinician and were later contacted by the research team.

2.4.2. Procedure

Two online Focus Groups were conducted via Microsoft Teams, one with HCPs and one with parents of children with CSLD. Each session lasted approximately 90 min and was moderated by a professor experienced in qualitative research, assisted by two facilitators. The discussions followed a semi-structured topic guide (Supplementary Table S1), which was previously pilot-tested and refined. Sessions were recorded using OBS Studio and later transcribed verbatim. Participants were recruited through email invitations and verbal referrals, provided informed consent, and directly completed the demographic data collection form.

2.4.3. Data Analysis

A thematic analysis was conducted for the current qualitative study. A verbatim transcription was carried out followed by thematic analysis of the discussions. Initiating theme development included a thorough review of all codes to identify patterns, relationships, and interconnections, which subsequently informed the formulation of preliminary thematic categories.

2.5. Stage 2: Delphi Survey

A two-round Delphi survey was employed to reach consensus on the listed items, facilitating agreement on those considered most important [14]. This approach is extensively applied within medical and nursing fields and is recommended when aiming to capture nationwide perspectives and establish priority areas [15].

2.5.1. Sample and Recruitment

One group was invited to participate: HCPs (pediatricians and physiotherapists) with at least one published work related to CSLDs in the past three years, those who delivered keynote or invited presentations at major meetings focused on pediatric pulmonology or respiratory physiotherapy, and those with postgraduate certification in CSLDs.

The Focus Group of HCPs was asked to nominate a list of 50 participants from their professional networks, including pediatricians and physiotherapists, who had adequate scientific training and clinical experience to take part in the Delphi process and possibly expand the sample size. Selecting participants was considered crucial for ensuring the validity of the study's conclusions. Therefore, purposive sampling was used to target individuals with proven expertise and practical experience, relevant backgrounds related to the study topic, the ability to provide valuable insights, and a willingness to revise their initial or previous judgments to achieve the highest possible level of consensus.

2.5.2. Formulation of the Survey Items

A steering committee was formed to oversee the Delphi process, including preparing the list of items and assessment findings for Round 1, evaluating the outcomes of Round 1, and reviewing responses to Round 2. The 36 items of Round 1 were derived directly from the thematic analysis of the Focus Group discussions (Supplementary Tables S2a,b and S3a,b). Each main theme and its subthemes were converted into specific, concise questionnaire items using wording that closely reflected the participants' original phrasing. Two researchers (VS and AM) independently coded the transcripts and proposed candidate items. Discrepancies

were resolved through discussion with a third senior researcher (EKo) to ensure reliability and content validity. A detailed mapping of Focus Group themes, representative quotes, and corresponding Delphi items is presented in Supplementary Table S4. The committee consisted of three members with expertise in chronic pediatric lung diseases: one Professor of Pediatric Pulmonology and two Professors of Physiotherapy. An online survey was developed, and pilot tested to ensure clarity, feasibility, and technical performance before data collection.

2.5.3. Delphi Survey: Round One (R1)

A total of 49 participants evaluated each outcome's significance based on their personal experience and opinions. A three-point Likert scale was used to score items according to their importance [16]. A score of 1 signified an outcome of limited importance, 2 important but not critical, and 3 critical. An open-ended section allowed respondents to propose additional outcomes, which, if absent from the initial list, were incorporated into the second-round survey. Data collection took place between 15 September and 15 October 2024, with weekly email reminders issued to promote participation.

2.5.4. Delphi Survey: Round Two (R2)

Participants who completed R1 were sent invitations to complete R2, which was open from 1 November 2024 to 2 December 2024. Items that reached a consensus level between 50 and 80% were carried forward to R2, along with new items proposed through the open-ended question in R1. Participants were asked to consider the previous group ratings and re-evaluate each item using the same Likert scale. Weekly email reminders were sent to encourage participation.

2.5.5. Data Analysis

Data analyses were performed and presented separately for pediatricians and physiotherapists. Participant rating percentages for each item from both the first and second rounds were used to determine the level of consensus, based on predefined criteria. Consensus was defined as agreement equal to or greater than 80%. Near-consensus was defined as agreement between 50 and 80%, while disagreement (or lack of consensus) was defined as less than 50% agreement for any of the possible responses. Consensus thresholds were pre-specified based on methodological guidance for health-related Delphi studies [17]. Although the COMET Handbook and other studies frequently define consensus as at least 70% of participants rating an outcome as critical and no more than 15% rating it as unimportant, there is no universally accepted standard for establishing consensus in Delphi surveys [18,19]. Thresholds between 70% and 80% have been used in previous studies [20]. We opted for the 80% cut-off to ensure more stringent agreement among participants, given the need for high confidence in prioritizing outcomes in this study.

For the descriptive analysis of the data from both the first and second round questionnaires, parametric statistical testing was performed. The Kolmogorov–Smirnov test was used to assess the normality of the distribution. All continuous variables (e.g., demographic characteristics) were expressed as mean $\pm$ standard deviation and median (interquartile ranges). Categorical variables (e.g., level of agreement, response rate) were presented as numbers (n) and percentages (%). Based on the normal distribution, the independent t-test, Mann–Whitney U test, and Fisher's exact test were used to explore differences between demographic characteristics. To enhance the clarity of data presentation, percentages and decimal points were rounded where appropriate. Statistical analysis was conducted using SPSS for Mac, Version 29.0 (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Focus Group Participants' Characteristics

A total of thirteen individuals participated in the study: seven HCPs (median age 51 years; interquartile range (IQR): 36–59) and six parents (median age 43 years; IQR: 39–48). Five out of the seven HCPs (71.42%) worked at a public hospital, and four of them (57.14%) held an MSc in pediatrics. All parents were female. Participants' demographic characteristics are presented in Table 1.

Table 1. Demographic data collection for participants of Focus Group.

Professionals' Characteristics		Parents' Characteristics		
ID/Professions	**Work Experience**	**ID/Parents**	**Diagnosis**	**Child Age**
HCP1/MD	>31	P1	Primary ciliary dyskinesia	6–12
HCP2/MD	>31	P2	Bronchiectasis	6–12
HCP3/PT	21–30	P3	Bronchiectasis	6–12
HCP4/PT	11–20	P4	Cystic Fibrosis	6–12
HCP5/PT	11–20	P5	Cystic Fibrosis	12–18
HCP6/MD	5–10	P6	Bronchiectasis	12–18
HCP7/PT	5–10			

ID: identification; HCP: healthcare professional; MD: medical doctor; PT: physical therapist.

3.2. Delphi Participants' Characteristics

Of 50 participants, 49 (98%) responded in R1: 12 (24.5%) pediatricians and 37 (75.5%) physiotherapists. In total, 38 (77.6%) respondents were female, while 11 (22.4%) were male. Detailed demographics of participants for R1 are displayed in Table 2. Given that only one participant did not respond in R1, it was not possible to assess the systematic differences between responders and non-responders.

Table 2. Demographic data collection for participants of Round 1 (n = 49).

Characteristics			
	Pediatrician	**Physiotherapist**	***p*-Value**
Number (n)	12 (24.5%)	37 (75.5%)	<0.001 *
Age (years)	37.5 (35.5–58.25)	42.76 ± 9.15	0.598
Work experience (years)	12 (10–34.5)	18.59 ± 8.65	0.600
Gender (male/female)	1/11	10/27	0.252
Level of education			
MSc	8 (66.7%)	26 (70.3%)	
PhD	4 (33.3%)	7 (18.9%)	
Employer			
Private clinic	3 (25%)	26 (70.3%)	
Public hospital	9 (75%)	11 (29.7%)	
MSc in pediatrics	9 (75%)	13 (35%)	
Publications related to pediatrics	9 (75%)	10 (27%)	

Data are presented as mean ± SD, median (IQR: Q1–Q3), numbers (n), and % percentage; MSc: masters; PhD: doctor of philosophy; * Statistically significant differences ($p < 0.001$).

In R2, 44 of 50 participants (88%) responded; 10 (22.7%) pediatricians and 34 (77.3%) physiotherapists. Detailed demographics of participants for R2 are displayed in Table 3.

Table 3. Demographic data collection for participants of Round 2 (n = 44).

Characteristics			
	Pediatrician	**Physiotherapist**	***p*-Value**
Number (n)	10 (22.7%)	34 (77.3%)	<0.001 *
Age (years)	46.2 ± 12.53	42.97 ± 9.34	0.464
Work experience (years)	13 (9.5–35)	18.77 ± 8.9	0.707
Gender (male/female)	1/9	10/24	0.408

Table 3. *Cont.*

Characteristics		
Level of education		
MSc	8 (80%)	24 (70.6%)
PhD	2 (20%)	6 (17.6%)
Employer		
Private clinic	2 (20%)	24 (70.6%)
Public hospital	8 (80%)	10 (29.4%)
MSc in pediatrics	8 (80%)	11 (32.4%)
Publications related to pediatrics	8 (80%)	8 (23.5%)

Data are presented as mean ± SD, median (IQR: Q1–Q3), numbers (n), and % percentage; MSc: masters; PhD: doctor of philosophy; * Statistically significant differences ($p < 0.001$).

3.3. Focus Group's Results

3.3.1. Content

Participants in both Focus Groups emphasized the importance of developing a child-centered website tailored to the daily management of CSLDs. Five main themes emerged: information provision, aesthetics, gamification, evidence, and co-design (Supplementary Tables S2a and S3a). Key similarities and differences were observed between HCPs and parents, with both groups focusing on the accessibility and engagement of the digital platform.

Information

Clear, reliable, and accessible medical information was highlighted by all HCPs and five parents. HCPs stressed the inclusion of evidence-based content about the disease and its treatments:

> *"The website should include clear explanations of the disease—what chronic suppurative lung disease is and how it affects children."* (HCP2)

Parents, in turn, emphasized the challenge of recalling instructions after medical visits and the desire for medically approved, trustworthy resources:

> *"Sometimes we leave the hospital with so many instructions that it's hard to remember—if it was written on the website, it would help a lot."* (P2)

> *"We often google things, but it's hard to know what to trust. I'd prefer having reliable, doctor-approved information in one place."* (P6)

Key areas of interest for both groups included physiotherapy techniques (mentioned by six HCPs and four parents), nutritional guidance (five HCPs, three parents), and exercise recommendations tailored to the child's condition.

Aesthetics

Aesthetic appeal was considered essential for child engagement, mentioned by five HCPs and all parents. Parents particularly stressed the need for colorful, joyful, and age-appropriate designs:

> *"It should be something colorful, something cheerful that catches their attention."* (P2)

> *"... in our case, for children around the age of six, it should be something colorful, something joyful that captures their interest."* (P4)

HCPs echoed this view, adding the need for content to remain dynamic and avoid monotony:

> *"It should be entertaining and a little different each time—the same ideas but varied presentations."* (HCP1)

Simplicity and ease of use were also emphasized by four HCPs and five parents.

Gamification

Gamification was viewed as a core engagement tool, mentioned by four HCPs and five parents. HCPs proposed the integration of serious games and interactive features such as blowing games connected to remote monitoring:

"Games that involve blowing, the measurements of which will be sent directly to the corresponding center of the website." (HCP6)

Parents highlighted the idea of a digital "imaginary friend" or hero to accompany children through their therapy journey:

"A hero could be created who grows with them and experiences the therapy alongside them." (P5)

"Well, I believe that a digital friend within the tool would be very helpful. An electronic friend that they could see on their phone through virtual reality." (P4)

Three-dimensional animation was suggested by three HCPs and three parents as a means to sustain engagement during therapy.

Evidence

All HCPs emphasized the importance of ensuring that all content is based on clinical evidence and supervised by qualified professionals:

"All information should be drawn from evidence-based research and literature." (HCP4)

"The final advice should come from the specialist paediatric respiratory physiotherapist and the doctor." (HCP6)

Co-Design

Involving end users in the design process was supported by five HCPs:

"Children should be part of the design process—they're the end users, and their input is crucial for usability." (HCP2)

"Parents are aware of the daily challenges better than anyone." (HCP6)

3.3.2. Functions

Five main functional themes emerged: technical support, training, remote monitoring, accessibility, and multilingual access (Supplementary Tables S2b and S3b). The priorities of HCPs focused more on clinical utility and customizability, while parents highlighted communication, support, and daily usability.

Technical Support

Both groups emphasized the importance of system-guided reminders and sound notifications to enhance adherence, with seven HCPs and five parents mentioning this feature:

"Some kind of electronic reminders for children, telling them that it's time to take their medication, it's time for physiotherapy." (HCP1)

"A daily reminder or whenever necessary, in a pleasant way that doesn't feel burdensome." (P1)

Additionally, four parents requested features such as phone support, email, and chat systems, especially for real-time emotional or technical concerns.

Training

Training was seen as crucial by five HCPs and four parents. HCPs suggested structured in-clinic instruction and asynchronous resources:

"Training is needed . . . dedicating time and frequent practice. Repetition is the key to learning." (HCP1)

Parents appreciated the value of visual aids to support correct implementation at home:

"A video that shows them how to do their respiratory physiotherapy." (P5)

Remote Monitoring

Discussed by four HCPs and three parents, remote monitoring features such as electronic spirometers and clinical progress tracking were seen as beneficial:

"I want to monitor the child's progress—whether there is a steady course, whether things are being done well." (P3)

Accessibility

The issue of affordability was mentioned as a potential barrier. Free access to the website was emphasized by all parents and four HCPs:

"If it's free, they will be able to do it regularly and sustain it." (P5)

"Perhaps it could be provided to families through donations." (HCP4)

Multilingual

The importance of offering content in different languages to accommodate non-Greek speakers was raised:

"It should definitely be available in multiple languages." (HCP6)

3.4. Delphi Results

A total of 36 Delphi survey items were derived directly from the thematic analysis of the Focus Group discussions. Each main theme (e.g., Information) was mapped to specific survey items (e.g., medical, physiotherapy, nutrition, exercise), ensuring continuity between the qualitative and quantitative phases. A detailed mapping of themes, subthemes, representative quotes, and corresponding Delphi items is provided in Supplementary Table S4.

Of the total 36 items included in the first-round questionnaire (Table 4), 31 items reached a consensus level of ≥80% and were considered final; these were not re-evaluated in R2. The remaining five items, which had a consensus level between 50 and 80%, were carried forward to R2 for re-evaluation. Furthermore, in R1, participants suggested three new items through the open-ended responses, which were also included in the R2 questionnaire (Table 5).

Table 4. Delphi survey Round 1.

Content of a Website				
Question 1: Do you believe that the following items related to the content could be incorporated into a website for children with CSLDs?				
	Content	Disagree	Neutral	Agree
1.	Information (medical, physiotherapy, nutrition, exercise)	2.1%	2%	95.9%
2.	Simple	2.1%	2%	95.9%
3.	User-friendly	2.1%	2%	95.9%
4.	Interactive (e.g., diary)	2.1%	2%	95.9%
5.	Colorful	2%	10.2%	87.8%
6.	Gamification	2%	2.1%	95.9%
7.	Imaginary friend (avatar)	4.1%	10.2%	85.7%
8.	3D animation	2.1%	16.3%	81.6%
9.	Evidence-based content	2.1%	2%	95.9%
10.	Co-design	2%	10.2%	87.8%

Table 4. *Cont.*

Functions of a Website				
Question 2: Do you believe that the following functions could be incorporated into a website for children with CSLDs?				
1.	Reminders	2%	8.2%	89.8%
2.	Sound notification	4.1%	10.2%	85.7%
3.	Communication form	2%	18.4%	79.6%
4.	User manual	2%	8.2%	89.8%
5.	Updates	2%	10.2%	87.8%
6.	Modular	2.1%	22.4%	75.5%
7.	Calendar/weekly questionnaire	2%	8.2%	89.8%
8.	Evaluation form	8.2%	14.2%	77.6%
9.	Telephone support	-	8.2%	91.8%
10.	Email	2%	12.3%	85.7%
11.	Chat box	4.1%	16.3%	79.6%
12.	Social media	10.2%	14.3%	75.5%
13.	Diary	6.2%	12.2%	81.6%
14.	Child's training	-	10.2%	89.8%
15.	Parent's training	-	6.1%	93.9%
16.	Healthcare professionals' training	-	6.1%	93.9%
17.	Video	-	2%	98%
18.	Multilingual	-	10.2%	89.8%
19.	Compatible with other devices	-	6.1%	93.9%
20.	Interaction between patients and healthcare professionals	-	4.1%	95.9%
21.	Image uploading	-	4.1%	95.9%
22.	Portable forms (pdf)	-	8.2%	91.8%
23.	Easy navigation	-	4.1%	95.9%
24.	Language adaptability	-	4.1%	95.9%
25.	Strict privacy policies	2%	10.2%	87.8%
26.	Free supply	2.1%	2%	95.9%

CSLDs: chronic suppurative lung diseases

Table 5. Delphi survey Round 2.

Content of a Website				
Question 1: Do you believe that the following items related to the content could be incorporated into a website for children with CSLDs?				
	Content	Disagree	Neutral	Agree
1.	Electronic leaflets *	8.2%	42.8%	49%
Functions of a Website				
Question 2: Do you believe that the following functions could be incorporated into a website for children with CSLDs?				
1.	Communication form	4.6%	13.6%	81.8%
2.	Modular	4.1%	12.2%	83.7%
3.	Evaluation form	2.3%	15.9%	81.8%
4.	Chat box	2.3%	13.6%	84.1%
5.	Social media	4.6%	13.6%	81.8%
6.	Live video conference *	16.3%	55.1%	28.6%
7.	Emergency button *	14.2%	42.9%	42.9%
8.	Communication form	4.6%	13.6%	81.8%

CSLDs: chronic suppurative lung diseases. * indicates the items suggested from round 1.

In R2 of the questionnaire, eight items were assessed in total. Of these, five reached the consensus threshold ($\geq$80%) and were retained, while three did not achieve consensus:

electronic leaflets, live video conference, and emergency button. The lack of consensus for certain innovative digital features suggests that these areas remain uncertain and may warrant further investigation in future research.

4. Discussion

This study contributes to the limited body of literature on digital health sources for improving self-management in children with CSLDs. It is the first to document the development and implementation process of a website designed to provide physiotherapy, exercise, and disease-related information for pediatric CSLDs. Using mixed qualitative and quantitative approaches, it presents a comprehensive overview of the website's required content and functionalities that are most likely to support a successful adoption of a digital health resource. The website was developed through a human-centered design approach with a focus on children, incorporating the perspectives of HCPs and parents, and addressing the daily management of CSLD. Patient-centered care is essential in the design of digital health technologies, particularly for pediatric populations [21]. The enhanced communication between providers and patients or families can also support the development and implementation of child-centered digital health technologies by encouraging relationship-centered skills in team-based care [22].

4.1. Focus Groups

Initially, the comprehensive list of the website's content and functions that was developed using a Focus Group study with HCPs and parents established 10 main themes. Similarities and differences were observed between HCPs and parents, with both groups focusing on the accessibility and engagement of the digital platform. HCPs and parents underlined the need for clear, reliable, accessible medical information and evidence-based content. Key areas of interest for both groups included physiotherapy techniques, nutritional guidance, and exercise recommendations tailored to the child's condition. Evidence-based content and access to accurate information strengthen parents' and patients' knowledge about the treatment and increase their self-efficacy [23]. Users of a mobile health platform for self-management of pediatric cystic fibrosis also preferred a mobile application with multiple functions that facilitate access to information, automate disease management, and facilitate communication with the health care team [24].

The aesthetic appeal of the website was considered essential for child engagement. A colorful, joyful, and age-appropriate design is important. Simplicity and ease of use were emphasized by both groups. As reported in other studies regarding digital health, a user-friendly, relevant, and aesthetically pleasing digital environment enhances user satisfaction [25]. Moreover, user-friendly elements, such as incorporating colored line graphs to represent symptom states, are all considered equally important [26]. Gamification was seen as a core component for engagement in remote monitoring. Recent studies have also shown that when the digital environment is presented as a game, it becomes more appealing for systematic and consistent use, such as in practicing respiratory physiotherapy techniques, making gamification a desirable feature [26,27].

Similar approaches have been applied in digital health interventions for other chronic pediatric conditions, offering valuable insights for CSLD website development. For instance, gamified breathing exercise programs in cystic fibrosis have been shown to improve treatment adherence and engagement, particularly when incorporating visual feedback and progressive challenges [10,25]. In asthma management, mobile platforms integrating symptom diaries, medication reminders, and interactive educational modules have demonstrated increased self-management skills and reduced exacerbations [11]. These examples support our emphasis on 3D animations, avatars, and interactive features as strategies to

sustain children's interest and improve adherence to daily physiotherapy. Furthermore, co-design processes used in cystic fibrosis and pediatric obesity interventions have resulted in more acceptable and user-friendly tools, suggesting that the inclusion of children and parents in the design of a CSLD-specific website is likely to enhance its long-term adoption and effectiveness.

Furthermore, HCPs emphasized the importance of ensuring that all content is based on clinical evidence and supervised by qualified professionals. Communication with HCPs, as noted in other studies, also supports the concept of self-management [28]. Co-design is equally important, with participants acknowledging that user involvement in the design process enhances both acceptability and relevance. Research indicates that engaging end users throughout every stage of mHealth development, along with collaboration with healthcare system experts, can lead to applications that sustain user engagement, enhance co-production of services, and ultimately improve self-management and health outcomes [24]. Co-design, in particular, shows strong potential as an effective and empowering strategy for creating interventions that strengthen adolescents' digital health literacy [29].

Regarding the function of the website, five main themes emerged: technical support, training, remote monitoring, accessibility, and multilingual access. HCPs focused on clinical utility and customizability, while parents highlighted communication, support, and daily usability. Both groups emphasized the importance of system-guided reminders and sound notifications. Additionally, parents requested features such as phone support, email, and chat systems. Moreover, HCPs called for structured training within clinic visits and through asynchronous platforms. Parents appreciated the value of visual aids to support correct implementation at home.

In previous studies, HCPs and parents also agreed that accessibility and technical support are essential in promoting the adoption of digital health technologies. Reminders, telephone supports, user-friendly manuals, audio assistance, etc., improved the ability to handle health situations [21,30]. Additionally, preparation and training time is needed to identify and address technical issues (e.g., internet connection) when they arise, and patients should be introduced to the application's functionalities in a gradual manner [23]. Allowing them to interact with the app according to their current needs enables a progressive appreciation of its benefits over time, without imposing extra burden [21].

In our study, the potential for integrating remote monitoring was also acknowledged. HCPs referred to tools such as electronic spirometers and tracking forms. Parents echoed a desire for feedback on treatment effectiveness and their children's health progression. Previous studies have shown that collecting patient-generated health data can lead to more scalable and dynamic platforms, facilitating the use and implementation of mHealth apps [24]. The issue of affordability was mentioned as a potential barrier. Both groups emphasized that the website should be free of charge. Developing affordable and accessible digital health is crucial, as socioeconomic factors significantly affect the use, with users of higher digital literacy and resources benefiting more [31,32]. Finally, the importance of offering content in different languages to accommodate non-Greek speakers was raised, making the multilingual aspect of a website an important factor. Although not a website, the First Nations-specific multilingual Asthma App was found to be easy to use and acceptable for use by HCPs, demonstrating how culturally and linguistically tailored digital tools can effectively support health education in diverse populations [33]. Similarly, a file-based approach was developed to support a multilingual platform, allowing dynamic updates to medication and treatment lists based on clinician input and patient preferences [24].

4.2. Delphi Survey

The Delphi process yielded a high level of agreement among HCPs, with 31 items reaching consensus in R1 and an additional 5 items in R2. These results highlight the shared priorities among pediatricians and physiotherapists regarding the content, design, and functionalities that should be incorporated in a website.

A notable finding was the strong consensus on the inclusion of content related to physiotherapy techniques, exercise, and disease education—core pillars in the management of CSLDs. These outcomes reflect current clinical best practices and underscore the role of digital tools in enhancing continuity of care and self-management. Furthermore, the prioritization of interactive features (such as gamification and training videos), alongside practical elements (like reminders, technical support, and multilingual access), suggests that HCPs value engagement and accessibility as key elements in a successful pediatric website.

The Delphi results also demonstrated the experts' awareness of caregiver and family needs. The inclusion of items related to parent support, communication tools, and remote monitoring indicates an understanding of the broader psychosocial and logistical challenges families face. These elements align with emerging trends in pediatric digital health interventions, where holistic and family-centered design is increasingly emphasized.

Interestingly, while in some cases the Delphi method is often characterized by variability in consensus levels, our study achieved a relatively high and consistent agreement across two rounds. This may reflect the fact that participants were carefully selected based on expertise and recent academic or clinical contributions in the field. It may also suggest a growing convergence of opinion on the minimum digital standards expected in pediatric care for CSLDs.

Compared to previous core outcome sets or digital design Delphi studies, the present study focused not only on what information should be delivered, but also how it should be accessed and experienced by children and families [34]. Thus, the resulting website model incorporates both clinical and experiential dimensions, marking a shift toward more user-centered and participatory approaches in tool development.

While the majority of items reached strong consensus, certain proposed features did not meet the $\geq$80% threshold. For example, "Electronic leaflets" and "Live video conference" received lower agreement, possibly reflecting concerns about their added value and the considerable resources required for their implementation and ongoing support. Similarly, the "emergency button" function concerns a technical issue which, although it may be practically useful, is usually not included in websites whose main objective is to create informative material. These lower consensus levels suggest that participants prioritized core self-management and communication functions over supplementary or resource-intensive features.

To ensure that the consensus findings translate into a practical digital health tool, the next phase will involve developing a prototype website incorporating the agreed-upon content and functions. This will be followed by usability testing with children and parents to refine design and features, a pilot implementation in selected clinical settings to assess engagement and feasibility, and finally, efficacy trials to evaluate the impact on treatment adherence, health outcomes, and quality of life. This staged approach will facilitate the creation of an evidence-informed, user-centered platform ready for broader clinical integration.

5. Strengths and Limitations

This study followed a rigorous, two-phase Delphi methodology with high response rates and expert participation from both pediatricians and physiotherapists. The inclusion

of a broad set of items reflecting clinical, technical, and user-centered aspects strengthens the relevance and applicability of the findings. The systematic identification and prioritization of features through consensus enhances the potential for real-world implementation and adoption.

However, this effort was specifically targeted at a Greek-speaking population, which may limit the generalizability of the findings. Cultural and contextual factors, along with differences in healthcare infrastructure, funding models, and attitudes toward technology, could influence both the perceived relevance of digital health features and the feasibility of their implementation. In addition, while expert consensus was achieved, validation through end-user testing with children and caregivers is needed to confirm usability and long-term impact. Future research should broaden the sample to include international experts from diverse healthcare systems, enabling comparison of priorities across cultural and organizational contexts. Once a prototype is developed, cross-cultural adaptation and validation studies will be conducted to ensure that the tool is acceptable, relevant, and effective in varied international settings.

The Delphi process was limited to two rounds; although this is a common approach, some researchers recommend a third round to further stabilize consensus, which could have refined the prioritization of items. The study also relied on self-reported ratings of importance without behavioral validation, meaning that stated preferences may not always translate into actual usage or adherence in practice. Finally, physiotherapists represented 75% of respondents, which may have skewed the prioritized content toward physiotherapy-related elements. However, as the scope of this study was disease management rather than exclusively medical management, the strong representation of physiotherapists also reflects their central role in comprehensive care while highlighting the need for more balanced multidisciplinary input in future work.

6. Conclusions

This study identified and prioritized the essential features for a CSLD-focused digital health platform through a rigorous, two-phase Delphi process informed by Focus Group insights from both parents and healthcare professionals. The integration of these complementary perspectives ensured that the proposed design reflects both clinical priorities and family needs. Features receiving the highest consensus included evidence-based content, engaging gamification elements such as 3D animations and avatars, multilingual access, and personalised reminders. By combining user-centred design principles with expert consensus, this work provides a concrete roadmap for developing an accessible, engaging, and clinically relevant tool to support the long-term management of CSLDs in children.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app15179291/s1, Table S1: Semi-structured interview guide for online Focus Group discussions; Table S2: Content and functions of a website for use in children with chronic suppurative lung diseases: Professionals' Focus Group; Table S3: Content and functions of a website for use in children with chronic suppurative lung diseases: Parents' Focus Group; Table S4: Mapping of Focus Group rhemes to Delphi Round 1 items.

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Abbreviations

The following abbreviations are used in this manuscript:

CSLDs	chronic suppurative lung diseases
DHS	digital health sources
HCPs	healthcare professionals
HRCT	high-resolution CT
NCFB	non-cystic fibrosis bronchiectasis
PCD	primary ciliary dyskinesia
PPB	protracted bacterial bronchitis

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Relationship Between Physical Fitness Attributes and Dynamic Knee Valgus in Adolescent Basketball Athletes

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Abstract: (1) Background: Dynamic knee valgus (DKV) is a common biomechanical risk factor for knee injuries, particularly in sports involving high-intensity movements, such as basketball. While neuromuscular control and structural alignment contribute to DKV, recent evidence indicates that lower limb muscle power (LLMP) and cardiorespiratory fitness (CRF) may significantly influence DKV. This study aims to examine the relationship among LLMP, CRF, and DKV in adolescent basketball athletes. (2) Methods: A total of 104 adolescent basketball athletes (63.5% boys), 12 to 17 years old (13.87 ± 1.46 years) participated in this study. Anthropometric and demographic characteristics such as sex, age, height, weight, and body mass index (BMI) were recorded. The Counter Movement Jump (CMJ) was used for the evaluation and prediction of the LLMP, the 20 m shuttle run test (20mSRT) was used for the evaluation and prediction of CRF, and the single-leg drop jump (SLDJ) was used for the evaluation of DKV via a two-dimensional (2D) kinematic analysis. Statistical analysis included Pearson and Spearman correlations, as well as multiple linear regression, to determine the relationship among LLMP, CRF, and DKV. (3) Results: A statistical analysis revealed strong correlations among LLMP, CRF, and DKV. Pearson's correlation coefficients demonstrated significant associations between the VO_2max and frontal plane projection angle (FPPA) (r = 0.78, $p < 0.001$), as well as between LLMP and FPPA (r = 0.82, $p < 0.001$). Multiple linear regression analysis showed that VO_2max and LLMP together accounted for 85% of the variance in FPPA ($R^2 = 0.85$, $p < 0.001$). (4) Conclusions: The findings highlight that both aerobic capacity and lower limb muscle power significantly contribute to knee valgus control among adolescent basketball players. Implementing training programs focused on improving lower limb muscle power and cardiorespiratory fitness may enhance knee stability and reduce the risk of lower limb injuries. Given the strong predictive value of VO_2max and LLMP for knee control, targeted training programs focusing on neuromuscular conditioning and aerobic capacity may be effective for injury prevention.

Keywords: frontal plane projection angle; muscle power; cardiorespiratory fitness; physical attributes; sports-specific testing; young athletes

1. Introduction

Basketball is a team sport that demands a high level of physical fitness to manage the intense physical effort required during the game [1,2]. It is a physically demanding sport that involves constant changes in pace, direction, and speed, frequent jumps and landings, intense physical contact, and essential technical and tactical skills. Therefore, basketball athletes, and especially adolescents, are at high risk of injuries [3,4]. Knee

injuries, especially, are common among adolescent basketball athletes, with incidence rates ranging from 1.52 injuries per 10,000 athlete-exposures to a seasonal prevalence of 25.3% for anterior knee pain [5–7].

Dynamic knee valgus (DKV), characterized by the inward collapse of the knee during dynamic movements, has been widely associated with an increased risk of injury, particularly in sports, like basketball, that involve high-intensity activities, such as running, jumping, landing, and cutting [8–11]. This abnormal knee motion is often observed during single-leg movements, such as a single-leg landing or a change of direction, and can contribute to the development of conditions such as anterior cruciate ligament (ACL) injuries and patellofemoral pain syndrome, especially in adolescent populations [3,4,12–15].

The biomechanical mechanisms underlying DKV are complex and multifactorial, involving both neuromuscular control and structural alignment [11,16]. However, an emerging body of evidence suggests that physical fitness or physical abilities may play a significant role in the manifestation of DKV during dynamic tasks that lead to sport injuries [16–21].

Identifying modifiable risk factors for sports-related knee injuries is crucial for developing effective prevention strategies [21–25]. The definition of physical fitness is a collection of characteristics that a person possesses or achieves that pertain to their capacity to carry out daily duties. Some of the major components of physical fitness are balance, agility, cardiorespiratory fitness, body composition, flexibility, muscle strength, muscle power, muscle endurance, reaction time, and speed [21,26,27].

Lower limb muscle power (LLMP), which refers to the ability of the muscles in the legs to produce force rapidly, has been implicated as a key determinant of knee stability during dynamic movements [20,28,29]. Research has shown that deficits in lower limb strength and power are associated with an increased risk of knee valgus [29–31].

Cardiorespiratory fitness (CRF), a measure of the efficiency of the cardiovascular and respiratory systems in supporting sustained physical activity, has also been shown to influence knee control in dynamic tasks [18,20,32]. While the link between aerobic fitness and knee valgus may not be as immediately apparent as that of muscle power, emerging evidence suggests that individuals with higher CRF tend to display improved neuromuscular control during dynamic tasks [21,24,33].

The relationship among lower limb LLMP, CRF, and DKV has important implications for injury prevention and rehabilitation programs. Previous studies have indicated that training programs focused on improving lower limb strength and muscle power, as well as aerobic fitness, can mitigate the risk of dynamic knee valgus by improving neuromuscular control and muscle coordination [21,30,34,35]. Interventions that target these physical abilities may not only reduce the occurrence of knee valgus but also enhance overall athletic performance and reduce the risk of long-term musculoskeletal disorders.

To further investigate how different physical fitness attributes correlate with DKV, a reanalysis of data previously published in the studies of Stojiljkovic (2024) and Karagianni (2025) was performed [17,32]. This approach allowed for a deeper examination of how multifactorial a movement such as DKV can be and provides new insights into the variables that should be trained to have a positive impact on the prevention of such injury-prone movements.

Up to now in the literature, there is limited research on adolescent basketball athletes in Greece, and the assessment of physical abilities has mainly been performed with the use of expensive equipment. In this study, it was chosen to use simpler methods because many teams and team's academies do not have access to expensive assessment equipment.

Lower limb muscle power (LLMP) and cardiorespiratory fitness (CRF) were chosen over other potential factors due to their strong influence on DKV and their practical

applicability in athletic settings [23,24,36]. By examining the correlations between muscle power or cardiorespiratory fitness we aim to provide a comprehensive understanding of their association with knee control to propose better practices for athletic training, injury prevention, and clinical rehabilitation.

2. Materials and Methods

2.1. Study Design

Prior to the study, the study protocol was approved by the Ethics Committee of the Department of Physiotherapy at the University of Thessaly (1083/21-10-2022). The study was performed following the principles in the Declaration of Helsinki; thus, it was consistent with the value of respect for the volunteers who would participate.

2.2. Sample

The present study is based on a reanalysis of data from the studies of Stojiljkovic (2024) and Karagianni (2025) originally collected for correlating anthropometric characteristics and movement behavior with DKV and modeling associations of the cardiometabolic profile with sedentary behavior [17,32]. The dataset was re-examined using different variables and new statistical approaches to explore the association of novel physical fitness attributes with DKV.

The study sample's characteristics, as described in the studies of Stojiljkovic et al. (2024) and Karagianni (2025), were adolescents from two basketball academies from two different cities in Central Greece [17,32]. The final sample consisted of 104 adolescents (63.5% males, 36.5% females) from the 177 available (Figure 1).

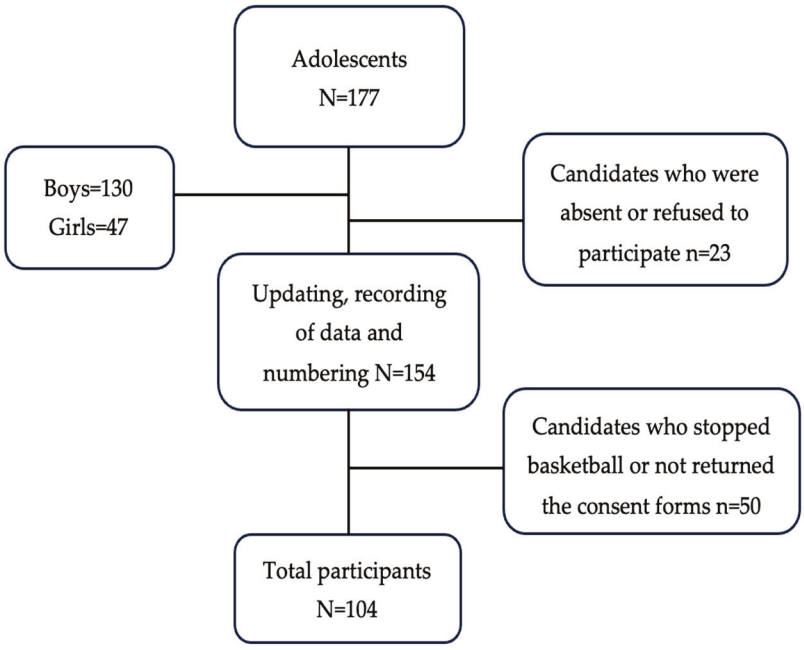

Figure 1. Flowchart of the sample.

The eligibility criteria were (a) adolescents aged between 12 and 17 years, (b) no lower limb injuries in the last 3 months or any other comorbidity (e.g., illness, cognitive or neurological condition) precluding exercise implementation, and (c) parents who signed informed consent [17]. The sample size was calculated using the G*Power 3.1.9.4 program with a 95% confidence level and a significance level of 5% or 0.05.

2.3. Data Collection

Data collection was performed daily, for 5 days per week, during the scheduled afternoon basketball practices for 8 weeks. Three independent physiotherapists, who were trained on the testing procedures prior to the beginning of the study, under the supervision of the research team, performed all the measurements and data collection. The measurements were taken without the presence of the study's main investigator. Initially, all the data were recorded on a laptop and backed up on an external hard drive. At the completion of all measurements, access to data was given to the main researcher for data processing.

2.4. Equipment

For the sample's anthropometric characteristics' measurements, a precision electronic ultrasonic stadiometer (SOEHNLE 5003, Spaichingen, Germany) and a precision electronic weighting scale (TANITA BC418-MA, Tokyo, Japan) were used to calculate the participants' height and weight and Body Mass Index (BMI) [37,38].

For the recording of the tests, a Go Pro camera (4K, 30fps, San Mateo, CA, USA) that was mounted on a tripod at a height of 50 cm from the ground and 3 m in of the point of where the tests were performed, a laptop, 5 reflective markers, and a 30 cm-height wooden box were used to collect the data from the countermovement jump test and the single-leg drop jump test.

The Kinovea software (2023.1.2) was used for the 2-dimensional analysis, since its validity and reliability have been demonstrated as good to excellent for the kinematic analysis of the single-leg drop jump (SLDJ) to assess DKV and for the measurement of jump height in the countermovement jump (CMJ) [39–43].

For the evaluation of CRF, the 20 m shuttle run test (20mSRT) or beep test was used, which is a valid and reliable cardiorespiratory test [44,45]. Based on the original application, the 20mSRT was executed using the Beep Shuttle Advanced VER0320 program, and a standard procedure was followed [45,46].

2.5. Assessment

All the data-collection procedures and measuring tests were conducted on the practice facilities (basketball courts) of the two participating teams (Figure 2).



Figure 2. Practice facilities and testing environment.

For the height assessment, the participants stood tall barefoot, in a straight position, with their heels touching each other and their eyes looking straight forward to be at the same height with their ears. For the weight assessment, participants had to stand on the scale barefoot and keep steady until their weight was indicated on the scale.

The BMI was calculated in accordance with the International System (SI) units with the following formula: Body Mass Index = weight (kg)/height^2 (m^2), and depending on the result, each participant was categorized as a z-score in three categories: normal/overweight/obese [37,38,47].

After recording the anthropometric characteristics, an appropriate warm-up that consisted of basketball-related running drills and movements, lay ups, and shots for 10 min was suggested for the implementation of the dynamic tests.

Prior to testing, 5 reflective markers were placed on each participant's dominant leg as reference points (Figure 3). The dominant leg was determined depending on the participant's answer on which leg he/she would use to kick a ball [43,48]. The anatomical landmarks were the anterior superior iliac spine, the lateral and medial femoral condyle, and the lateral and medial malleolus [43,48]. Before each test, athletes went through a familiarization process each having 3 trials on the CMJ and SLDJ tests.



Figure 3. Guide points for placing the five reflective markers and the Frontal Plane Projection Angle (FPPA).

The CMJ was the test used for the prediction of LLMP. Each participant performed two jumps with a 1 min rest in between. The instructions given were to jump as high as possible and with the hands always on their waist to not be able to use them [49]. A trial was considered valid only if the participant did not lose balance or fall during the test and did not use arm swing [49].

For the prediction of the LLMP, an equation was used, utilizing the participant's jump height and weight [49]. The height of the best performing jump was picked after a 2D kinematic analysis of both trials. This equation showed the highest accuracy rates

and reliability (R = 0.93, R^2 = 0.87) in the existing literature. The equation used was as follows [49]:

$$\text{Power [W]} = -1354.820 + (\text{jump height} \times 35.455) + (\text{body mass} \times 43.942).$$

For the SLDJ test, each participant stepped up and dropped off a 30 cm box and landed on their dominant leg, immediately performed a direct single leg jump as high as possible, and landed on the same leg again [43,48]. The instructions given were to remain still on the final landing for at least 2 s [43,48]. A trial was not considered valid only if the participant jumped instead of dropped off the box, if the non-supporting leg touched the floor throughout the test, and if he/she lost balance or fall on the final landing [43,48].

For the calculation of the DKV angle, the first three valid trials were selected for the kinematic analysis. Two axes were conducted, with the first axis corresponding to the femur and was considered the line from the anterior superior iliac spine to the middle of the distance between the reflective markers on the knee. The second axis was corresponding to the tibia bone and started from the middle point of the distance between the two markers on the knee to the midpoint of the distance between the two markers on the ankle [43,48]. The smaller the angle formed by the two axes, which will be referred as the Frontal Plane Projection Angle (FPPA), the bigger the DKV angle. The angle of DKV selected for analysis was when the knee showed the maximum FPPA after contact with the ground.

The 20mSRT was conducted last because it was the most demanding between the tests, and if it was performed first, the fatigue could alter the other tests and consequently their results [45]. The participants had to continuously keep running between two points for a 20 m distance, which was considered one run (Figure 4). To start running from one point to the other, the participants had to hear the characteristic "beep" sound from the audio feedback. The starting running speed was 8.5 km/h, and it increased every minute (new level) per 0.25 km/h with a special tone heard through the audio feedback [45]. The criteria for test termination were if the participant was not able to continue running due to fatigue or any other symptoms, if the participant failed to reach one of the two limit points on time, or if the participant completed all the levels [45].



Figure 4. The 20mSRT testing.

For the estimation of CRF, a valid and reliable equation was used, utilizing each participant's performance data on the 20mSRT, which was delivered through the appli-

cation [44,45]. For each participant, performance was recorded as the number of runs completed, and the running speed of the final level for each participant and his/her age were used for the calculation of the maximum oxygen uptake (VO_2max) [45]. The equation used was as follows [45]:

$$VO_2\text{max [mL/kg/min]} = 31.025 + (3.238 \times \text{speed}) - (3.248 \times \text{age}) + (0.1536 \times \text{speed} \times \text{age}).$$

2.6. Data Analysis

The two-dimensional (2D) analysis program Kinovea was used to analyze the CMJ and the SLDJ. The use of Kinovea software in evaluating athletic movements such as the countermovement jump and single-leg landing is well documented, and the results show that it is a valid and reliable tool [39,40,42,43,48].

For the statistical analysis, the Statistical Package for Social Sciences (SPSS) V.29.0 was used. For data analysis and calculations, Microsoft Office Excel 2013 was utilized. The significance level was set at $p = 0.05$.

LLMP and CRF were defined as independent variables, while the FPPA was defined as the dependent variable.

Descriptive statistics (mean, standard deviation) were calculated for all the variables to provide an overview of the sample's characteristics. Kolmogorov–Smirnov and Shapiro–Wilk tests indicated that height, BMI, power, and FPPA followed a normal distribution, while the other variables would require non-parametric statistical approaches. An independent samples *t*-test and Mann–Whitney U test were used in order to investigate differences between groups (boys vs. girls). Pearson's and Spearman's coefficients were used to measure the strength and direction of the associations, while a multiple linear regression analysis was used to assess the ability of the variables selected to predict FPPA. The regression analysis model included an analysis of variance (ANOVA) to evaluate the overall significance of the model.

3. Results

A total of 104 adolescents participated in the study (66 boys and 38 girls). A descriptive analysis revealed an average participant's age of 13.87 ± 1.46 years, height of 1.65 ± 0.1 m, an average weight of 62.52 ± 14.92 kg, and an average BMI of 22.71 ± 3.9 kg/m^2. The average LLMP was 2626.11 ± 734.78 Watts, VO_2max was 39.66 ± 3.85 mL/kg/min, and FPPA was 163.4 ± 7.7°. Descriptive statistics are presented in Table 1.

Table 1. Descriptive statistics.

	Total N-104		**Boys N = 66**		**Girls N = 38**	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**
Age [years]	13.87	1.58	13.71	1.50	14.13	1.35
Height [m]	1.65	0.1	1.66	0.11	1.63	0.06
Weight [kg]	62.56	14.92	63.9	16.7	60.1	10.8
BMI [kg·m^{-2}]	22.71	3.98	22.9	4.36	22.32	3.23
LLMP [W]	2626.11	734.78	2742.13	831.1	2424.61	473.09
VO_2max [mL/kg/min]	39.66	3.85	41.03	3.79	37.26	2.62
FPPA [°]	163.4	7.7	163.03	7.79	164.03	7.62

SD = standard deviation, BMI = Body Mass Index, LLMP = lower limb muscle power, FPPA = frontal plane projection angle.

The normality tests Kolmogorov–Smirnov and Shapiro–Wilk revealed that the variables height, power, and VO_2max did not significantly deviate from a normal distribution ($p > 0.05$), whereas age, weight, BMI, and FPPA significantly deviated from normality ($p < 0.05$) (Table 2).

Table 2. Normality tests.

	Kolmogorov–Smirnov			Shapiro–Wilk		
	Statistic	**df**	**Sig.**	**Statistic**	**df**	**Sig.**
Age	0.194	104	<0.001	0.906	104	<0.001
Height	0.080	104	0.099	0.989	104	0.549
Weight	0.090	104	0.036	0.971	104	0.022
BMI	0.066	104	0.200 *	0.971	104	0.021
VO_2max	0.088	104	0.047	0.977	104	0.067
Power	0.072	104	0.200 *	0.978	104	0.086
FPPA	0.078	104	0.133	0.962	104	0.004

* This is a lower bound of the true significance.

To examine potential differences between boys and girls, variables that followed a normal distribution (height, power, and FPPA) were analyzed using independent samples *t*-tests, while non-normally distributed variables (age, weight, and VO_2max) were analyzed using Mann–Whitney U tests (Table 3).

Table 3. Comparison of parameters between genders.

Variable	Boys (M ± SD)	Girls (M ± SD)	Test Used	Test Statistic	*p*-Value (2-Tailed)
Age	14.2 ± 0.9	13.9 ± 1.0	Mann–Whitney U	U = 1029.00	0.120
Heigh	162.3 ± 7.5	160.0 ± 6.8	Independent *t*-test	t(101.99) = 1.688	0.094
Weight	55.8 ± 9.6	53.4 ± 8.7	Mann–Whitney U	U = 1122.00	0.373
BMI	21.1 ± 2.3	20.8 ± 2.0	Independent *t*-test	t(95.49) = 0.828	0.410
Power	224.5 ± 32.1	207.3 ± 28.7	Independent *t*-test	t(101.99) = 2.483	0.015
VO_2max	52.6 ± 6.4	45.7 ± 5.9	Mann–Whitney U	U = 539.50	<0.001
FPPA	8.7 ± 5.2	9.3 ± 4.9	Independent *t*-test	t(78.68) = −0.640	0.524

The analysis revealed statistically significant differences between the two genders in power (t (101.99) = 2.483, $p = 0.015$) and VO_2max (U = 539.50, $p < 0.001$), with boys demonstrating higher values in both variables, indicating that gender may influence LLMP and aerobic capacity. No significant differences were observed in age, height, weight, BMI, or FPPA (all $p > 0.05$), suggesting that these characteristics are relatively similar between genders.

Pearson and Spearman correlations were performed to assess relationships between the independent variables VO_2max and power and the dependent variable FPPA (Table 4). Pearson's correlation coefficient showed a strong positive correlation between VO_2max and power (r = 0.85, $p < 0.001$), VO_2max and FPPA (r = 0.78, $p < 0.001$), and power and FPPA (r = 0.82, $p < 0.001$).

Table 4. Correlation between the independent and the dependent variables.

	FPPA					
	Pearson	**Sig. (2-Tailed)**	**N**	**Spearman**	**Sig. (2-Tailed)**	**N**
Power	0.82	<0.001	104	0.80	<0.001	104
VO_2max	0.78	<0.001	104	0.76	<0.001	104

Similarly, Spearman's correlation coefficients indicated strong positive relationships: VO_2max and power (rho = 0.83, $p < 0.001$), VO_2max and FPPA (rho = 0.76, $p < 0.001$), and power and FPPA (rho = 0.80, $p < 0.001$). These findings confirm that higher VO_2max and power values are strongly associated with increased FPPA.

A multiple linear regression analysis was conducted to predict FPPA using VO_2max and power as independent variables (Table 5). The regression model demonstrated a strong fit, with an R-squared value of 0.85, indicating that 85% of the variability in FPPA is explained by these two predictors. The adjusted R-squared value of 0.84 further supports the model's predictive strength.

Table 5. Multiple linear regression analysis.

Variable	**B (Coefficient)**	***p*-Value**
Constant	120.00	<0.001
VO_2max	3.20	<0.001
Power	1.80	<0.001

The ANOVA results confirmed the statistical significance of the model, F (2,101) = 150.7, $p < 0.001$. Both independent variables were significant predictors of FPPA, with VO_2max (B = 3.20, $p < 0.001$) and power (B = 1.80, $p < 0.001$) contributing meaningfully to the regression equation. These findings suggest that increases in VO_2max and power lead to a significant rise in FPPA values. The resulting regression equation was as follows:

$$\text{FPPA } [^\circ] = 120.00 + 3.20 \times (VO_2\text{max}) + 1.80 \times (\text{power}).$$

These results indicate that both VO_2max and LLMP are significant predictors of FPPA in adolescent basketball athletes.

4. Discussion

The objective of the current investigation was to examine the potential correlations between some physical fitness abilities, such as LLMP and CRF fitness, and DKV in adolescent basketball athletes. The study involved young Greek athletes, which make it one of the first national studies to focus on injury pattern analysis for injury prevention in Greece.

The findings of this study provide valuable insights into the relationship between physical fitness attributes and dynamic knee valgus (DKV) in adolescent basketball athletes. The results reveal significant correlations among LLMP, CRF, and DKV, suggesting that these physical attributes are key predictors of frontal plane knee control.

These findings align with previous research, which suggests that deficits in LLMP contribute to increased knee valgus during dynamic movements [16,21,23,24]. The observed relationships highlight the importance of targeted strength and conditioning programs aimed at enhancing power and aerobic capacity to reduce injury risk.

The multiple linear regression analysis demonstrated that both CRF and LLMP are significant predictors of DKV, with the model explaining 85% of its variability. This suggests that improving these physical attributes can lead to better knee stability and lower injury susceptibility. It must be noted here though that this is an overly simplified model and that other external factors might still contribute to DKV.

VO_2max, which is highly associated with cardiorespiratory fitness and endurance capacity, appears to play a crucial role in sustaining neuromuscular control during prolonged physical activity [20,33]. This finding reinforces the notion that fatigue negatively impacts biomechanical control, increasing the risk of DKV and subsequent lower limb injuries [20,21,33].

Additionally, the strong correlations between LLMP and DKV underscore the importance of explosive strength in maintaining proper knee alignment. Given that basketball involves plenty of jumps, landings, and rapid directional changes, athletes with insufficient lower limb power may exhibit compromised knee mechanics, predisposing them to injuries such as anterior cruciate ligament (ACL) tears and patellofemoral pain syndrome [21,31,35,50]. Implementing plyometric and resistance training exercises that focus on the hip, knee, and ankle stabilization may mitigate these risks and enhance overall athletic performance [30,34,35,51].

A notable finding is the significant gender difference in VO_2max and power, suggesting potential sex-based variations in neuromuscular endurance and knee stability. While no other anthropometric variables differed significantly between genders, the discrepancy in cardiorespiratory fitness levels indicates a potential disparity in endurance-based neuromuscular control, which could influence knee biomechanics [20]. Future research should explore gender-specific intervention strategies to address these differences and further refine sex-specific injury prevention programs.

While the literature provides strong evidence supporting the role of LLMP and CRF in mitigating DKV, further research is needed to determine how training programs should be adapted for individuals with varying physical fitness levels [23,24]. Adolescent athletes with lower baseline LLMP or CRF may require progressive training strategies that emphasize gradual power and endurance development, while more advanced adolescents might benefit from sport-specific training. Additionally, factors such as age, sex, and training experience should be considered when designing interventions to ensure effectiveness and injury prevention.

Although the results of this study agree with many others in the current literature, a correlation between variables does not automatically mean causation [16,25]. Causation indicates that one event is the result of the occurrence of the other event, i.e., there is a causal relationship between the two events. The literature indicates that DKV, like most sports injuries, is complex and multifactorial, and it results not from the linear combination of isolated and predictive factors, but from the interaction among them [16]. In this sense, we need a broader approach to better understand the complex relationships between risk factors/predictors and injuries. Unmeasured factors such as prior injuries, training load, or limb dominance could influence the results and bring new insights to improve even more injury-prevention programs.

In conclusion, the results of this study emphasize the critical role of LLMP and CRF in controlling DKV. Injury-prevention programs that target lower limb power and cardiorespiratory fitness may not only reduce the risk of knee injuries but also improve overall athletic performance. Future studies should consider longitudinal analyses to assess how targeted training interventions influence knee valgus over time and whether individualized training regimens can yield optimal results for injury prevention in adolescent basketball players.

5. Study Limitations

The heterogeneity between the sexes was the primary limitation of this study, since there were almost twice as many boys as girls, which could affect the generalization of the study results.

While validated equations were employed to estimate these parameters, indirect assessments introduce potential inaccuracies that may affect the precision of the findings. Direct measurement methods, such as force plate analysis for LLMP or gas exchange analysis for CRF, would provide more accurate and individualized data but are often impractical in field-based settings due to cost and accessibility constraints. The reliance on estimation models may introduce variability, particularly in diverse populations with different biomechanical and physiological characteristics.

Additionally, the choice of a 2D analysis to a 3D analysis may have prevented the thorough impact assessment of the testing structures and the real landing behavior.

6. Conclusions

This study highlights the strong association among LLMP, CRF, and DKV in adolescent basketball athletes.

The findings suggest that targeted LLMP and CRF training programs can play a crucial role in minimizing knee valgus and reducing the risk of related injuries. Given the strong predictive value of VO_2max and LLMP for knee control, targeted training programs that focus on neuromuscular conditioning and aerobic capacity are likely to be effective for injury prevention.

Strength and conditioning coaches and physiotherapists can apply these findings by implementing targeted and accessible testing for their athletes to determine their fitness level and conduct individualized training programs for each athlete for improvement and injury prevention.

Future research should further explore individualized training approaches and assess their long-term effectiveness in improving knee mechanics and athletic performance.

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Data Availability Statement: All the data are saved in an external drive that belongs to A.S. and can be provided if needed.

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Abbreviations

The following abbreviations are used in this manuscript:

DKV	Dynamic Knee Valgus
LLMP	Lower Limb Muscle Power
CRF	Cardiorespiratory Fitness
CMJ	Countermovement Jump
20mSRT	20 m Shuttle Run Test
SLDJ	Single Leg Drop Jump
2D	Two Dimensional
FPPA	Frontal Plane Projection Angle

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Review

Sauna Exposure and Rehabilitation: An Underutilized Adjunct for Physiotherapy Practice

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Abstract

This narrative review explores sauna exposure as an emerging adjunctive intervention with potential relevance to physiotherapy practice. The physiological effects of sauna exposure are presented as related to neuromusculoskeletal performance, cardiorespiratory function, exercise recovery, and systemic health domains relevant to advanced physiotherapy care. The key benefits, owing to hyperthermia and upregulation of heat shock proteins, include thermoregulatory, cardiovascular, neuroendocrine, and cytoprotective responses that support homeostasis and adaptive stress tolerance. From a clinical perspective, frequent sauna use is linked to improved aerobic capacity and blood pressure regulation, particularly when combined with exercise. Furthermore, sauna exposure may support post-exercise and post-intervention recovery through attenuation of muscle soreness and modulation of inflammatory and hormonal responses, contributing to tissue repair and a timely return of neuromuscular function. Despite these potential benefits, substantial variability in evidence-informed dosing parameters exists, underscoring the need for appropriate patient selection and safety considerations. Despite inconsistent dosing parameters, sauna exposure represents a physiologically plausible and increasingly evidence-informed intervention that may complement established physiotherapy interventions. Further clinical research is needed to define optimal dosing, safety guidelines, and its targeted role within rehabilitation populations. Moreover, studies comparing sauna exposure to other physiotherapy thermal modalities are needed to determine efficacy. This manuscript is classified as level 5 evidence based on the Oxford Centre for Evidence-Based Medicine guidelines. Thus, no indication of the superiority of sauna over other interventions is being established.

Keywords: sauna; infrared; heat shock protein; mobility

1. Introduction

Whole-body heating modalities such as conventional sauna bathing (CSB) and infrared sauna (IFS) have gained increased attention within both the health promotion and rehabilitation fields. Although CSB has been practiced for centuries, its resurgence has been driven by a growing body of evidence suggesting its physiological effects and potential clinical applications. In short, sauna exposure induces mild hyperthermia, which is characterized by an elevation in core body temperature and activation of thermoregulatory responses. This process stimulates neuroendocrine, cardiovascular, and cytoprotective mechanisms that may enhance physiological resilience to subsequent stressors. Although

several whole-body heating approaches exist, including steam rooms and hydrotherapy, the present review focuses specifically on dry heat sauna modalities.

The term "sauna bathing" encompasses a range of passive heating interventions, with CSB being the most extensively studied. In recent years, infrared technology has gained popularity, with IFS offering comparable thermal exposure at lower ambient temperatures and reduced humidity [1]. Despite differences in heat delivery, most sauna protocols involve intermittent heating cycles, cooling or cool-down periods, and rehydration to optimize recovery and physiological adaptation [1]. Conventional sauna units are typically constructed from wood; however, modern fitness and wellness centers may utilize hybrid designs that include hard floors. Most conventional sauna units operate at temperatures between 85 °C and 90 °C as a form of dry heat with relatively low humidity, depending on the specific design and use conditions [1].

The potential health benefits of CSB use are increasingly recognized within both preventive and rehabilitative frameworks. Reported effects include reductions in perceived stress, modulation of blood pressure, anti-inflammatory and antioxidant responses, and improvements in overall cardiovascular function [2]. Sauna exposure has also been shown to influence multiple physiological systems, including the cardiovascular, neuroendocrine, and immune systems [2]. These systemic adaptations suggest that sauna bathing may serve as a valuable adjunct to physiotherapy interventions by promoting repair and recovery, enhancing circulation, and supporting general health. Furthermore, emerging evidence indicates that regular sauna use may complement established lifestyle interventions, such as exercise and cardiorespiratory conditioning, and may help mitigate systemic inflammation and risk of hypertension [2].

Another form of whole-body heat exposure that has gained traction in both clinical and community settings is IFS. Unlike CSB, which uses convection as a means of heating, IFS systems utilize infrared radiation to directly heat body tissues rather than the surrounding air [1]. As a result, these systems typically operate at lower temperatures, generally between 45 °C and 60 °C, with minimal humidity, while maintaining comparable exposure durations to CSB [1]. Modern IFS units may emit either near- or far-infrared wavelengths depending on the heating elements used. Near-infrared systems typically utilize incandescent bulbs, whereas far-infrared systems rely on ceramic or metal heating elements [1]. See Figure 1 for a comparison of CSB and IFS.

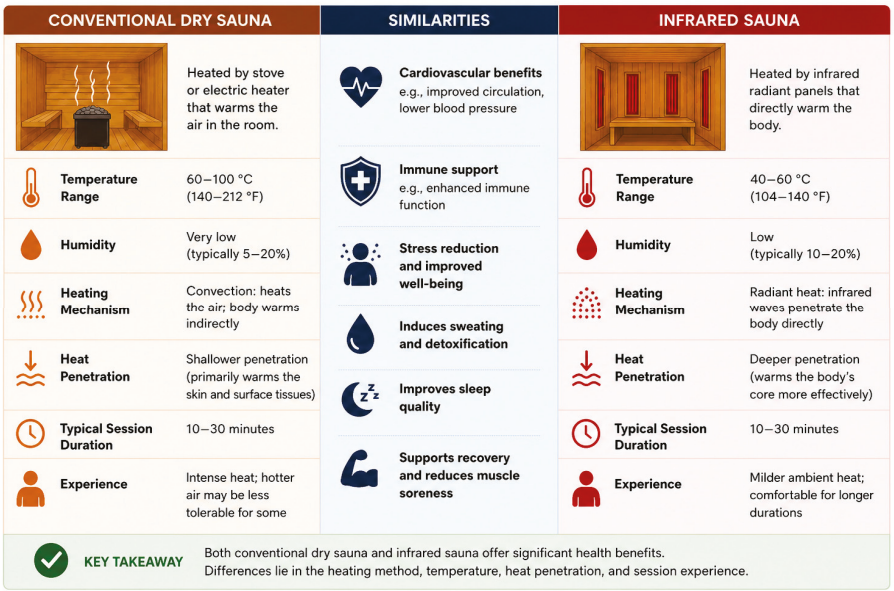

Figure 1. Sauna Comparison for Conventional and Infrared Sauna.

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While whole-body heating has long been used for relaxation and general wellness, its role within physiotherapy is potentially evolving as scientific evidence continues to expand. Existing literature suggests that sauna exposure may have meaningful applications in improving muscle performance, enhancing flexibility, facilitating heat acclimation, and promoting cardiovascular and metabolic health. Thus, the purpose of this narrative review is to examine the therapeutic potential of sauna-based interventions, with particular emphasis on their effects on musculoskeletal function, exercise performance, recovery processes, heat acclimation, and overall health outcomes. A brief overview of the cellular and molecular responses to sauna is first presented to establish the physiological adaptations underpinning its health and fitness benefits.

2. Health and Fitness Benefits

Sauna exposure has been associated with a broad range of physiological and performance-related adaptations that are increasingly relevant to physiotherapy practice. These include improvements in muscle performance (e.g., endurance and strength), flexibility, heat acclimation, aerobic capacity, and exercise recovery, as well as modulation of hormonal and molecular pathways. Many of these effects are mediated, in part, by the upregulation of heat shock proteins (HSPs), which contribute to cellular protection and adaptation under thermal stress. From a clinical perspective, these adaptations position sauna therapy as a potentially valuable adjunct to traditional physiotherapy interventions, particularly in populations requiring enhanced recovery, improved circulation, or modulation of musculoskeletal function.

2.1. Heat Shock Proteins

Shock proteins, which include both cold and HSPs, are a group of stress-responsive proteins that the body produces in response to extreme temperatures. Both cold and HSPs have a critical function in cellular protection, repair, and adaptation. HSPs are produced in response to stressors such as heat exposure and act as molecular chaperones, stabilizing protein structure, preventing misfolding, and assisting in the repair or removal of damaged proteins. The HSPs are typically activated at core body temperatures that range from 38.1–42 °C (Celsius) (100.6–107.6 Fahrenheit), with the latter range providing the most robust HSP response, albeit above safe core temperature for humans [3,4]. These functions are essential for maintaining cellular integrity and function, particularly in the context of physical stress and injury.

Sauna exposure has been shown to significantly upregulate HSP expression, particularly HSP-70 (also referred to as HSP-72), which is closely associated with skeletal muscle adaptation and recovery [5]. Increases in HSP-70 have been observed following both single and repeated sauna sessions, with the most pronounced elevations occurring after initial exposure [5]. In the aforementioned study, subjects underwent three 15-min CSB sessions with a 2 min cool-water rinse between each session for a total of 10 sessions over 3–4 weeks. The CSB temperature was reported at 90° C and rectal temperatures on average increased from 37° on average up to 38.66° after the 1st CSB session. Interestingly, after 10 sessions, the increase in rectal temperatures was slightly smaller compared with changes after the first session, suggesting heat acclimation. With regard to HSP-70, a 144–271 percent increase was reported after the first session; however, higher rectal temperatures did not necessarily correlate with greater increases in rectal temperature, as there appeared to be a level of heat acclimation. From a physiotherapy standpoint, this rapid response may be clinically advantageous in early-stage recovery, where cellular protection and repair are critical.

HSPs also contribute to reductions in oxidative stress, modulation of inflammation, and improved cellular resilience. For example, HSP-27 has been implicated in antioxidant

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activity, protection against apoptosis, and maintenance of cytoskeletal integrity [6]. These functions are particularly relevant in conditions involving muscle damage, neurodegenerative processes, and chronic inflammation. Differences in HSP responses have been observed between trained and untrained individuals, with non-athletes demonstrating greater expression of HSP-related genes following sauna exposure [6]. Thus, sauna therapy may be particularly beneficial in clinical or deconditioned populations, where baseline adaptive capacity is lower and the potential for physiological improvement is greater.

From a clinical perspective, the upregulation of HSPs provides a reasonable basis for the use of sauna therapy as an adjunct to physiotherapy. Specifically, by enhancing protein repair, reducing cellular stress, and supporting recovery processes, sauna exposure may facilitate tissue healing, improve muscle function, and enhance tolerance to rehabilitation loading.

2.2. Hormonal and Molecular Adaptations

Heat stress induced by sauna exposure has been shown to modulate a wide range of hormonal and inflammatory responses that are relevant to recovery, adaptation, and overall physiological function. Exposure to high temperatures (e.g., 90–91 °C) has been associated with acute and chronic changes in endocrine activity, including alterations in cortisol, β-endorphin, adrenocorticotropic hormone (ACTH), growth hormone (GH), testosterone, dehydroepiandrosterone (DHEA), thyroid hormones, and both pro- and anti-inflammatory cytokines. Furthermore, sauna use has been shown, via muscle biopsy, to increase anabolic upregulation and downregulate catabolism [7]. From a physiotherapy perspective, these responses may underpin many of the observed benefits of sauna exposure on recovery, tissue repair, and systemic adaptation.

Hormonal responses to sauna exposure appear to be both dose- and duration-dependent. Pilch et al. demonstrated that repeated sauna sessions (30–45 min over two weeks) significantly increased GH, ACTH, and cortisol levels in healthy women, with shorter-duration sessions (30 min at 80 °C) eliciting greater GH responses than longer sessions incorporating cooling intervals [8]. Mild reductions in thyroid hormone profiles were also observed [8]. GH in particular plays a central role in tissue repair, protein synthesis, and muscle regeneration, suggesting that sauna exposure may support recovery and adaptation following musculoskeletal injury or exercise-induced stress.

In contrast, Podstawski et al. reported reductions in cortisol levels and non-significant increases in testosterone following repeated sauna exposure in healthy men [9]. Similarly, Rissanen et al. demonstrated that sauna use, both independently and following resistance exercise, resulted in complex hormonal responses influenced by time of day and training type [10]. Notably, testosterone increased following afternoon sauna sessions, particularly when combined with resistance training, while cortisol levels consistently declined following sauna exposure [10]. These findings suggest that sauna therapy may contribute to a more favorable anabolic–catabolic balance, which is critical in optimizing recovery, reducing physiological stress, and enhancing rehabilitation outcomes and timely recovery.

Importantly, reductions in cortisol, a key stress hormone, may have direct clinical implications. Elevated cortisol levels are associated with delayed healing, increased fatigue, and impaired recovery. Therefore, sauna-induced reductions in cortisol may support stress modulation, autonomic recovery, and improved readiness for subsequent rehabilitation sessions. Additionally, observed increases in GH and testosterone, particularly when combined with exercise, suggest that sauna therapy may augment training-induced adaptations and tissue remodeling.

Catecholamine responses to heat exposure further support these findings. Laatikainen et al. reported significant increases in norepinephrine following sauna exposure, indicating

activation of the sympathetic nervous system, although no consistent changes were seen in β-endorphins or cortisol [11]. Sex-related differences in hormonal responses have also been observed, with greater ACTH responses reported in women and similar catecholamine responses between sexes [12]. These findings reinforce the importance of individualized treatment approaches, as hormonal responses to sauna may vary based on sex, baseline physiology, and conditioning level. Longer-term adaptations have also been demonstrated. Leppäluoto et al. reported reductions in cortisol and ACTH alongside increased catecholamine excretion following repeated sauna exposure over seven days [13]. Notably, a substantial increase in GH (up to 16-fold) was observed in male participants [13]. These findings suggest that cumulative sauna exposure may drive meaningful endocrine adaptations that support metabolic function, tissue repair, and overall resilience to stress, all of which are highly relevant to physiotherapy populations.

In addition to endocrine responses, sauna exposure influences inflammatory pathways that are central to recovery and tissue healing. Pilch et al. demonstrated increases in both interleukin-6 (IL-6) and interleukin-10 (IL-10) following repeated sauna exposure, with a greater increase in IL-10, suggesting an overall anti-inflammatory effect [5]. IL-10 plays a key role in resolving inflammation and promoting tissue repair, while IL-6, although traditionally viewed as pro-inflammatory, also contributes to anti-inflammatory signaling through stimulation of IL-10 release [14]. These responses are particularly relevant in physiotherapy, where modulation of inflammation is essential for optimizing recovery following injury or exercise. Additional studies further support the anti-inflammatory potential of sauna therapy. Behzadi et al. reported increases in IL-6 and interleukin-1 receptor antagonist (IL-1ra), an anti-inflammatory cytokine, following sauna exposure, without significant changes in C-reactive protein [15]. Zychowska et al. observed differential inflammatory and stress-related gene expression responses between athletes and non-athletes, with non-athletes demonstrating greater increases in IL-6, IL-10, and C-reactive protein [6]. These findings suggest that training status influences the magnitude of inflammatory responses, emphasizing the need for patient-specific dosing and progression of sauna interventions in clinical practice.

Collectively, these hormonal and inflammatory adaptations highlight the potential role of sauna therapy in facilitating recovery, enhancing tissue repair, and modulating systemic stress responses. When appropriately prescribed, sauna exposure may complement exercise-based interventions by optimizing the internal physiological environment for healing and adaptation. In fact, it is reasonable to view sauna exposure as an anti-inflammatory treatment modality given the reported increases in IL-10 and IL-1ra. These benefits are inarguably desirable in routine physiotherapy care. See Figure 2 for a summary of cytokine responses to sauna exposure.

2.3. Muscle Performance

One of the primary physiological adaptations associated with sauna use is plasma volume expansion, a critical determinant of endurance performance. Intermittent post-exercise sauna exposure has been shown to significantly enhance exercise capacity in trained middle-distance runners under both hot and temperate conditions [16]. These improvements are largely attributed to enhanced thermoregulatory efficiency and increased plasma volume, which collectively support improved cardiovascular output and oxygen delivery to working musculature. Similarly, Scoon et al. reported a 32% increase in plasma volume alongside a 1.9% improvement in 5 -km time-trial performance following three weeks of post-exercise sauna use [17]. From a physiotherapy standpoint, these findings support the integration of sauna therapy into conditioning and return-to-sport programs, particularly for endurance athletes or tactical populations. Enhancing plasma volume and

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cardiovascular efficiency may allow patients to tolerate higher training loads, progress rehabilitation more effectively, and reduce fatigue during prolonged activity.

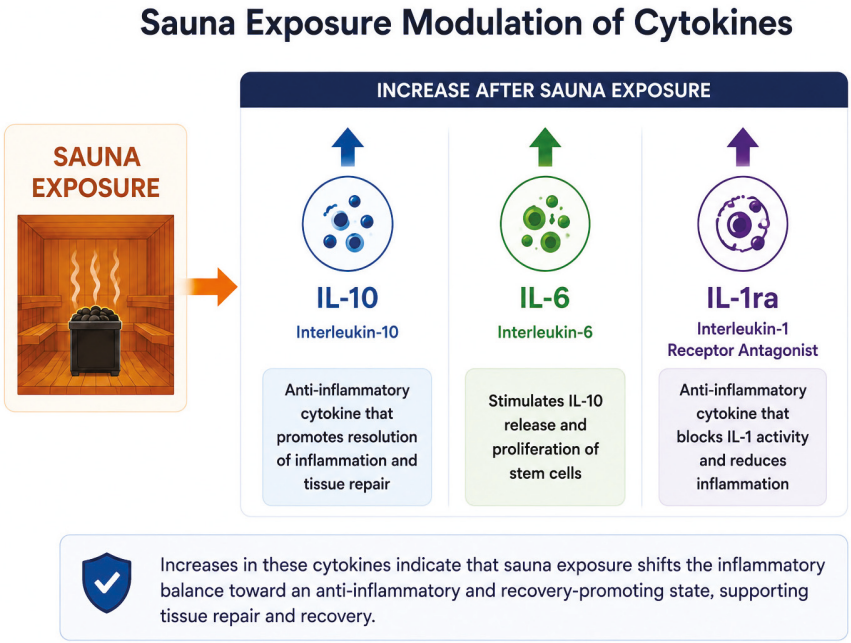

Figure 2. Sauna Exposure Modulation of Cytokines.

Heat acclimation represents an additional mechanism through which sauna exposure may improve endurance performance. Cardiovascular stability during exercise is enhanced through regular exposure to passive heat via increased plasma volume and improved heart rate variability [18]. These findings are further supported in elite populations, with improved thermophysiological responses, such as reduced core body temperature and increased perspiration rate, observed following heat acclimation protocols [19]. Clinically, these adaptations may be particularly beneficial for patients returning to activity in hot environments, such as athletes, military personnel, or firefighters, where heat tolerance is a critical component of safe performance.

Increases in muscle temperature associated with sauna exposure have also been shown to enhance muscle contractility, including improvements in electrically evoked contractions [20–23]. However, these improvements are not consistently linked to increases in maximal voluntary contraction (MVC) or peak twitch torque. Rather, thermal exposure appears to preferentially enhance rapid force production characteristics, such as rate of force development and time to peak torque [23]. This distinction is clinically meaningful, as improvements in rapid force production are critical for functional tasks such as fall prevention, gait, and explosive movements, making sauna exposure potentially beneficial in both athletic and geriatric rehabilitation contexts.

Additional evidence suggests that sauna exposure may augment strength adaptations during training. Bartolomé et al. demonstrated that incorporating resistance training in a sauna environment resulted in significant improvements in maximal isometric handgrip strength in both trained and untrained extremities. Notably, no such improvements were observed in thermoneutral conditions [24]. This finding may reflect cross-education effects and heightened neuromuscular activation, which are highly relevant in unilateral injury rehabilitation, where maintaining strength in the contralateral limb is critical. Furthermore, given that handgrip strength is a recognized predictor of morbidity and mortality across diverse patient populations [25], these improvements highlight the potential value of sauna interventions in general health screening and functional resilience.

The neuromuscular effects of sauna exposure have also been examined in controlled experimental settings. Cernych et al. demonstrated enhanced sarcolemma excitability and improved muscle contractility during recovery following sauna exposure [26]. Although transient reductions in force steadiness were observed, these did not translate into increased neuromuscular fatigability during sustained contractions. Clinically, this suggests that sauna therapy may be used to facilitate recovery without impairing subsequent performance, making it a practical adjunct following rehabilitation sessions or training.

Beyond endurance, sauna exposure may have important implications for skeletal muscle function, particularly in populations experiencing muscle loss or weakness due to chronic disease or aging. Conditions such as diabetes, cancer, renal failure, heart failure, and acquired immunodeficiency syndrome are commonly associated with reductions in muscle mass and force-generating capacity. Passive heat exposure has been proposed as a potential adjunct to mitigate these declines by promoting hypertrophy, attenuating atrophy, and enhancing strength [23]. For example, one study reported improvements in quadriceps strength as well as anabolic upregulation in patients with heart failure after 10 sessions [7]. In physiotherapy practice, this suggests a role for sauna interventions in low-load or early-stage rehabilitation, where traditional resistance training may be limited due to pain, immobilization, or medical restrictions.

At the cellular level, heat stress stimulates the upregulation of HSPs and activates anabolic signaling pathways, including the Akt/mTOR pathway, which regulates protein synthesis and cellular growth [23]. These molecular adaptations mirror the effects of resistance exercise, supporting the use of sauna therapy as a complementary modality to enhance muscular adaptation, particularly in deconditioned or clinical populations.

Overall, the evidence indicates that sauna-induced plasma volume expansion and thermoregulatory adaptations are key contributors to improved endurance performance and delayed fatigue. In addition, passive heat exposure may enhance muscle contractility and neuromuscular function through both systemic and molecular mechanisms. These findings support the consideration of sauna therapy in physiotherapy as an adjunct to improve performance, accelerate recovery, and address muscle dysfunction.

2.4. Flexibility

The effects of whole-body heating on tissue extensibility and flexibility remain less extensively studied than other physiological outcomes; however, emerging evidence suggests clinically meaningful benefits. From a physiotherapy perspective, improving flexibility and tissue extensibility is central to restoring range of motion, reducing injury risk, and optimizing movement quality.

Bucht and Donath demonstrated that repeated sauna exposure combined with movement (sauna yoga) significantly improved flexibility in older adults, as measured by standardized functional tests [27]. These findings suggest that sauna-based interventions may be particularly useful for aging populations experiencing reduced mobility, joint stiffness, or functional decline. Importantly, the feasibility of this intervention highlights its potential role in promoting adherence and engagement in therapeutic programs. In athletic populations, Bartolomé et al. reported significant improvements in hamstring flexibility following repeated sauna exposure [28]. Notably, these improvements occurred without a dedicated stretching intervention, suggesting that passive heating alone may influence tissue extensibility. This has important clinical implications, as sauna therapy could be used as a pre-treatment modality to enhance the effectiveness of stretching, manual therapy, or other mobility interventions.

Physiologically, increases in tissue temperature reduce muscle stiffness and promote relaxation through enhanced circulation and decreased viscoelastic resistance [29]. These

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mechanisms support improved tissue compliance and extensibility, which are critical for effective rehabilitation. Additionally, passive heating may facilitate reductions in muscle tone and promote post-exercise relaxation, further contributing to improvements in flexibility [29]. From a clinical application standpoint, sauna exposure may be most beneficial when used prior to therapeutic exercise or manual interventions, where increased tissue pliability can enhance treatment effectiveness. It may also serve as a recovery modality to reduce residual muscle tightness following activity. However, given the limited and heterogeneous evidence base, further research is needed to establish optimal dosing parameters and clarify its role within standardized physiotherapy protocols.

2.5. Heat Acclimation for Optimizing Performance

High-performance athletes and individuals in high-demand tactical occupations (e.g., military personnel, firefighters, and law enforcement officers) are required to maintain optimal physical performance under diverse environmental conditions, including extreme temperatures, humidity, and altitude. Heat acclimation, defined as repeated exposure to thermal stress resulting in adaptive physiological responses, is a well-established strategy to enhance performance and safety in hot environments.

In response to thermal strain, the human body triggers a sequence of integrated physiological and perceptual adaptations aimed at preserving performance and minimizing the risk of heat-related illness [30]. Among the most consistently reported adaptations are increases in plasma volume and total blood volume, which enhance cardiovascular stability and improve heat dissipation [19]. Additional adaptations include reductions in resting core temperature, decreased heart rate during submaximal exercise, and earlier onset and increased rate of perspiration, all of which contribute to improved thermoregulation and decreased physiological strain [19]. These changes ultimately support greater exercise tolerance and performance in thermally stressful environments.

To elicit these adaptations, a sufficient thermal stimulus is required, typically achieved when core body temperature increases by approximately 1.3–1.5 °C [19,31]. However, the rate and magnitude of adaptation vary considerably between individuals and are influenced by baseline fitness level, training intensity, and prior heat exposure [32]. Furthermore, the specific modality of heat exposure, whether active or passive, and whether occurring in air or water, may influence adaptation outcomes depending on the physical demands of the activity or occupation [33]. From a physiotherapy perspective, this highlights the importance of task-specific conditioning, where heat acclimation strategies should align with the environmental and physiological demands of the patient's sport or occupation.

While active heat acclimation protocols (e.g., exercise in hot environments) are commonly utilized, a systematic review and meta-analysis by Tyler et al. demonstrated that meaningful physiological adaptations can be achieved irrespective of the heating modality [30]. Consequently, passive heating strategies, such as sauna exposure, represent a practical and cost-effective alternative. Clinically, sauna use may be particularly beneficial in rehabilitation settings where active exercise capacity is limited, allowing patients to achieve thermophysiological adaptations without additional mechanical loading. This is especially relevant for injured athletes or tactical personnel progressing through return-to-duty or return-to-sport programs.

Overall, sauna exposure provides a viable method to induce heat acclimation by replicating thermal stress, promoting adaptive responses, and enhancing tolerance to heat. Its integration into physiotherapy practice may support performance optimization, injury prevention in hot environments, and safe return to occupational or athletic demands.

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2.6. Aerobic Performance and Cardiorespiratory Health

Maximal oxygen uptake (VO_2 max) is a key determinant of aerobic capacity and endurance performance, reflecting the efficiency of oxygen delivery and consumption during sustained physical activity [34]. While acute heat exposure can transiently reduce VO_2 max, repeated exposure through acclimation strategies may mitigate these effects and, in some cases, improve aerobic performance [35].

Sauna use has been increasingly investigated as a strategy to enhance aerobic fitness, particularly when incorporated following exercise. Lee et al. conducted an 8-week randomized controlled trial in a sedentary population with cardiovascular disease (CVD) risk factors and demonstrated that post-exercise sauna use significantly improved VO_2 max and reduced cholesterol levels [36]. From a physiotherapy perspective, these findings suggest that sauna therapy may serve as a valuable adjunct intervention for cardiopulmonary rehabilitation and chronic disease management, particularly in populations with limited exercise tolerance.

In contrast, findings in highly trained populations appear more nuanced. Pokora et al. reported that repeated sauna exposure did not significantly improve VO_2 max in elite cross-country skiers, likely due to pre-existing physiological adaptations from high-level training [19]. However, sauna use may still play a role in the maintenance of cardiovascular fitness during periods of reduced training, such as injury recovery or off-season conditioning.

Beyond VO_2 max, sauna exposure may positively influence other markers of aerobic performance and recovery. Sutkowy et al. demonstrated that a single sauna session reduced exercise-induced oxidative stress following aerobic activity, suggesting improved recovery at the cellular level [37]. Similarly, Scoon et al. reported enhanced endurance performance following three weeks of post-exercise sauna use, attributed to increases in plasma volume [17]. Collectively, these findings support the integration of sauna therapy into physiotherapy programs as a recovery modality to enhance training adaptations and reduce physiological stress.

Sauna exposure also has well-documented benefits for cardiovascular health. Frequent sauna bathing has been associated with reductions in hypertension, CVD, dementia, chronic kidney disease, and respiratory conditions [2]. Longitudinal evidence demonstrates that increased frequency and duration of sauna use are associated with decreased cardiovascular morbidity and mortality, with significant risk reductions observed at four sessions per week totaling approximately 45 min [38]. Amongst individuals with heart failure who have preserved ejection fraction, 10 sessions of sauna use (twice per week) have been shown to improve peak VO_2 max and the 6 min walk test [7]. Furthermore, anaerobic threshold, quadriceps strength, and diastolic function improved [7]. The 6 min walk test has also been shown to improve following sauna exposure amongst patients with chronic kidney disease [39]. Specifically, IFS exposure was implemented and compared to a control following one session, with improvements in leg blood flow, macrovascular function, and 6 min walk test, suggesting acute improvements in both vascular function and exercise capabilities. These effects are particularly relevant in physiotherapy, where cardiovascular risk reduction and health promotion are central components of care, especially in aging and clinical populations.

Additional metabolic benefits have also been reported. Regular sauna use has been associated with improved lipid profiles, including reductions in total cholesterol, low-density lipoproteins, and triglycerides, alongside increases in high-density lipoproteins [40,41]. In an intervention combining exercise and sauna exposure, participants demonstrated greater improvements in VO_2 max, systolic blood pressure, and cholesterol compared to exercise

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alone [36]. These findings reinforce the role of sauna therapy as an adjunct to exercise in physiotherapy for enhancing cardiometabolic health outcomes.

2.7. Sauna and All-Cause Mortality

Emerging evidence from large-scale longitudinal studies suggests that regular sauna bathing may be associated with reduced all-cause mortality. Laukkanen et al. followed 2315 middle-aged Finnish men over a 20-year period and found that individuals engaging in sauna bathing 4–7 times per week had an approximately 40% lower risk of all-cause mortality compared with those using the sauna once per week [42]. Similarly, Kunutsor et al. reported a 16% reduction in all-cause mortality among men who used the sauna 3–7 times per week after adjusting for established risk factors [43].

From a physiotherapy perspective, these findings highlight the broader role of sauna bathing as a health-promoting lifestyle intervention that may complement exercise therapy and contribute to long-term patient outcomes. While causality cannot be definitively established, the consistent association between frequent sauna use and reduced mortality underscores its potential value as part of a comprehensive approach to preventive care, chronic disease management, and wellness promotion.

2.8. Exercise Recovery

Sauna therapy is widely utilized as a recovery modality due to its potential to mitigate the physiological consequences of intense training and facilitate biological regeneration [44]. Within athletic populations, sauna use is commonly incorporated into recovery routines. A survey of 149 combat sport and martial arts athletes reported that sauna use was the most frequently utilized recovery modality (38%), exceeding other strategies such as hydromassage (26%), taping (20%), and manual therapies (10%) [44]. From a physiotherapy perspective, this highlights the perceived value of sauna exposure as a practical and accessible tool to support recovery and maintain training continuity.

IFS in particular has been investigated for its role in aiding neuromuscular recovery and minimizing post-exercise muscle soreness. Ahokas et al. conducted a randomized controlled trial examining the effects of IFS on muscle soreness and biomarkers of muscle damage following high-intensity resistance training in male basketball players [45]. Participants completed a standardized exercise protocol, after which the experimental group underwent a 20 min IFS session (43 $\pm$ 5 °C; ~21% humidity), while the control group completed passive recovery at room temperature. Outcome measures included subjective muscle soreness assessed via a Visual Analog Scale, as well as biochemical markers of muscle damage, including creatine kinase (CK) and myoglobin.

Both groups demonstrated increases in muscle soreness following exercise; however, the IFS group reported significantly lower absolute soreness scores compared to the passive recovery group [45]. Despite these perceptual improvements, no significant differences were observed between groups for CK or myoglobin levels [45]. These findings suggest that while IFS exposure may not directly attenuate biochemical markers of muscle damage, it may positively influence subjective recovery and perceived readiness.

Several physiological mechanisms may explain these observed effects. Passive heat exposure increases peripheral blood flow and induces vasodilation, enhancing the delivery of oxygen and nutrients to recovering tissues while facilitating the removal of metabolic byproducts. Additionally, sauna-induced hyperthermia stimulates activation of the autonomic nervous system, encouraging a shift toward parasympathetic dominance, which is associated with improved recovery, relaxation, and reduced perceived fatigue. At the cellular level, heat stress upregulates HSPs, which play a critical role in cellular repair, protein stabilization, and protection against oxidative stress. These molecular responses

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may contribute to improved tissue recovery despite the absence of measurable changes in traditional markers such as CK and myoglobin. Furthermore, increased muscle temperature reduces muscle stiffness and viscoelastic resistance, which may alleviate discomfort and improve perceived muscle readiness following exercise.

From a clinical standpoint, reductions in perceived muscle soreness are highly relevant, as they may improve patient tolerance to rehabilitation and facilitate adherence to exercise programs. In physiotherapy practice, IFS may therefore serve as a useful adjunct modality to enhance recovery, reduce discomfort, and support progression of therapeutic exercise, particularly in athletic populations or among individuals with reduced pain or load tolerance.

Although current evidence indicates that IFS does not significantly influence traditional markers of muscle damage, its effects on subjective recovery and underlying physiological processes underscore its potential value within a multimodal rehabilitation framework. Incorporating short-duration sauna sessions (e.g., ~20 min) following exercise may help optimize recovery without adding mechanical stress, making it particularly applicable in early rehabilitation phases, high-frequency training programs, or return-to-sport protocols.

Overall, sauna-based interventions, especially IFS, appear to provide meaningful benefits in perceived recovery, neuromuscular readiness, and symptom management. These effects support their integration into physiotherapy practice as a non-invasive, low-risk strategy to enhance recovery, improve patient comfort, and facilitate ongoing participation in rehabilitation and performance programs.

3. Sauna Parameters

At present, there are no standardized or condition-specific guidelines for the use of sauna therapy to augment physiotherapy treatment. Therefore, parameter selection should be informed by the current body of evidence and adapted to align with individual patient needs, treatment goals, and clinical presentation. Key considerations include frequency, duration, temperature, and progressive acclimation, all of which must be carefully prescribed to optimize therapeutic benefit while minimizing risk.

3.1. Frequency

The existing literature suggests that a frequency of approximately 3–7 CSB sessions per week is associated with the most favorable health outcomes [46]. Higher frequencies (4 or more sessions per week) have also been linked to reductions in all-cause mortality compared to lower frequencies (less than 4 sessions per week) [42]. Additionally, repeated exposure appears to promote greater physiological adaptation, including enhanced heat acclimation and plasma volume expansion [18]. From a physiotherapy perspective, session frequency should be individualized based on patient tolerance, co-morbidities, stage of rehabilitation, and overall recovery capacity. For example, higher-frequency protocols may be appropriate for healthy or athletic populations, whereas lower frequencies may be more suitable in early rehabilitation or medically complex patients. For example, a patient with insulin-dependent diabetes may experience enhanced insulin absorption and a hypoglycemic effect from sauna use lending to a need for close monitoring of blood sugar [47].

3.2. Duration

Session duration typically ranges from 10–20 min, with durations up to 30 min reserved for individuals with greater tolerance or prior heat exposure experience. Evidence indicates that sessions within the 10–20 min range are sufficient to induce meaningful

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cardiovascular and thermoregulatory responses while minimizing the risk of adverse events such as dehydration or excessive heat strain [48]. Shorter exposures (10–15 min) have also been shown to reduce muscle tension and improve circulation, particularly in individuals new to sauna use [1]. Longer post-exercise exposures (up to 30 min) have been associated with improvements in endurance performance and recovery [17]. Clinically, a progressive dosing strategy is recommended, beginning with shorter durations and gradually increasing over time based on patient response. This approach aligns with physiotherapy principles of graded exposure and minimizes unanticipated responses to heat. An important consideration for physiotherapists who do not have a sauna in their clinic is the consideration of variable temperatures in public access saunas. Saunas in recreational facilities and public settings often maintain inconsistent temperatures, which would directly influence the duration a patient can tolerate.

3.3. Temperature

Temperature selection varies depending on the type of sauna utilized. Traditional dry saunas typically operate within a range of 60–100 °C, which has been shown to produce cardiovascular and thermoregulatory benefits while remaining safe for most individuals [48]. In contrast, IFS units operate at lower temperatures, generally between 40–60 °C, while still eliciting comparable physiological responses. From a clinical standpoint, IFS may be particularly advantageous for heat-sensitive individuals, older adults, or patients with lower exercise tolerance, as it allows for therapeutic benefit at reduced thermal stress. It is important for physiotherapists to educate patients on the variability of temperatures in public access saunas and how that would influence duration. One consideration that should not be overlooked is the potential effects of extreme heat on pregnant women as the possibility of a reduction in placental blood flow and dehydration may occur [49].

3.4. Acclimation and Progression

Gradual acclimation is a critical component of safe and effective sauna therapy. Initial exposure should involve shorter durations and lower cumulative thermal stress, with progressive increases implemented over several weeks. This approach has been shown to improve thermoregulatory efficiency, increase plasma volume, and enhance heat tolerance [18]. Furthermore, gradual progression reduces the likelihood of adverse events, particularly in individuals unaccustomed to heat exposure [1].

In physiotherapy practice, this graded approach mirrors principles used in exercise prescription and ensures that sauna therapy can be safely integrated into broader rehabilitation programs. Clinicians should also consider patient-specific factors such as hydration status, cardiovascular health, medication use, and overall tolerance when prescribing sauna exposure.

Overall, sauna parameters should be individualized and progressively advanced, with careful consideration of patient tolerance and therapeutic goals. When appropriately prescribed, sauna therapy may serve as a valuable adjunct to physiotherapy interventions, supporting recovery, enhancing cardiovascular adaptations, and facilitating return to activity while minimizing additional mechanical load. Table 1 provides a recommended integration dosing strategy. It should be noted that Table 1 represents suggested programming, as consensus for specific recommendations is not clear due to variable research protocols.

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Table 1. Suggested Rehabilitation Protocols Incorporating Sauna Therapy as an Adjunct to Physiotherapy.

Rehabilitation Phase/Population	Primary Clinical Applications	Sauna Modality & Parameters	Timing Relative to Therapy	Physiotherapy Implications
Early-Phase Musculoskeletal Rehabilitation	-Facilitate tissue healing and support cellular repair -Improve circulation and tissue extensibility -Promote relaxation -Decrease inflammation	Infrared sauna: 40–60 °C 10–15 min 2–3×/week	Prior to therapeutic exercise, manual therapy or post-treatment session	Potential for more rapid recovery with reduced pain sensitivity with decreased risk of mobility loss and atrophy associated with musculoskeletal injury/surgery
Mid-Phase Rehabilitation	-Support tissue recovery -Improve neuromuscular control -Enhance hypertrophy and strengthening at lower loads -Improve flexibility and tissue extensibility	Conventional or infrared sauna Conventional: 60–80 °C Infrared: 40–60 °C 15–20 min 3–4×/week	Prior to stretching or mobilization or immediately post-exercise	Promotes a favorable environment for tissue recovery and enhanced muscle performance response as training loads are slowly increased; enhances motor control and mobility for return to higher-level functional performance
Late-Phase Rehabilitation/Return-to-Sport or Work Conditioning	-Optimize endurance and recovery -Increase neuromuscular control -Minimize post-exercise muscle soreness -Enhanced thermo-physiological adaptations	Conventional sauna: 80–90 °C 20–30 min (intermittent bouts if needed) 3–6×/week	Post-training or as standalone heat-acclimation sessions	Supports adherence to rehab program through consistent performance with reduced perceived soreness; supports return-to-sport or return-to-duty performance, particularly in hot or physically demanding environments
Chronic Disease or Deconditioned Populations	-Improve cardiovascular efficiency -Improved muscle function and rapid force production -Attenuate atrophy	Infrared sauna: 40–60 °C 10–20 min 3–5×/week	Following low- to moderate-intensity exercise	Promotes cardiovascular, muscle performance, and recovery benefits that can improve reactive responses and reduce fall risk while improving functional mobility and enhancing overall health profiles
Recovery-Focused Protocol (High Training or Rehab Load)	-Maximize recovery efficiency -Enhance cardiovascular efficiency -Improved endurance -Increased rapid force production	Infrared sauna: ~45 °C Conventional sauna: 80–100 °C ~20 min Up to 4×/week as needed	Within 0–2 h post-exercise	Helps optimize hormonal balance and molecular adaptations to maximize recovery from high training loads, ensuring readiness between sessions; heat acclimation prepares the user for return to physically demanding environments; muscular performance adaptations promote gains in explosive movement

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3.5. Sauna Versus Traditional Physiotherapy Heating Modalities

This narrative review has focused on sauna bathing as an adjunct to physiotherapy services; however, heating modalities such as hot packs (HP), deeper heat via thermal ultrasound (US), and full-body hot water immersion (HWI) are all potentially viable heating options and many factors must be considered when integrating additional modalities into routine clinical care. Some of the primary differences involve local versus systemic effects, the ability to perform activity while utilizing the modality, and cost. While this review is not intended to establish superiority or provide a robust comparison, a brief overview is necessary to establish the merits and limitations of sauna bathing.

HPs are a cost-effective modality that has a role in short-term pain relief; however, the effects are confined to the local region of the application and the user is typically sitting or lying still during usage [50]. Thermal US is also a passive heating technique that provides local hyperthermia and is purported to promote collagen synthesis, although evidence of its clinical effectiveness has been mixed [51].

Interestingly, while sauna has shown promising findings in improving muscle extensibility, hamstring flexibility is generallynot affected by pre-application of heat with either HPs or US [52,53]. With respect to muscle recovery, a 2021 systematic review with meta-analysis determined there is low-quality evidence to support the use of US versus no treatment in the reduction in post-exercise DOMS, but other studies have shown no effect when US was performed prophylactically prior to exercise, neither providing a compelling argument for utilizing US over sauna for recovery, particularly in larger muscle groups [54,55]. Neither HP nor US provides the benefit of a change in core temperature that is achieved with sauna and thus may not provide the same beneficial effects on the cardiovascular system or HSP modulation. In fact, Sontag and Kruglikov (2009) [56] determined that the induction of HSPs (HSP 72 specifically) was not achieved with the use of US below 10 MHz, a parameter which is significantly outside the therapeutic range used in physiotherapy. While saunas have demonstrated the ability to modulate inflammatory responses in humans, research into US effectiveness on cytokine levels has been most promising in animal or in vitro models. Iacoponi et al. [57] found a decrease in pro-inflammatory TNF-α, IL-1β, and IL-8, although again at an intensity well outside typically utilized therapeutic US ranges and has not been replicated in human clinical trials to this point. Furthermore, unlike US and HP applications, patients are able to be active during sauna bathing, adding to the benefits of performance optimization and heat acclimation.

Sauna and full-body hot water immersion (HWI) are both modalities that systemically induce core temperature increases, and therefore have similar effects on thermoregulatory, cardiovascular, and immune response. Additionally, users are able to be active while employing sauna and HWI, as opposed to US and HP, in which the user is generally a passive recipient. Sauna has greater long-term, large cohort studies than HWI associated with improvements in cardiovascular health and overall mortality, indicating lower risks of heart-related conditions and death, as well as all-cause mortality [58]. Safety profiles are similar between sauna and HWI, however, HWI has the unique risk of accidental drowning associated with it, as well as the potential for slipping on wet surfaces within the environment. Beyond the aforementioned discussion, the choice between these 2 modalities may then depend on personal factors. For example, the duration of treatment of HWI is approximately 45 min, while sauna treatment duration is typically a maximum of 30 min, leading to a more efficient session. Lower cost, increased ease of maintenance, and clinical space are other factors that may sway clinicians toward one particular heating modality [59].

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4. Adverse Events and Caution

Despite the growing popularity of sauna use, with an estimated annual market growth of approximately 5% [60], the potential risks and adverse events associated with its use remain less well characterized. A retrospective analysis of sauna-related injuries between 2005 and 2021 identified 209 cases requiring medical attention, with the most common causes being slips and falls, dizziness, and syncopal episodes [60]. Injuries most frequently involved the head and face, followed by the spine, shoulder, and lower extremities, and included contusions, wounds, fractures, ligament sprains, concussions, and, less commonly, burns and internal injuries [60]. Notably, slips and falls accounted for the majority of injuries (57.5%), often occurring secondary to syncope [60]. Alcohol consumption has been identified as a significant contributing factor, with over half of sauna-related fatalities involving intoxication, which increases the risk of loss of consciousness, particularly in individuals with underlying CVD [61]. Additional risk factors include orthostatic hypotension, especially in older adults, which may predispose individuals to dizziness and falls during or following heat exposure [62]. Although severe adverse events such as burns are relatively rare, with an incidence of approximately 7 per 100,000 and largely associated with prolonged exposure while unconscious [63], these findings emphasize the importance of appropriate screening and monitoring.

From a physiotherapy perspective, the safe integration of sauna therapy requires careful consideration of patient-specific risk factors, including cardiovascular status, blood sugar in those prone to hypoglycemia, hydration, medication use, and tolerance to heat exposure. Clinicians should implement precautionary strategies such as gradual heat acclimation, ensuring adequate hydration, supervising initial exposures when appropriate, and educating patients on safe behaviors (e.g., avoiding alcohol use, slow positional transitions, nutrition to prevent low blood sugar). Attention to environmental safety, including proper sauna maintenance to prevent mechanical injuries (e.g., splinters, slips), is also essential [60]. Ultimately, individualized clinical decision-making and adherence to established precautions and contraindications are critical to minimizing risk and optimizing the safe use of sauna therapy as an adjunct within physiotherapy practice.

While a definitive list of contraindications for sauna does not exist, recommendations to avoid sauna use for individuals with uncontrolled blood sugar, dehydration, severe aortic stenosis, recent myocardial infarction, and unstable angina pectoris should be recognized [61].

An important consideration for physiotherapists desiring to integrate sauna into their programming is access to a sauna. Most certainly, a sauna housed within the clinic or wellness center offers the ability to maintain temperatures and specific durations. However, patients who would be instructed to engage in sauna bathing outside of a controlled clinical setting should be educated on the inverse relationship between duration and temperature. While strict programming that emulates research protocols is always desirable, an element of flexibility with parameters is necessary to avoid both over- and underexposure. Physiotherapists prescribing saunas for their patients should recognize that there is no clear dichotomy for precautions versus contraindications and make individual decisions for their patients. Most certainly, patients with multiple co-morbidities are at a higher risk for an adverse event and may be better served with a local heating modality. Furthermore, controlled versus uncontrolled medical conditions should be considered, as a patient with uncontrolled blood sugar or hypertension, or an individual with a propensity for dehydration, should not be considered for sauna use, as the risk may outweigh the benefits.

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5. Practical Deployment

Although the benefits of CSB and IFS have been reported, there are workflow and cost considerations that may be a deterrent for use, as a commercial unit is most likely to be required for a clinical setting where higher volume use is expected. A commercial sauna unit that would seat up to four people is likely to cost anywhere from $2000.00 dollars up to $12,000.00 US dollars, excluding construction costs. A conventional sauna that uses dry heat is more expensive due to a heavier heater and build complexity, as well as the need for a dedicated 240 Volt circuit. Thus, an IFS may have a lower cost and be an easier integration as it will, in most cases, operate on a 120 Volt circuit. From an operating cost, the electrical bill for a dry sauna is greater due to increased heat generation, thus an IFS would likely use 60–75% less electricity and be a better unit from a cost perspective (https://sunhomesaunas.com/blogs/saunas/sauna-energy-consumption-and-operating-costs accessed on 20 June 2026). From a time perspective, a CSB unit would require constant heating during clinic hours, as the heating time may take 30 min or longer, whereas an IFS heats up in less than 20 min. From a space and cost perspective, smaller units would be less expensive and require less dedicated floor space.

6. Conclusions

Sauna exposure, including both CSB and IFS, has emerged as a scientifically supported adjunct intervention with broad applications across physiotherapy, health promotion, and performance enhancement. Evidence demonstrates that sauna therapy elicits multifactorial physiological adaptations such as plasma volume expansion, improved thermoregulatory efficiency, upregulation of HSPs, and modulation of endocrine and inflammatory pathways, which collectively contribute to improvements in cardiorespiratory health, muscular strength and endurance, flexibility, aerobic capacity, and exercise recovery.

From a physiotherapy perspective, these adaptations have meaningful clinical implications. Sauna exposure may enhance muscle contractility, rate of force development, and neuromuscular performance, while also facilitating improvements in tissue extensibility and mobility. Additionally, its role in heat acclimation provides a practical strategy for preparing athletes and tactical populations for performance in thermally demanding environments. Benefits are not limited to high-performance populations; improvements in VO_2 max and cardiovascular markers have also been observed in recreational and sedentary individuals, supporting its application in cardiopulmonary rehabilitation and general health optimization.

The recovery-promoting effects of sauna therapy are supported by reductions in perceived muscle soreness and improvements in neuromuscular readiness, with IFS demonstrating particular utility in post-exercise contexts. At the molecular level, favorable changes in cortisol, GH, testosterone, and cytokine activity, along with increased expression of HSPs (e.g., HSP-70 and HSP-27), further support its role in facilitating tissue repair, reducing physiological stress, and enhancing cellular resilience. Despite these benefits, the safe integration of sauna therapy into physiotherapy practice requires careful consideration of potential risks. Although adverse events are relatively infrequent, occurrences such as syncope and fall-related injuries, often influenced by factors such as dehydration, orthostatic intolerance, or alcohol use, underscore the importance of appropriate screening, patient education, and clinical monitoring. Physiotherapists should apply principles of individualized care, graded exposure, and risk stratification, particularly in populations with cardiovascular or metabolic comorbidities. While these benefits are all positive, it is likely that a core temperature of at least 38 °C is needed to achieve many of the benefits attributed to HSPs. One aspect of this narrative review that was not highlighted due to a paucity of research is a robust comparison of CSB and IFS. While we can postulate that

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the benefits of sauna bathing are dependent upon achieving elevations in core body temperature, it is best to extrapolate individual benefits based on the specific sauna modality, rather than assuming translational benefits.

In summary, sauna therapy represents a valuable adjunct to exercise-based physiotherapy when implemented thoughtfully and safely. The ability of sauna to enhance recovery, support physiological adaptation, and improve tolerance to rehabilitation and performance demands positions it as a promising tool in contemporary physiotherapy practice. Future research is warranted to establish standardized protocols and further define its role across diverse clinical populations. The current literature may help establish an evidence-informed approach to implementation; however, standardization of studies to specific patient populations is a necessity for future research. Generalization of findings should be limited to comparable populations based on age, diagnosis, activity, level and comorbidities.

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Review

Predictive Factors of Inpatient Rehabilitation Stay After Elective Hip and Knee Replacement: A Scoping Review

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Abstract

Patient stratification strategies based on digital databases and advanced information technology can predict inpatient rehabilitation outcomes and support safe hospital discharge for patients who underwent joint replacement for hip and knee osteoarthritis. The degree of continuity between surgery and rehabilitation, the perioperative process integration, and the setting where rehabilitation is provided are crucial factors to improve care effectiveness, access, minimize readmissions, and cost increase. The primary aim of this scoping review of the literature is to identify perioperative variables that are predictive of inpatient rehabilitation stay after hip and knee arthroplasty for osteoarthritis. These factors are divided by time of assessment through the perioperative pathway and surgical procedure site. The secondary aim is to explore how different data sources and facilities are linked into a patient-centered perioperative pathway. An electronic search of the literature was performed on PubMed, Embase, and Scopus. No time restrictions were applied. All primary research studies investigating predictive factors of inpatient rehabilitation stay after hip and knee osteoarthritis were included. In total, 25 studies were included in the review. Age, caregiver presence, presence of comorbidities, sex, Body Mass Index, Risk Assessment and Prediction Tool composite score, pre-operative Clinician-Reported Outcome Measures, pre-operative Patient-Reported Outcome Measures, and post-operative Barthel Index of autonomy in the Activities of Daily Living were predictive of some degree of inpatient rehabilitation stay in more than one study. The studies were fairly distributed between retrospective and prospective, with multicentric databases more spread among the latter. Data collection occurred in acute hospitals more than in specialized rehabilitation facilities. Using comprehensive models supported by electronic health records and powerful information technologies, analyzing specific inpatient rehabilitation LOS as distinguished from surgical ward rehabilitation, using institutional registries, and including specific rehabilitation factors in these registries, and promoting vocabulary and federated data sharing can strongly enhance the predictivity of models investigating rehabilitation outcomes and support appropriate discharge from inpatient rehabilitation units.

Keywords: hip arthroplasty; data management; electronic health records; inpatient rehabilitation; knee arthroplasty; osteoarthritis; perioperative care; prediction models

1. Introduction

Patient stratification strategies to optimize inpatient length of stay (LOS) after hip and knee replacement have long been advocated for clinical, organizational, and allocative purposes, pushed by the growing burden of hip and knee osteoarthritis in aging societies [1–7].

The elective nature of the procedure enables planning hospital admission, intraoperative arrangements, postoperative rehabilitation, and possibly also prehabilitation programs, promoting multidisciplinary, perioperative research to identify any possible measures to accelerate patient recovery and reduce waiting lists.

Medical progress, population aging, cost containment and sustainability issues have made the reduction in hospital LOS increasingly possible and necessary, resulting in different accelerated protocols like fast-track [8], enhanced recovery after surgery [9], short stay programs [10], and same-day discharge protocols [11], maintaining high standards of care, comparable safety [12], and non-inferior to better outcomes [13–16]. At the same time, older patients being clinically fit for discharge may prolong inpatient stay because of disadvantaged living conditions and postoperative fragmentation of care, further delaying hospital admissions to the detriment of acute patients [17,18].

After the pandemic, promising information technologies are becoming more common in joint arthroplasty, not only supporting the *reduction* in hospital LOS, but making the *prediction* of hospital LOS easier, through the analysis of large, heterogeneous datasets collected from multiple units, facilities, and professionals [19–21]. Clinicians, researchers, and administrators can track socio-behavioral data, patient visits, clinical observations, and procedures across the pathway, potentially distinguish rehabilitation-specific LOS from total hospital LOS, and link these data through the use of electronic patient identifiers. In this way, predictive factors can be more easily identified at different stages, supporting patient-centered, clinical, and organizational arrangements accordingly. Preoperative, intraoperative, and postoperative information on patient's health, function, and social resources can support an optimal rehabilitation process in advance by making clinicians and administrators able to estimate the time of recovery, the potential complications, design patient-centered pathways (e.g., prehabilitation, nutrition, anesthesia, pain medications, iron diet, physical therapy intensity, Activities of Daily Living recovery), and organize facility shifts efficiently (e.g., from surgical ward to inpatient rehabilitation, and from inpatient rehabilitation to home or primary care facilities). Moreover, medical technology suppliers can identify, develop, and market useful devices to accurately measure clinically relevant, predictive conditions (e.g., wireless wearable accelerometers to measure physical activity levels before surgery) [22,23].

After the COVID-19 pandemic, substantial financial investments are being addressed to the digitalization of healthcare and the integration of acute and post-acute, intermediate and primary care, ideally merging data into patient-centered information systems able to track the patient's pathway across different facilities and professionals [24,25]. Therefore, digital health records, artificial intelligence, and machine learning can improve the perioperative streamlining even further, provided adequate validation measures [26,27]. The goal is to preserve the healthcare system effectiveness, responsiveness, and sustainability building on proactive population health management across healthcare and community settings, both entering and leaving the hospital (e.g., allowing access to the patient's history based on integrated medical records, activating post-acute care on time, facilitating safe home discharge, reducing complications and hospital readmissions due to care fragmentation, monitoring parameters from remote areas, preventing the exacerbation of chronic conditions outside hospitals).

In this context, the degree of continuity between surgery and rehabilitation, the perioperative process integration, and the setting where rehabilitation is provided are crucial factors to improve care effectiveness and access and avoid readmissions and financial losses, both in hip and knee arthroplasty [28–30]. The more predictive variables are known to clinicians, researchers, and policy makers, the more room for patient-centered arrangements to improve postoperative outcomes and care continuity. In turn, sharing experiences

about data collection and linking across different providers is key to a) efficiently map, integrate, and plan retrospective and prospective studies, and b) provide good quality digital sets to train and run artificial intelligence, machine learning, and statistical analyses on big data.

The primary aim of this scoping review of the literature is to identify perioperative variables that are predictive of inpatient rehabilitation stay after elective hip and knee arthroplasty. Then, among the studies identified by the review, we aim to describe how different databases (monocentric and multicentric) or registries (institutional, scientific societies) are linked among different professionals, units, and facilities, considering the importance of data integration across different levels.

2. Materials and Methods

The extended version of the Arksey and O'Malley framework for scoping reviews [31] was adopted as a protocol for this research (Table 1). The protocol is also compliant with Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist (Supplementary Material S1).

Table 1. Scoping review protocol.

Identifying research question	– Primary question: what variables are predictive of inpatient rehabilitation stay after elective hip and knee arthroplasty? – Secondary question: among the resulting studies in which there is a linkage between different settings, how are data collected and linked?
Identifying relevant studies	– The PICOS framework [32] was used to define inclusion/exclusion criteria. – Population: patients undergoing joint replacement for hip and knee osteoarthritis (non-elective procedures excluded, e.g., hip replacement for femoral neck fracture). – Intervention: use of any predictive variable of inpatient rehabilitation LOS, regardless of model and method (e.g., linear regression, logistic regression, machine learning techniques). – Control/Comparison: not necessary. – Outcome: inpatient rehabilitation LOS; – Study design: primary research, either observational or interventional, prospective or retrospective, completed or protocol. No literature reviews.
Study selection	– An electronic review of the literature was performed on PubMed, Embase, and Scopus. No time restrictions were applied. No language restrictions were applied, provided that at least an English abstract with all the relevant information was clearly reported. – The following keywords were combined on each platform to find the most possible results: "hip", "knee", "joint replacement", "osteoarthritis", "predictive", "prediction", rehabilitation", "length of stay", "length of rehabilitation". – The research was performed between 5 and 7 August 2025.
Charting the data	– The variables to extract in order to answer the question(s) were identified by the researcher who conducted the review (FP). A person with experience in clinic and research administration evaluated and confirmed the variables and the research results (GB). Although not directly relevant to answer the primary and secondary questions, the study country was reported in order to help potential readers from the same origin retrieve information from similar contexts to those in which they work (e.g., for policy, healthcare organization, mandatory outcomes or reimbursement reasons); the study population size was reported for similar reasons and to give an idea of the study significance. – A pilot review on ten studies was initially performed for iterative purpose; these studies confirmed that the approach was consistent with the research question and purpose. – Qualitative information was standardized and reported by using categories of interest (e.g., data management, data source, hospital vs. inpatient rehabilitation unit stay).
Collating, summarizing, reporting	– The results are reported in Table 2 (See results). – Numerical summary analyses and qualitative thematic results (e.g., data management, data source, hospital vs. inpatient rehabilitation unit stay) are reported narratively in the results; – The variables that were predictive in more than one study ($\geq$2) were discussed in the dedicated section, along with findings related to study purpose and implications for future research, practice, and policy.

The Population, Intervention, Control/Comparison, Outcome, and Study (PICOS) framework was adopted to define the research question, inclusion, and exclusion criteria [32] (Table 1). Put in the terms of the Population, Concept and Context (PCC) framework, the population is made up of patients undergoing joint replacement for hip and knee osteoarthritis, the concept is the investigation of potentially predictive factors of inpatient rehabilitation stay, and the context is all healthcare facilities providing inpatient rehabilita-

tion stay (both as a part of general hospital LOS, as a part of postoperative surgical ward LOS, as a part of postoperative specialized unit LOS in the same facility where surgery was performed, and as a separated facility from the hospital where surgery was performed). Of the studies included in the research, the data collection methodology (prospective or retrospective) and links (professional/scientific registry, institutional registry, monocentric database, multicentric database) through any different sources and providers (general hospital, surgical ward, inpatient rehabilitation unit) were also considered.

A PRISMA flowchart was developed to describe study selection (Results, Figure 1). Two reviewers selected the studies. It was planned to use a third reviewer to resolve any discrepancies. However, no discrepancies needed to be handled, as population, intervention, outcome, and study design (or concept and context) were clear, and no intervention control or comparison was relevant to our scope. The protocol was not registered before initiating, as permitted by the Arksey and O'Malley extended framework for scoping reviews [31]. However, the full electronic research, along with data and results, is available in Supplementary Material S1 in order to ensure reproducibility and transparency.

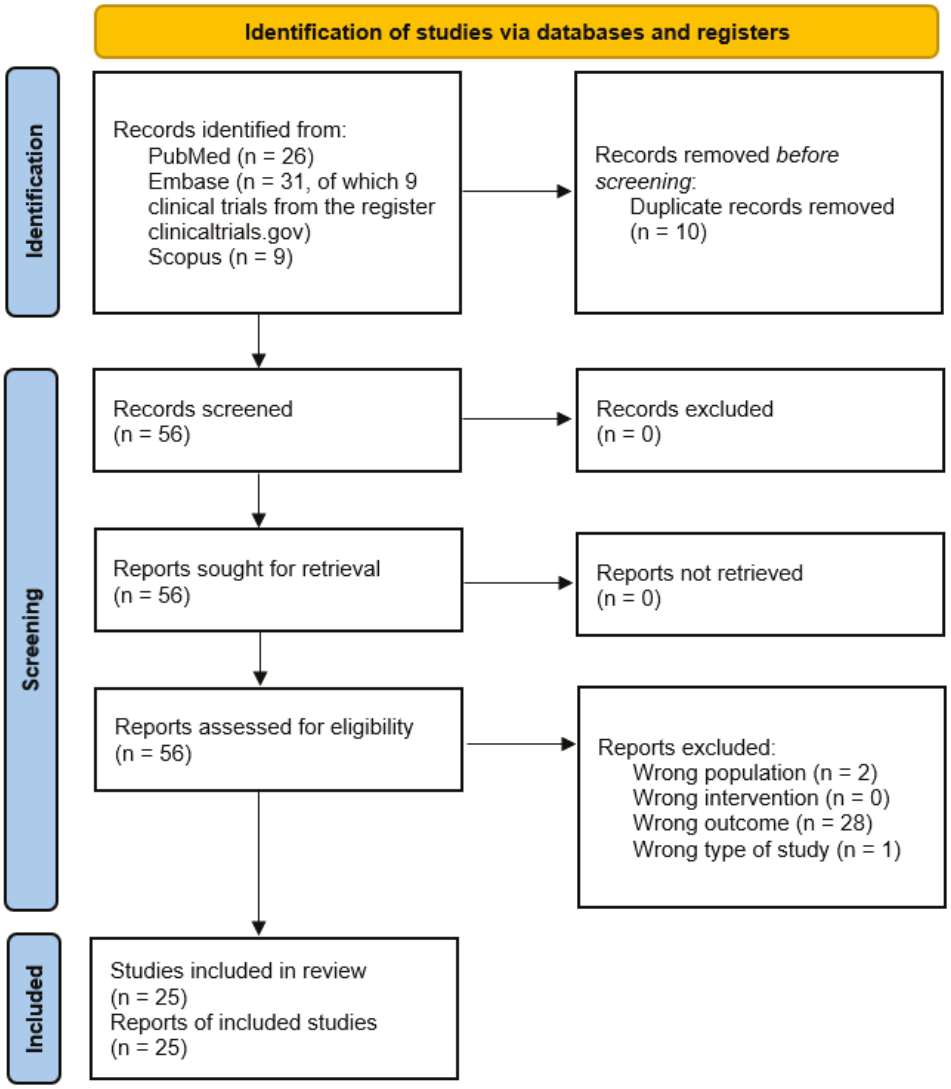

Figure 1. PRISMA 2020 flow diagram (https://www.prisma-statement.org/prisma-2020-flow-diagram accessed on 2 November 2025) for database and register search.

When considering data collection and linking results, data management categories were grouped into professional/scientific society registry, institutional registry, multicentric

database, and monocentric database. By data management, we mean the source of data repository and integration. The difference between an institutional registry and a database is the difference between institutional ongoing systems of surveillance and monitoring—see, for instance, European Reference Networks [33], the Swedish Knee Arthroplasty Register [34], or the Italian Registro Nazionale Artroprotesi [35]—and local, spontaneous initiatives from one or more hospitals and healthcare providers, no matter how extended in patient population and time, generally requiring approval from local ethical committees. The professional/scientific society registry category was also added to include data-driven, monitoring registries from the clinical records available to healthcare professionals (e.g., The American College of Surgeons National Surgical Quality Improvement Program) [36].

Data sources were grouped into hospital (if data were collected from a hospital, either including surgical and/or subsequent inpatient rehabilitation stay) and inpatient rehabilitation facility (if data were collected from an external inpatient rehabilitation facility, like a physical medicine and rehabilitation center). For example, if a study is performed in a hospital providing both surgery and subsequent inpatient rehabilitation in the same facility, it is categorized as a hospital study. Otherwise, if a study is performed into a physical medicine and rehabilitation center that also retrieves a patient's history from the previous surgical hospitalization, it is categorized as an inpatient rehabilitation facility study.

3. Results

In total, 66 studies were initially identified from 3 databases; 56 studies resulted after removing duplications, and 25 final studies resulted after applying PICOS criteria from abstract screening to full text reading (Figure 1). The results of the review are represented in Table 2.

Table 2. Final results.

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.1186/s12891-024-07878-0. (DOI)	2024.	Denmark, two centers.	Knee replacement.	200 (expected).	Pre-operative physical activity levels (as measured with a wireless medical accelerometer).	Not Applicable (N/A) (protocol).	Length of hospital stay.	Protocol for a Randomized Controlled Trial (RCT).	Multicentric database.
https://doi.org/10.3390/app142411993. (DOI)	2024.	Italy, single-center.	Total hip and knee replacement.	1678	Age, sex, American Society of Anesthesiologists score (ASA), Body Mass Index (BMI), transfusion occurred, blood-borne infection, type of anesthesia, day of surgery, post-operative pain, post-operative cognitive function, living alone/presence of a caregiver/caregiver conditions, occupation, post-operative Barthel Index (BI) of autonomy in the Activities of Daily Living (ADL) at rehabilitation admission, duration of surgery, surgical ward LOS, hemoglobin at rehabilitation admission, post-operative verticalization day, anatomical region (hip or knee), post-operative autonomy in ADL, post-operative autonomy in postural transition, post-operative walking autonomy.	Age, living with a family, occupational status, post-operative BI, duration of surgery.	Length of rehabilitation unit stay.	Observational, retrospective.	Monocentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.11622/smedj.2021142. (DOI)	2024.	Italy, single-center.	Primary total knee replacement.	1082	Age, sex, comorbidities (number and type), BMI, presence of caregiver at home, BI at rehabilitation admission, Functional Independence Measure (FIM).	Age, sex, number of comorbidities, heart disease, BMI, presence of a caregiver at home.	Length of rehabilitation unit stay.	Observational, retrospective.	Monocentric database.
https://doi.org/10.21653/tjpr.998961. (DOI)	2023.	Turkey, single-center.	Total knee arthroplasty.	41	Preoperative serum cytokine levels.	Preoperative serum cytokine levels were not predictive.	Length of rehabilitation unit stay up to five days or more.	Observational, prospective.	Monocentric database.
https://doi.org/10.1016/j.arth.2023.05.010. (DOI)	2023.	United States, singe-center.	Primary unilateral knee and hip.	17,713	Single variables: anatomical region (hip or knee), age, sex, BMI, smoking status, payer status, ASA, type of anesthesia, operational time, estimated blood loss, preoperative Hip Osteoarthritis Outcome Score–Joint Replacement (HOOS-JR), Knee Osteoarthritis Outcome Score-Joint Replacement (KOOS-JR), Patient-Reported Outcome Measures Information System (PROMIS)–mental and physical health, Veterans Rand-12 Item Score–mental and physical health, Lower Extremity Activity Scale (LEAS), pain. Multivariate analysis: Risk Assessment and Prediction Tool (RAPT) score.	RAPT score, knee, operational time.	Length of hospital stay.	Observational, retrospective.	Monocentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
NCT06005623. (NCT)	2023.	Denmark, two centers.	Total and unicompartmental knee arthroplasty.	150 (expected).	Pre-operative physical activity levels (as measured with a wireless medical accelerometer).	N/A (protocol).	Length of hospital stay.	Protocol for an RCT.	Multicentric database.
https://doi.org/10.15619/NZJP/50.1.05. (DOI)	2022.	Australia, single-center.	Total hip and knee replacement.	74.	Age, sex, BMI, anatomical region (hip or knee), ASA, type of anesthesia, post-operative physical activity levels (as measured with step count, sit-to-stand transitions, time upright).	Post-operative physical activity measures (all).	Length of hospital stay.	Observational, prospective.	Monocentric database.
NCT03227120. (NCT)	2020.	United States, single-center.	Total knee arthroplasty.	60.	Prehabilitation compared to standard care.	N/A (protocol).	Length of hospital stay.	Protocol for an RCT.	Monocentric database.
https://doi.org/10.1186/s12891-021-04211-x. (DOI)	2021.	Japan, single-center.	Simultaneous bilateral total knee arthroplasty.	191.	Age, sex, BMI, living alone, Knee Society Function Score (KSFS), ASA, pre-operative hemoglobin, albumin level, Range of Motion (ROM), Kellgren-Lawrence scale.	Age, pre-operative hemoglobin.	Length of hospital stay (three weeks or more).	Observational, retrospective.	Monocentric database.
NCT03894514. (NCT)	2021.	Spain, two-centers.	Total knee arthroplasty.	243.	Pre-operative Oxford Knee Score (OKS), International Physical Activity Questionnaire (IPAQ)–short form, Euro Quality of Life 5D (EQ-5D), Geriatric Depression Scale (GSD), pain, expectations on pain and function, strength, ROM, Timed-Up-and-Go-Test (TUG), Five times sit to stand test, One leg balance test.	N/A (protocol).	Length of rehabilitation unit stay.	Protocol for an Observational, prospective.	Multicentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.1503/cjs.003919. (DOI)	2020.	Canada, single-center.	Unilateral primary total hip or knee arthroplasty.	283.	Sat on the bedside on postoperative day 0 (POD0); stood by the bed or walked in place POD0; Walked in the room POD0; Walked in the hall POD0.	Walked in the hall at POD0. In turn, mobilization was predicted by other factors.	Length of hospital stay.	Observational, retrospective.	Multicentric database.
https://doi.org/10.3928/01477447-20190321-01. (DOI)	2019.	United States, registry.	Primary total hip arthroplasty.	43,179.	Age, sex, BMI, comorbidities (including chronic steroid use), preoperative hematocrit, smoking status, National Surgical Quality Improvement Program (NSQIP)-functional status, type of anesthesia, duration of surgery.	NSQIP functional status.	Length of hospital stay.	Observational, retrospective.	Professional/scientific society database.
https://doi.org/10.1097/rnj.0000000000000126. (DOI)	2019.	Portugal, singe-center.	Total hip arthroplasty.	40.	Age, sex, marital status, education level, number of household members, area of residence, comorbidities, pre-operative vital signs (heart rate, respiratory rate, blood pressure, body temperature), pain, clinical chemistry, BMI, body composition analysis, Mini-Mental State Examination (MMSE), GSD, FIM, Morse Fall Scale, Braden scale.	Weight of the lower limb not affected by osteoarthritis, general overweight, pain before surgery.	Length of hospital stay.	Observational, prospective.	Monocentric database.
https://doi.org/10.1007/s00264-018-3833-y. (DOI)	2018.	Canada, single-center.	Hip or knee arthroplasty.	108.	ASA, Charlson Comorbidity Index (CCI), TUG.	ASA, TUG.	Length of hospital stay.	Observational, prospective.	Monocentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.1016/j.knee.2016.09.022. (DOI)	2017.	Italy, single-center.	Unilateral total knee arthroplasty.	353.	Age, BMI, CCI, depression, previous total hip or knee arthroplasty, pre-operative hemoglobin, BI at rehabilitation admission.	Age, BI at rehabilitation admission.	Length of rehabilitation unit stay.	Observational, retrospective.	Monocentric database.
https://doi.org/10.1016/j.arth.2016.02.017. (DOI)	2016.	United States, singe-center.	Primary total hip and knee arthroplasty.	744.	Model set score 1: age, sex, pre-existing medical conditions (quantified with the CCI); Medical set score 2: Activity Measure for Post-Acute Care 6 Clicks score (24 h after surgery), age, sex, CCI.	No-one. Model 2 was more accurate than model 1, but still characterized by poor predictive performance.	Length of hospital stay (3 days or more).	Observational, retrospective.	Monocentric database.
NCT03044028. (NCT)	2016.	United States, single-center.	Unilateral total knee arthroplasty.	66 (expected)	Use of NeuroMuscular Electrical Stimulation (NMES) device before and after surgery, use of NMES device only after surgery, no use of NMES device (traditional rehabilitation protocol).	N/A (protocol).	Length of hospital stay.	Protocol for an RCT.	Monocentric database.
https://doi.org/10.1016/j.rehab.2014.02.002. (DOI)	2014.	France, 12 centers.	Total hip arthroplasty.	134.	RAPT.	RAPT.	Place of discharge after surgical ward stay. (An RAPT score >9, combined with remote patient home, was predictive of external inpatient rehabilitation LOS).	Observational, retrospective.	Multicentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.5301/hipint.5000100. (DOI)	2014.	United Kingdom, single-center.	Unilateral total hip replacement.	100.	ASA, CCI, age.	CCI, age.	Length of hospital stay.	Observational, prospective.	Monocentric database.
https://doi.org/10.1016/j.arth.2013.06.033. (DOI)	2014.	Canada, single-center.	Total knee arthroplasty.	72.	Age, BMI, comorbidity, post-operative pain, Pain Catastrophizing Scale (PCS), non-operative knee extensor isometric strength, TUG, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) -function score.	Age, comorbidity.	Length of hospital stay.	Observational, retrospective.	Monocentric database.
https://doi.org/10.1007/s10195-013-0264-9. (DOI)	2013.	Italy, single-center.	Total knee replacement.	100.	Age, sex, BMI, comorbidities, ASA, blood transfusion, postoperative analgesia protocol, physiotherapy protocol, day of surgery, surgical access.	ASA, BMI, blood transfusion, age.	Length of hospital stay.	Observational, retrospective.	Monocentric database.
28583060. (PMID)	2013.	United States, two centers.	Total hip or knee replacement.	189.	Age, sex, race, PCS, Medical Outcomes Study Social Support Scale (MOSS-SS).	Sex, race, PCS, MOSS-SS.	Length of hospital stay.	Observational, prospective.	Multicentric database.
https://doi.org/10.1007/BF03337745. (DOI)	2011.	Italy, single-center.	Total hip or knee replacement.	214.	BI at rehabilitation admission.	BI at rehabilitation admission was not predictive.	Length of rehabilitation unit stay (30 days or more).	Observational, retrospective.	Monocentric database.

Table 2. *Cont.*

Publication Identifier *	Year	Setting	Arthroplasty Procedure	Population	Intervention.		Outcome	Type of Study	Data Linkage
					Potential LOS Predictors	Actual LOS Predictors			
https://doi.org/10.1016/j.rehab.2009.01.001. (DOI)	2009.	France, single-center (single rehabilitation center, receiving patients coming from five hospitals).	Primary total knee arthroplasty in absence of complications.	244.	Age, sex, living alone, home help, previous leg arthroplasty, comorbidities, walking distance and autonomy before surgery, pain level, surgical ward LOS, IKSS (combining CROMs and PROMs), Lequesne Index.	Sex, living alone, home help, previous leg arthroplasty.	Length of rehabilitation unit stay.	Observational, retrospective.	Monocentric database.
https://doi.org/10.1302/0301-620X.91B4.21505. (DOI)	2009.	Scotland, single-center.	Unilateral primary total hip replacement.	2302.	Age, sex, BMI, operation day of the week, year of admission, knees, back and other musculoskeletal problems, comorbidities, ischemic heart disease, diabetes, pre-operative use of Non-Steroidal Anti-Inflammatory Drugs (NSAIDs), pre-operative use of Aspirin, smoking status, pre-operative hemoglobin level, consultant code, Scottish Index of Multiple Deprivation, Harris Hip Score (HHS)-combining PROMs and CROMS, Short-Form 36 (SF-36).	Age, sex, pre-operative use of NSAIDS, surgeon performing the operation, operation day of the week, year of admission, HHS–function and activity, SF36 -general health perception.	Length of hospital stay.	Observational, retrospective.	Monocentric database.

* The Digital Object Identifier (DOI) is the preferred identifier. Whether a DOI was not available, although the manuscript is accepted and published, a PubMed IDentifier (PMID) is reported. In case of studies registered on ClinicalTrials.gov, the National Clinical Trial (NCT) identifier is reported.

3.1. Predictive Factors of Inpatient Rehabilitation Stay

The results of the literature review are grouped in Table 3, representing the number of factors investigated ("Analyzed") and actually found to be predictive ("Predictive"). These factors are divided per time of assessment through the perioperative pathway ("Pre-existing patient characteristics; Pre-operative factors; Intra-operative factors; Post-operative factors") and surgical procedure site ("Knee procedures; Hip procedures; Both procedures in the same study").

Pain was considered separately from other Patient-Reported Outcome Measures (PROMs), being a core symptom of osteoarthritis. BI was also considered separately from other Clinician-Reported Outcome Measures (CROMs), because of the regulatory importance it may have in allowing or not allowing hospital discharge [37]. The resulting PROMs employed for predictivity analysis were EQ-5D, GDS, HOOS-JR, IPAQ–Short Form, KOOS-JR, LEAS, Lequesne Index, MOSS-SS, OKS, PCS, PROMIS-Mental and Physical Health, SF-36, Veterans RAND-12 Items core–Mental and Physical Health, and WOMAC-function. The resulting CROMS employed for predictivity analysis were the Braden Scale, FIM, HHS, KSFS, NSQIP–Functional Status, MMSE, and Morse Fall Scale. IKSS combines both Patient-Reported and Clinician-Reported Measures; therefore, it was included in both categories.

Among the pre-existing patient characteristics analyzed, age was the most common predictive factor (7 times predictive up to 13 times investigated), followed by caregiver presence (4 up to 6), sex (4 up to 10), occupation, race, previous leg arthroplasty, use of drugs (NSAIDS, Aspirin), heart disease (1 up to 1), CCI (1 up to 2), anatomical region affected in case of same-study hip and knee population (1 up to 3), and general presence of comorbidities (2 up to 9). Area of residence, blood-borne transmissible infections, chronic steroid use, other specific comorbidities, educational level, marital status, payer status, Scottish Index of Multiple Deprivation, and smoking status demonstrated no predictive value in the studies included.

Among the pre-operative factors analyzed, PROMs (pain excluded) were 3 times predictive up to 15 times investigated, followed by composite scores (2 up to 3), CROMs (2 up to 8), BMI (2 up to 11), hospitalization year (1 up to 1), non-operated limb weight (1 up to 1), pain catastrophizing (1 up to 2), pain (1 up to 4), clinical chemistry (1 up to 6) and ASA score (1 up to 8). Expectations on pain and function, performance, physical activity measures, prehabilitation, and vital signs demonstrated no predictive value in the studies included.

Among the intra-operative factors analyzed, the operating surgeon was 1 time predictive up to 1 time investigated, followed by day of surgery in the week, duration of surgery/operational time, and blood loss/transfusion(s) occurred (1 up to 3). Surgical access technique and type of anesthesia demonstrated no predictive value in the studies included.

Among the post-operative factors analyzed, BI was 2 times predictive up to 3 times investigated, followed by physical activity measures (1 up to 1) and verticalization day (1 up to 2). Analgesia protocol, autonomy in ADL (BI excluded), autonomy in postural transitions, clinical chemistry, cognitive function, composite score, pain, performance measures, physiotherapy protocol, PROMs, surgical ward LOS, and walking autonomy and/or distance demonstrated no predictive value in the studies included.

Table 3. Predictive factors of inpatient rehabilitation stay data chart.

Category	Analyzed	Predictive	Analyzed in Knee Procedures	Analyzed in Hip Procedures	Analyzed in Both Procedures in the Same Study
Pre-Existing Patient Characteristics.					
Age.	13	7	5	4	4
Anatomical region affected (hip or knee).	3	1			3
Area of residence.	1			1	
Blood-borne transmissible infection.	1				1
Caregiver presence (not in a composite score). *	5	3	4		1
CCI.	2	1		1	1
Chronic steroid use.	1			1	
Comorbidities (general presence).	9	2	5	4	
Comorbidities (specific: diabetes, heart disease, other musculoskeletal problems).	4	1	1	3	
Educational level.	1			1	
Marital status.	1			1	
Occupation.	1	1			1
Payer status.	1				1
Race.	1	1			1
Previous leg arthroplasty.	1	1	1		
Scottish Index of Multiple Deprivation.	1			1	
Sex.	10	4	4	3	3
Smoking status.	3			2	1
Use of drugs (NSAIDs, Aspirine).	1	1		1	
Category.	**Analyzed.**	**Predictive.**	**Analyzed in knee procedures.**	**Analyzed in hip procedures.**	**Analyzed in both procedures in the same study.**
Pre-operative factors.					

Table 3. *Cont.*

Category	Analyzed	Predictive	Analyzed in Knee Procedures	Analyzed in Hip Procedures	Analyzed in Both Procedures in the Same Study
ASA score.	8	1	2	1	5
BMI.	11	2	5	3	3
Clinical chemistry. **	6	1	3	3	
Composite scores (e.g., RAPT).	3	2		1	2
CROMs. ***	8	2	2	6	
Expectations on pain and function.	1		1		
Hospitalization year.	1	1		1	
Non-operated limb weight.	1	1		1	
Pain.	4	1	2	1	1
Pain catastrophizing.	2	1	1		1
Performance measures. ****	4		4		1
Physical activity measures.	2		2		
Prehabilitation.	2		1		1
PROMs (pain excluded). ***	15	3	7	1	7
Vital signs.	1			1	
Walking autonomy and/or distance (separated from composite scores).	1		1		
Intra-operative factors.					
Blood loss amounts/transfusion(s) performed.	3	1	1		2
Day of surgery in the week.	3	1	1	1	1
Duration of surgery/operational time.	3	1		1	2
Surgeon.	1	1		1	
Surgical access technique.	1		1		
Type of anesthesia.	4			1	3
Category.	**Analyzed.**	**Predictive.**	**Analyzed in knee procedures.**	**Analyzed in hip procedures.**	**Analyzed in both procedures in the same study.**
Post-operative factors.					

Table 3. *Cont.*

Category	Analyzed	Predictive	Analyzed in Knee Procedures	Analyzed in Hip Procedures	Analyzed in Both Procedures in the Same Study
Analgesia protocol.	1		1		
Autonomy in ADL (multiple measures, Barthel excluded).	1				1
Autonomy in postural transitions.	1				1
Barthel Index (original or modified).	3	2	1		2
Clinical chemistry. **	1				1
Cognitive function.	1				1
Composite scores (e.g., RAPT).	1		1		
CROMS. ***	1		1		
Pain.	1				1
Performance measures. ****	2		2		
Physical activity measures.	1	1			1
Physiotherapy protocol.	1		1		
PROMs (pain excluded). ***	2		2		
Surgical ward LOS.	2		1		1
Verticalization day, including moving away from bed.	2	1			2
Walking autonomy and/or distance (separated from composite scores).	2	1			2

* Including living status, alone or not, number of household members, home help. ** Including albumin, haemoglobin, haematocrit, platelets, prothrombin time, fasting glucose, creatinine and urea, serum cytokine. *** The use of CROMs and PROMs in different populations is reported for every single questionnaire administered. For example, if one study on a knee population investigates the predictive factor of three different PROM questionnaires, the table reports the use of PROMs three times in knee procedures, although they are used in the same study. **** Including TUG, strength, Five times sit to stand test, one leg balance test, walking distance, waking autonomy.

In total, 17 studies included surgery and rehabilitation in a single hospital LOS. Eight studies considered inpatient rehabilitation LOS separately, either in the same hospital (e.g., patients moved from the surgical ward to an internal specialized rehabilitation unit) or in a separate facility (e.g., physical medicine and rehabilitation center). Among the latter, two studies considered surgical ward LOS as a potential predictor for inpatient rehabilitation LOS: one in which surgical stay and specialized rehabilitation stay were part of the same inpatient consecutive pathway, in the same orthopedic hospital [38], and another in which a specialized rehabilitation center received patients from five different hospitals [39].

Coudeyre et al. [30] considered the place of discharge after surgical ward stay as a primary study outcome (home vs. physical medicine and rehabilitation center), and a composite RAPT score as a potential predictor. An RAPT score greater than 9 was found to be actually predictive of home discharge. Among the 25 patients with an RAPT score greater than 9, 5 patients were actually discharged to a physical medicine and rehabilitation center, as they lived in rural, remote areas. These patients had a significantly shorter inpatient rehabilitation LOS than other patients in the same cohort. Therefore, an RAPT score greater than 9, combined with living in an isolated location, was predictive of a shorter inpatient LOS compared with other patients who underwent rehabilitation in an external physical medicine and rehabilitation center. Then, the study was eligible for inclusion.

3.2. Data Collection and Linking

In total, 14 studies were conducted retrospectively and 11 studies were conducted prospectively. In total, 20 studies were completed, and 5 were protocols. Skov et al. [22] and Skov [40] are possibly duplicates of the same study protocol, the former in the version of a clinical trial registration and the latter in the version of a peer-reviewed publication, as the only slight difference is the expected population size (150 vs. 200). In total, 21 studies were observational and 4 were interventional (randomized controlled trials, RCT).

In terms of data management and source, prospective data collection was performed seven times through a monocentric database and three times through a multicentric database, in all cases based on a hospital database. Two of these [22,40] are possibly duplicates of the same protocol. No prospective data collection was performed through an inpatient rehabilitation facility. Retrospective data collection was performed nine times through a monocentric database and three times through a multicentric database. Two of the nine retrospective studies based on a monocentric database retrieved data from a specialist inpatient rehabilitation facility [39,41]. No studies retrieved data from institutional registries. One study retrieved data from a scientific society registry [42].

More specifically, regarding the way these data were collected and linked, among the prospective studies, eight involve specific data collection that is not further detailed. One RCT protocol [43] involves electronic data collection with RedCap software. Two observational, completed studies involved multiple sources of collection and dedicated data linking (internal clinical records, administrative database, and further specific data manually collected) [44,45]. Dedicated data linking means that no pre-established platform existed to allow for routine data collection (e.g., an electronic, integrated health record system), but the dataset is created specifically for the single study and progressively populated.

Among the retrospective studies, 12 used internal data; 5 collected data from clinical records, 5 collected data from an administrative database, registry, or both, and 2 used manually linked data. One drew data from the multicenter registry of a professional society[44] and one used a single hospital's internal data without providing further details [46]. Data collection and linking are represented in Table 4.

Table 4. Data collection and linking.

Prospective Data Collection		
Data Management	**Data Source: Hospital**	**Data Source: Inpatient Rehabilitation Facility**
Professional/scientific society registry.		
Institutional registry.		
Monocentric database.	7	
Multicentric database.	4	
Retrospective data collection.		
Data management.	**Data source: hospital.**	**Data source: inpatient rehabilitation facility.**
Professional/scientific society registry.	1	
Institutional registry.		
Monocentric database.	9	2
Multicentric database.	2	

4. Discussion

Inpatient rehabilitation protocols are fairly standardized [47,48] and so can be the criteria for whether or not to authorize discharge depending on local regulation [37,39]. However, no literature reviews specifically investigate the predictive factors of inpatient rehabilitation LOS to our knowledge, despite the promising advancements of information technology. Moreover, the majority of studies resulting from this research did not distinguish between inpatient rehabilitation stay and acute or surgical stay, despite the necessity of developing specific model predictions of inpatient rehabilitation LOS [5,39].

Older age was the most frequent predictor of post-operative inpatient rehabilitation, both considered alone and associated with other perioperative factors, including pre-operative function (assessed with Clinician-Reported Outcome Measures) [42,49], performance (walking autonomy, distance, aids) [19,30], comorbidities (either in general or aggregated by CCI index) [10,37,50,51] and presence of a caregiver providing extra-hospital support [37–39]. This is in line with the literature [16,52–57] and supports the recommendation to consider age as part of a more comprehensive, pre-operative assessment, including potentially confounding factors like function and burden of care [58]. Interestingly, all the studies included here that found extra-hospital support as a predictor of postoperative LOS specifically considered inpatient rehabilitation unit LOS [37–39], while the studies that did not find such a factor predictive generally used postoperative hospital LOS [3,59]. This finding suggests increasing awareness towards the key role played by social support in rehabilitation outcomes [60].

The presence of extra-hospital, social, and household support was also recalled to hypothesize why male patients tend to have shorter LOS after hip and knee replacements in comparison to females [61–63], as having someone who cares for them at home more frequently can increase the motivation to leave the hospital [64]. Females having longer postoperative LOS is consistent with the results of this review, according to four multivariate analyses, two focusing specifically on the inpatient rehabilitation unit [37,39] and two using general hospital LOS [50,65]. Regardless of the reasons that may explain this trend, it is prudent to consider the possibility of an extended LOS when patients undergoing rehabilitation are females. If the hypothesis about having a caregiver at home less frequently

is true, taking into consideration the need for support as early as possible could improve safety and reduce inpatient stays.

Taking social factors into consideration could also have made the RAPT score more predictive [19,29] than other composite scores, including age, sex, comorbidities, and early post-operative performance [50]. The RAPT score was originally developed to predict the need for extended inpatient rehabilitation stay, combining age, sex, preoperative functional capacity with or without technical aids, social support at home, living alone, and patient's preference towards discharge destination into a single, numerical output; the higher the score, the higher the possibility of prosecuting a rehabilitation outpatient, stratifying patients into three levels of risk (high, intermediate, and low) [65].

In the two articles of this review where the RAPT score was investigated, however, it also demonstrated predictive value in terms of inpatient rehabilitation LOS. LeBrun et al. [19] found RAPT to be a strong predictor of postoperative inpatient LOS even after controlling for other relevant covariates, testing the score on almost 18,000 patients, of whom 92% were discharged home. Coudeyre et al. [30] found an RAPT score $\geq$9 to be predictor of home discharge; however, among the patients actually being clinically ready for home discharge, 20% were unable to comply with outpatient rehabilitation because of disadvantaged home arrangements, and were transferred to a physical medicine and rehabilitation unit, where they reported a shorter LOS in comparison to the inpatient rehabilitation LOS of other patients, presumably discharged here primarily because of a clinical need.

Interestingly, the possibility of using the score by modulating thresholds and patient characteristics makes the prediction adaptable to the local healthcare system needs [66,67]. The focus on key functional and social domains made the RAPT practical for routine preoperative assessment, with a good performance on predicting discharge destination in high-risk or low-risk patients; however, the predictive value seems to diminish in the case of intermediate-risk patients, losing granularity between the extremes [68–70]. Taking advantage of big data analysis, machine learning, and electronic health records, possibly combined [71], can provide more accurate predictions for more clusters of patients, intermediate risk included.

No singular PROM or CROM questionnaire resulted in predictive inpatient rehabilitation LOS in more than one study, either pre-operative or post-operative. Considering PROMs and CROMs on an aggregate level, three pre-operative PROMs (PCS; MOS-SS; SF-36-general health perception) demonstrated predictive value in two studies [50,72], and two pre-operative CROMS (HHS–function and activity; NSQIP–Functional Status) demonstrated predictive value in two studies [43,50]. All the results of this review investigated the predictive value of PROMs (either pre-operative and post-operative) along with other objective factors, including inpatient rehabilitation stay as a separate outcome from surgical ward stay [40,73]. Thanks to the possibility of integrating PROMs in routine clinical workflow [74], the use of PROMs as predictors of post-operative LOS reported good-to-fair results in large populations. For instance, pre-operative PROMs (EQ-5D-5L, EQ-Visual Analog Scale, HOOS-PS, KOOS-PS, PROMIS-Fatigue and Depression Short Forms) collected on almost 5,000 hip and knee replacements demonstrated predictive value for post-operative LOS when analyzed with machine learning and regression models, providing cues to clinicians and healthcare administrators for capacity planning, patient expectation management, and patient risk management [75]. Also, the integration of ordinary clinical workflow records and a dedicated PROM database into a patient-centered, perioperative pathway (including post-discharge follow-up at 3 months) could predict the ideal rehabilitation protocol even before the assignment of surgery based on a machine-learning, second opinion [76]. On the contrary, pre-operative PROMs (KOOS-JR, PROMIS-Mental

and Physical Health) collected on almost 3,000 knee replacements could predict extended postoperative stay, but not as effectively as the RAPT score did [77]. However, two of these studies [75,77] did not distinguish between surgical ward rehabilitation and specialist inpatient rehabilitation stay (in the same hospital or elsewhere).

In terms of predictive, pre-operative CROMs, both the questionnaires included in this review assessed patient function before surgery (HHS–function and activity; NSQIP–Functional status), both were collected from patients undergoing hip replacement, and both measured inpatient rehabilitation stay without distinguishing between the surgical ward and the specialist unit [43,50]. The introduction of prehabilitation in hip and knee elective arthroplasty is based on the hypothesis that functional improvement before surgery improves recovery outcomes [78], post-operative LOS reduction included [79,80], although the beneficial effect of prehabilitation itself in reducing postoperative LOS remains controversial [81–84]. In order to better understand the extent to which prehabilitation can reduce postoperative LOS while also improving postoperative outcomes (e.g., pain and function) [79,82], it would be important to capture whether postoperative recovery measures are limited to surgical ward rehabilitation or extended rehabilitation units, specifying the facility where inpatient rehabilitation is provided, both in primary studies and in meta analyses or systematic reviews.

Pre-operative BMI also resulted predictive of inpatient rehabilitation stay in this review. The role played by BMI in the spread of osteoarthritis is generally accepted [85] and used for planning operating lists, in combination with other factors [86]. Both the studies in which BMI demonstrated predictive value were conducted on knee arthroplasty, one considering general hospital stay [46], and one distinguishing between surgical ward and specialist rehabilitation unit 38]. The former study found that BMI $\geq$ 25 predicted 2.3 more hospitalization days, while the latter study found that BMI $\geq$ 30 predicted one fewer rehabilitation unit and overall hospitalization day (surgical ward followed by specialist unit). The other nine studies that investigated BMI in this review did not find such a variable to be predictive. These findings not only confirm the controversial relation between overweight and postoperative LOS [87–89], but possibly make it even more controversial, as being overweight had a protective value in terms of inpatient rehabilitation stay, not explainable by a concurrent extension of surgical ward stay, as this latter factor did not vary in relation to BMI [37].

BI (and subsequent modifications) is a rank-order scale that measures disability impairments to complete ADL, and as such, it is used to measure rehabilitation improvements after surgical interventions [90]. The higher the score, the more independent the patient is in completing ADL, and in turn, the more likely the patient is to return home after a hospital stay. A total score $\geq$ 75 is commonly considered enough to discharge a patient at home, and along with a 30% improvement from inpatient rehabilitation to discharge, it is used as a threshold to authorize patient discharge in orthopedic hospitals of Italy. This is a reasonable explanation of why all the studies that adopted postoperative BI as a potential predictor of inpatient rehabilitation stay are all based in the same region, and all these studies (one concerning hip and knee procedures, two concerning knee procedures only) specifically measured inpatient rehabilitation unit stay [37,38,48]. Two of them adopted inpatient rehabilitation stay in a specialist unit as a primary outcome, and found such a factor to be predictive (the higher the score, the shorter the LOS) [38,48].

Multicentric databases were more often employed in prospective studies (4 times up to 11) than in retrospective studies (2 times up to 14). *Planning* data collection from more than one facility is actually more common and easier than *retrieving* data from multiple facilities, which needs post hoc standardization procedures. Institutional registries sharing data from more facilities should facilitate data standardization and retrieval. However, no studies

resulting from this review employed such registries, including prospective studies. Only Raad et al. [42] retrieved data from the Registry of a Scientific Society, adding useful clinical information for research and quality improvement than insurance-based administrative databases [36]. Monocentric databases were fairly distributed between prospective studies (7 times up to 11) and retrospective studies (9 times up to 14). Monocentric databases should be easier to employ as long as data collection does not need the same standardization efforts that are needed among different facilities.

Only two studies, both retrospective, retrieved data from monocentric rehabilitation facilities. This may suggest an underdeveloped data infrastructure in specialist rehabilitation centers compared to acute hospitals. Shedding more light on these facilities could improve patient's health monitoring after hospital discharge, possibly using integrated (and therefore multicentric) datasets accessible by different healthcare providers (e.g., hospital surgeon, inpatient rehabilitation specialist, outpatient rehabilitation specialist, and general practitioner), researchers, healthcare administrators, and policy makers (e.g., to capture gaps in care continuity and find locally fit solutions). The role of digitalization in promoting user-friendly, integrated health records here is clear, along with the role of AI and machine learning analyses in support of patient stratification, outcome prediction, and continuity of care planning and strengthening [24], provided adequate protection measures.

This review has a number of limitations. First, the results of predictive analyses depend on the model. Second, multiple factors represented in Table 3 were predictive in only one study or a few more. Third, none of the studies included completed an external validation process, confirming the model's predictivity in another population [25]. However, we recall that the goal of this scoping review was not to provide evidence-based guidelines for developing ready-to-use prediction models in any context, nor to assess study quality and bias in support of clinical interventions. Rather, the goal was to review the existing practices in order to help healthcare professionals, researchers, and policy makers develop (or improve) specific prediction models in specific situations, having access to similar real-world studies (musculoskeletal population, facility setting, rehabilitation pathway, data management, local regulation, factors most relevant, and factors available). Any time a certain predictor in a certain context seems relevant to the needs of the reader, it is possible to read the methodological details of each study and take them into careful consideration before replying.

5. Conclusions

The idea behind real-world patient stratification for outcome prediction is that we should not seek the optimal outcome (in this case, inpatient rehabilitation LOS) for any patient, in any situation, but the realistic rehabilitation outcome for a certain type of patient, in a certain clinical, social, and organizational context, driving the most appropriate clinical and policy arrangements.

Age, caregiver presence, presence of comorbidities, sex, BMI, RAPT composite score, pre-operative CROMS, pre-operative PROMs, and post-operative Barthel Index were predictive to some degree of inpatient rehabilitation LOS in more than one study. The studies were fairly distributed between retrospective and prospective, with multicentric databases more spread among the latter. Data collection occurred in acute hospitals more than in specialized rehabilitation facilities.

- Using comprehensive models supported by electronic health records and powerful information technologies;
- Analyzing specific inpatient rehabilitation LOS as distinguished from surgical ward rehabilitation;

- Using institutional registries, and including specific rehabilitation factors in these registries;
- Promoting vocabulary standardization (including inpatient rehabilitation LOS across different countries) and federated data sharing;
  The above can strongly enhance the predictivity of models investigating rehabilitation outcomes and support earlier discharge from acute wards when appropriate.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app152211957/s1, File S1: Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) Checklist.

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Abbreviations

The following abbreviations are used in this manuscript:

ADL	Activities of Daily Living
ASA	American Society of Anesthesiologists
BI	Barthel Index
BMI	Body Mass Index
CCI	Charlson Comorbidity Index
CROMs	Clinician-Reported Outcome Measures
EQ-5D	EuroQol-5 Dimensions
FIM	Functional Independence Measure
GDS	Geriatric Depression Scale
HHS	Harris Hip Score
HOOS-JR	Hip dysfunction and Osteoarthritis Outcome Score–Joint Replacement
IKSS	International Knee Society Score
IPAQ	International Physical Activity Questionnaire
KOOS-JR	Knee dysfunction and Osteoarthritis Outcome Score–Joint Replacement
KSS	Knee Society Score
LEAS	Lower Extremity Activity Scale
LOS	Length Of Stay
MMSE	Mini-Mental State Examination
MOSS-SS	Medical Outcomes Study Social Support Scale
NICE	National Institute for health and Care Excellence

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Review

Exploring the Clinical Utility of Cardiorespiratory Optimal Point in Heart Failure Patients: Creating a New Research Gap

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Abstract: The cardiorespiratory optimal point (COP) is an emerging submaximal parameter from cardiopulmonary exercise testing (CPET) that reflects the optimal balance between cardiac workload and pulmonary ventilation. Recent studies have explored the clinical utility and prognostic value of the COP in various populations, particularly in patients with heart failure (HF). This comprehensive literature review evaluated the current evidence on the COP and its potential as an independent risk factor for cardiovascular disease and mortality. The COP has been identified as a predictor of all-cause and cardiovascular mortality, with elevated values being significantly associated with an increased risk. Studies have demonstrated that higher COP values correlate with greater mortality risk independent of traditional risk factors, with significant sex-based differences. Evidence suggests that COP values greater than 26 significantly influence mortality rates and lead to a worse prognosis in patients with HF. For example, individuals with a COP > 30 had an approximately six-fold higher mortality risk (17.1%) than those with a COP < 22, and the combination of a high COP (>30) + low VO_2max leads to a significant increase in the risks of adverse effects (30.9%). This underscores the importance of the COP in the clinical management and risk stratification of HF patients. While the COP shows promise as a valuable submaximal marker with significant prognostic implications, further research is needed to establish its superiority over other established prognostic markers and elucidate the underlying mechanisms linking the COP to health outcomes. Nonetheless, the ability of the COP to predict mortality and enhance risk stratification in diverse populations makes it a promising tool in clinical practice.

Keywords: cardiorespiratory optimal point; mortality; physical fitness; cardiovascular capacity; ventilation

1. Introduction

Cardiopulmonary exercise testing (CPET) has gained recognition as a valuable tool for assessing functional capacity based on various factors and on athletic performance. Various studies have shown that the utilization of CPET underscores the importance of identifying non-invasive prognostic markers to enhance the detection of cardiovascular risk (CVR) [1]. Previous studies have specifically highlighted the significance of key markers, including maximal oxygen consumption ($V'O_{2max}$) [2–4], the $V'E$-$V'CO_2$ slope ratio (ventilatory efficiency index) [5,6], periodic breathing [7,8], $\Delta VO_2/\Delta WR$ (work rate) [9], kinetics of oxygen consumption [10,11], circulatory power [12,13], and oxygen-uptake-efficiency slope (OUES) [14,15]. These markers provided valuable insights into patients' physiological status and overall cardiovascular health (Table 1).

Recent developments in this field have included the introduction of a novel marker known as *the cardiorespiratory optimal point* (COP) (first described by Hollmann) [16], which can be easily identified during submaximal tests (without the need to predispose patients to strenuous physical activity) [17]. The COP represents the exercise intensity that maximizes cardiorespiratory efficiency and is characterized by the lowest value of the ventilatory equivalent of oxygen ($V'E/V'O_2$) within a specific minute before reaching the first ventilatory threshold [17,18]. This marker is interpreted as the minimum number of liters of air required to extract one liter of oxygen through the bloodstream, thereby reflecting the efficiency of the respiratory response to oxygen consumption during exercise [17–20].

A lower COP implies better cardiovascular conditioning, and the subject exerts less effort to transport the same amount of oxygen, demonstrating a more efficient interaction between the heart and the lungs [17,19,20]. It is important to note that further research and scientific inquiry are necessary to better understand the implications and potential applications of the COP in CPET.

The COP is influenced by factors, such as fitness level, sex, and age, that are important in clinical practice. For instance, research has shown variations in the COP between men and women, and it may also vary across age brackets [17,18]. Understanding and identifying this marker is crucial because of its potential prognostic value [21]. Nevertheless, we acknowledge the existence of several other non-invasive prognostic markers, some of which have already been consolidated in the literature due to their predictive capacity for mortality, such as $V'O_2$, $V'E$-$V'CO_2$ slope, OUES, and others. Recently, Kroesen et al. [22] demonstrated that the COP proved to be an excellent predictor of adverse outcomes in patients with heart failure (HF), similar to the relative peak of VO_{2peak} and superior to other classic maximal, submaximal, and multicomponent variables, and can be used as an alternative to $V'O_{2peak}$.

Despite these findings, the extent to which the COP may be superior to these markers remains unknown. Additionally, there is a gap in knowledge regarding the behavior of the COP in patients with inspiratory muscle weakness, such as patients with HF. Therefore, our objective was to review studies with the highest quality of evidence regarding these topics and that evaluated and/or compared the COP with other variables acquired during CPET. Furthermore, we explore this new gap in the population with HF, in order to encourage new research on this relevant marker.

Table 1. Cut-point values for prognostic variables derived from cardiopulmonary exercise testing.

Prognostic Variable		Number of Patients	Cut-Point Values for Poor Prognostic
Peak $V'O_2$	Mancini et al. [3]	114	<14 mL/kg.min^{-1}
	Myers et al. [4]	644	<10 mL/kg.min^{-1}
	Stelken et al. [2]	181	<50% of predicted
V'E-$V'CO_2$ slope	Chua et al. [5]	173	>34
	Corra et al. [7]	600	>34
Periodic breathing	Corra et al. [6]	323	PB > 60% of time, amplitude > 14%
	Leite et al. [8]	84	More than 2 regular oscillations, amplitude > 5 L
$\Delta V'O_2/\Delta$WR	Koike et al. [9]	385	<7
$V'O_2$ kinetics in the recovery	Groote et al. [10]	153	Peak $V'O_2$ > 39% of predicted and R $V'O_2$ < 2.5
	Scrutinio et al. [11]	196	$T_{1/2}$ $V'O_2$ peak > 200 s
Circulatory power	Cohen-Solal et al. [12]	175	<3.047 mL/(kg.min^{-1}) mm Hg
	Scharf et al. [13]	154	<5.000% mm Hg
COP	Silva et al. [20]	2205	>23.3
	Laukkanen et al. [21]	3160	>24.3
	Laukkanen et al. [23]	2190	>29
	Peterman et al. [24]	3160	>24
	Ferreira et al. [25]	2190	>23.3
	Wernhart et al. [26]	2205	>26
	Ramos et al. [17]	277	Low: <26.0; Moderate: 26.0–30.7; high: >30.7
	Charitonidis et al. [27]	30	≥36

$\Delta V'O_2/\Delta$WR indicates delta oxygen-uptake/delta-work-rate slope; peak $V'O_2$, peak oxygen uptake; R $V'O_2$, the ratio between total $V'O_2$ during and after exercise; $T_{1/2}$ $V'O_2$ peak, time to reach 50% of peak oxygen uptake during recovery; V'E-$V'CO_2$ slope, the ratio of the increase in minute ventilation to the increase in carbon dioxide output expressed as a slope; and COP, cardiorespiratory optimal point.

2. Methods

Our research was conducted independently, focusing on trials published in English within the last 20 years to ensure a comprehensive body of evidence for discussion. Beginning in February 2024, two independent researchers (W.A.S. and G.C.) systematically searched multiple databases, including PubMed, Bireme, Web of Science, and Scopus. To enhance the thoroughness of our review, we also examined the reference lists of retrieved articles for additional relevant studies. Each researcher conducted an individual search, after which they compared their results to screen and select the most pertinent articles. The search strategy incorporated Boolean operators and keywords, including "cardiorespiratory optimal point" or "COP", "cardiopulmonary exercise testing" or "CPET", "submaximal exercise testing", "ventilatory efficiency" or "$V'E/V'CO_2$ slope", "oxygen uptake" or "VO_2" or "VO_2 max", "heart failure" or "congestive heart failure" or "HFrEF" or "HFpEF", and "prognostic marker" or "predictive value" or "mortality risk". However, it is necessary to emphasize that we did not significantly restrict the selection of studies given the scarcity of research involving the topic as this could have compromised our discussion.

3. Is the COP a New and Reliable Marker?

The COP is a relatively recent marker of cardiovascular risk. It was initially documented in 2012 by Ramos et al. [17] and subsequently corroborated by other studies as an additional non-invasive prognostic marker of interest in the field of cardiology [17,19–21,23,28]. Despite the limited number of publications on this topic that relate to healthy individuals, preliminary studies have indicated its potential utility as a predictive tool for assessing mortality and cardiovascular risk [16–19], especially in patients with a previous diagnosis of HF [22,25,26]. As mentioned above, one of the main advantages of the COP is that it can be measured relatively easily during submaximal exercise tests on a treadmill or stationary bicycle, as opposed to other available markers such as oxygen

consumption [21]. Recent studies have suggested that the COP may better indicate cardiovascular disease risk than other traditional markers [21,23]. In addition, research has shown that lower COP values are associated with a reduced risk of coronary artery disease, stroke, and HF [25].

The concept of the COP is important in exercise physiology [17,19,20,22,23,25,26,28]. The literature defines the COP as the highest level of interaction between the efficiencies of the cardiovascular and respiratory systems [17,19,23]. Studies have reported average values ranging from 24 to 26 in healthy individuals [17,19,24]. However, when analyzing the average values of patients with HF, an increase in these values was observed from 29 to 36 [18,22,23,25,26,29]. Previous studies have shown that higher COP values are associated with a higher risk of death (see Table 2).

Table 2. Description of mortality studies and cut-off point values of the COP.

Author, Year	Sample	Number Size	Age, Years (Mean ± SD)	VO_2	Results and Cut-Off Point Values
Ferreira Reis et al. [25]	Adult patients with HFrEF	442 (80% male)	56.2 ± 12.5	17.9 ± 6.1 mL/kg.min^{-1}	COP had the highest predictive power of all parameters analyzed in submaximal CPET, with a value ≥36 achieving a sensitivity of 100% and a specificity of 89% for the primary outcome (death and heart transplantation). Mean 29.6 ± 7.4—>36 (Worse prognostic) 20% reduction in survival at 30 months of follow-up
Ramos et al. [18]	Healthy (18%) or with chronic disease (81%)	3331	58 ± 11.1	23.9 ± 10.1 mL/kg.min^{-1}	The all-cause mortality rate increased from 1.4% for COP < 22 to 17.1% in subjects with COP > 30. That is, COP is a good predictor of all-cause mortality, as it indicates that individuals with COP > 30 exhibited approximately six times greater risk of mortality than those with COP < 22. The combination of high COP (>30) + low VO_2max showed high mortality (30.9%) and low COP (<22) + VO_2max mortality was only 0.5%. COP: 22–30 HR 2.15 [95% CI 1.15–4.03] >30—HR 3.72 [1.98–6.98]
Peterman et al. [24]	Healthy adults (46% females)	3160	44.0 ± 12.5	32.8 ± 10.5 mL/kg.min^{-1}	The cardiorespiratory optimum was significantly lower in participants identified as alive compared to those who died at follow-up (24.3 ± 4.7 and 26.0 ± 5.4, respectively). In conclusion, COP is predictive of all-cause mortality in men, regardless of traditional risk factors including VO_2. For women, however, COP is unrelated to mortality after adjusting for possible confounders. Mean 24.6 ± 4.9; Survivor 24.3 ± 4.7; Deceased 26.0 ± 5.4
Laukkanen et al. [29]	Men Participants of the Kuopio Ischaemic Heart Disease risk factor study was used for the current analysis	2.190	52.8 ± 5. 1	2427 ± 623 mL/min	In age-adjusted analysis, the HR (95% CI) per 1 SD increase in COP for SCD was 5.02 (2.85–8.85), which was attenuated to 2.51 (1.36–4.62) after further adjustment for the conventional risk factors (smoking status, history of type 2 diabetes, systolic blood pressure, total cholesterol, high-density lipoprotein-cholesterol, low-density lipoprotein cholesterol, body mass index, fasting plasma glucose, alcohol consumption, prevalent coronary heart disease, family history of coronary heart disease, use of cholesterol medication, total physical activity and socioeconomic status. Mean: 23.3 ± 4.5; COP adjusted for age: <24.6 = HR 1.30 [0.92–1.84] (p = 0.14) >24.7 = HR 2.11 [1.52–2.94] (p < 0.001) COPD adjusted for other risk factors <24.6 = HR 1.23 [0.87–1.75] (p = 0.24) >24.7 = HR 1.55 [1.10–2.19] (p < 0.001)

Table 2. *Cont.*

Author, Year	Sample	Number Size	Age, Years (Mean ± SD)	VO_2	Results and Cut-Off Point Values
Laukkanen et al. [23]	Participants of the Kuopio Ischaemic Heart Disease	2.205	52.8 ± 5.2	30.5 ± 7.9 mL/kg.min^{-1}	During a median follow-up of 28.8 years, there were 402 CHD deaths, and risk of CHD mortality increased continuously with increasing COP from 26. During the follow-up period, there were 607 CVD deaths and the risk of CVD mortality increased continuously with increasing COP from 25. A total of 1348 all-cause deaths occurred during the follow-up period, and the risk of all-cause mortality increased continuously with increasing COP from 25 onwards. all causes in dose–response modes. COP during exercise may improve long-term risk prediction for CVD mortality. Mean 23.3; COP to all-cause mortality 1 SD increase HR 3.46 [2.66–4.51] Quintile (23.97–26.30): HR 1.35 [1.12–1.61]; Quintile (>26.30) HR 1.99 [1.67–2.37]
Kroesen et al. [22]	HF patients	277	67 [58–74] Years	13.9 [11.0–17.5] mL/kg.min^{-1}	Median COP was 28.2 [24.9–32.1] and was reached at 51 ± 15% of VO_2peak. Lower age, female sex, higher body mass index, the absence of a pacemaker or the absence of chronic obstructive pulmonary disease and lower NT-pro-BNP concentrations were associated with a lower COP. Participation in cardiac rehabilitation (CR) reduced COP (−0.8, 95% confidence interval (CI): −1.3; −0.3). Low COP had a reduced risk (adjusted hazard ratio 0.53, 95%CI 0.33; 0.84) for adverse clinical outcomes as compared to high COP. The low COP group (18.0–26.0) had a 0.53 times risk (95% CI: 0.34; 0.85) of clinical outcomes compared to the high COP group (30.7–57.7). HRs of the moderate COP group (26.0–30.7) did not differ from the high COP group

Abbreviations: COP = cardiorespiratory optimal point; SD = standard deviation; $V'O_2$ = oxygen uptake; and HFrEF = heart failure with reduced ejection fraction. In brackets = minimum and maximum values.

Significantly higher COP values represent an imbalance between the cardiac and respiratory systems, directly impacting the efficiency of these mechanisms, compromising the ventilatory response during exercise, and, consequently, culminating in an increase in the $V''E$-$V'CO_2$ intercept, as well as ventilation variability, which may be associated with a higher incidence of periodic breathing [30,31].

Additionally, changes in central mechanisms, such as cardiac output (SV × HR), and peripheral mechanisms, such as peripheral extraction rate, can compromise cardiopulmonary interactions. This has been observed in patients with HF and chronic obstructive pulmonary disease [32–34]. These adaptations could lead to changes in the COP values. Kroesen et al. [22] demonstrated that the COP is associated with classic risk factors and that a cardiac rehabilitation program can significantly reduce COP values and improve the clinical prognosis of patients with HF.

Several studies have investigated differences in the COP between men and women [19,23,24]. Ramos et al. [17] analyzed COP behavior in 624 middle-aged individuals (387 men and 237 women) and observed differences between the sexes, which were mainly attributed to lower $V'O_2$ max, $V'E$, and body dimensions. Additionally, age and sex significantly predicted the COP variable based on linear regression analysis ($p < 0.001$), explaining 18% and 13% of COP variations in healthy men and women, respectively. Oyarzo-Aravena et al. [19] added that, in trained individuals, the COP also differed significantly by sex, being lower in male athletes (COP between 22 and 30; $p < 0.001$). The authors also highlighted that such differences seem to be independent of the training regime, which corroborates the previously described points [19]. We believe that other factors may also influence the COP and should be investigated, such as general health status, the type of ergometer used, and the force generation capacity of the inspiratory muscles.

Regarding the force generation capacity of inspiratory muscles, no studies have examined the relationship between inspiratory muscle weakness (maximal inspiratory

pressure [PImax] < 70 cmH_2O) [35] and the COP response in patients with HF. However, in order to broaden the perspective on the subject, we will present information derived from secondary data from our databases (not published, but carried out from the population available in the article by Ramalho et al. [36]). Our group observed this phenomenon in 256 patients with HF with preserved inspiratory muscle strength (n = 54 and COP = 24.27 ± 3.29). These patients had lower COP values than those with inspiratory muscle weakness (IMW) (IMW, n = 202; COP = 42.91 ± 9.98; and $p < 0.001$) (Figure 1). Furthermore, IMW was negatively correlated with the COP (r = −0.51; $p < 0.001$), suggesting that a decrease in PImax may increase the COP. In this cohort, we found that HF patients with IMW showed a higher mortality rate than those with preserved inspiratory muscle strength (χ^2 = 6.988 and $p = 0.03$; Figure 1). Illustrative examples of HF patients with and without IMW are shown in Figures 2 and 3. It is worth noting that HF patients with IMW experience significant changes in functional capacity, ventilation efficiency, and exercise tolerance. The differences between these two conditions, which are primarily related to the IMW component, were noteworthy.

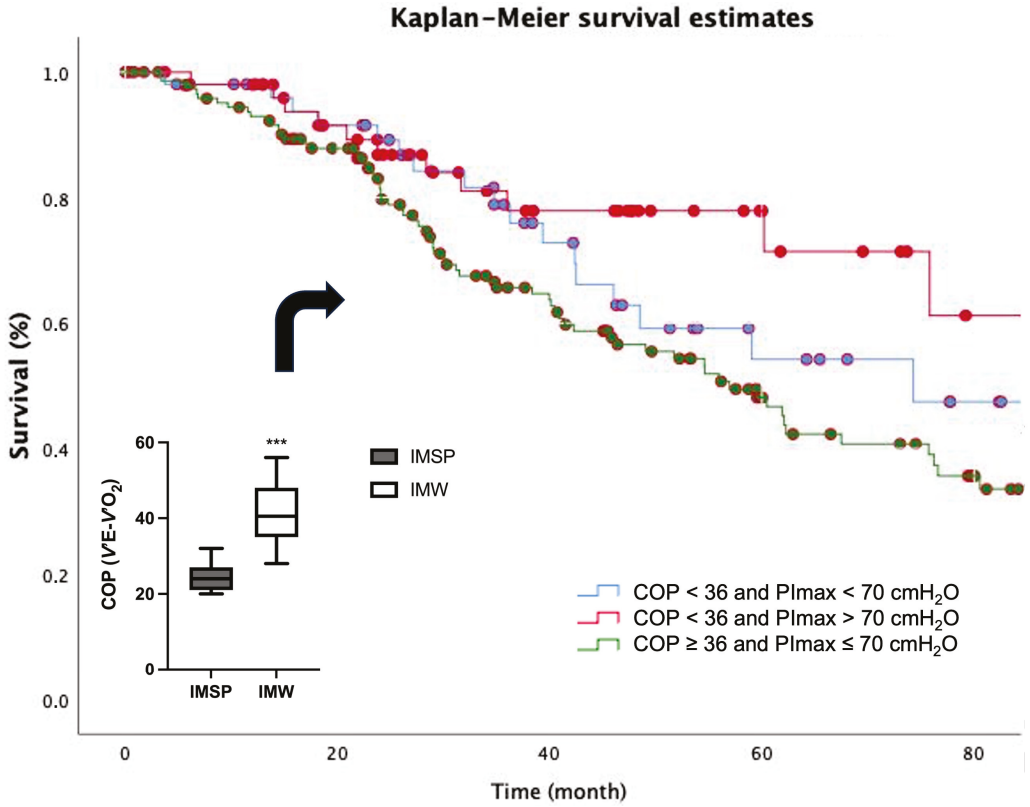

Figure 1. Kaplan–Meier survival estimates based on pulmonary reserve capacity (COP) and maximal inspiratory pressure (PImax) levels. The curves represent different combinations of COP and PImax: COP < 36 and PImax < 70 cmH_2O (blue line), COP < 36 and PImax ≥ 70 cmH_2O (red line), and COP ≥ 36 and PImax ≤ 70 cmH_2O (green line). The inset boxplot compares COP between IMSP and IMW group, showing a statistically significant difference (*** $p < 0.001$).

The presence of inspiratory muscle weakness in HF has been considered an independent predictor of mortality that is more accurate than the 6 min walk distance and left ventricular ejection fraction, as referenced previously [36]. However, the effect of the combination of the COP and IMW on mortality in patients with HF remains unknown.

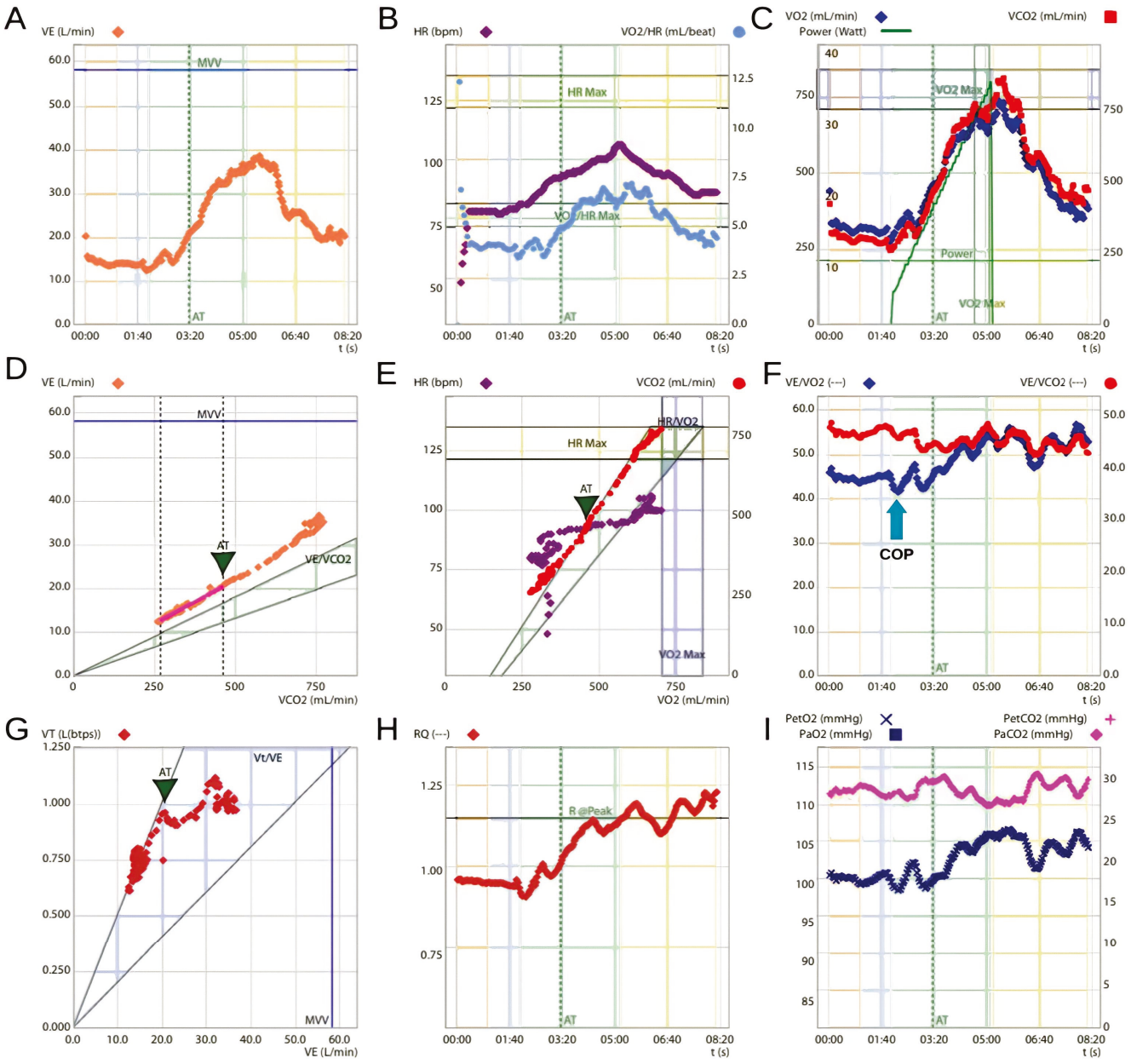

Figure 2. Illustrative examples of cardiopulmonary exercise test responses in HF patients with IMW. A multi-panel graphic display to represent metabolic (**C**,**E**), cardiovascular response (**B**,**E**), ventilatory (**A**,**D**,**F**), gas exchange (**F**,**H**,**I**), and breathing pattern (**G**) variables during an incremental CPET. In a 58-year-old heart failure patient with inspiratory muscle weakness (PImax = 40 cm H_2O), with a severely reduced ejection fraction.

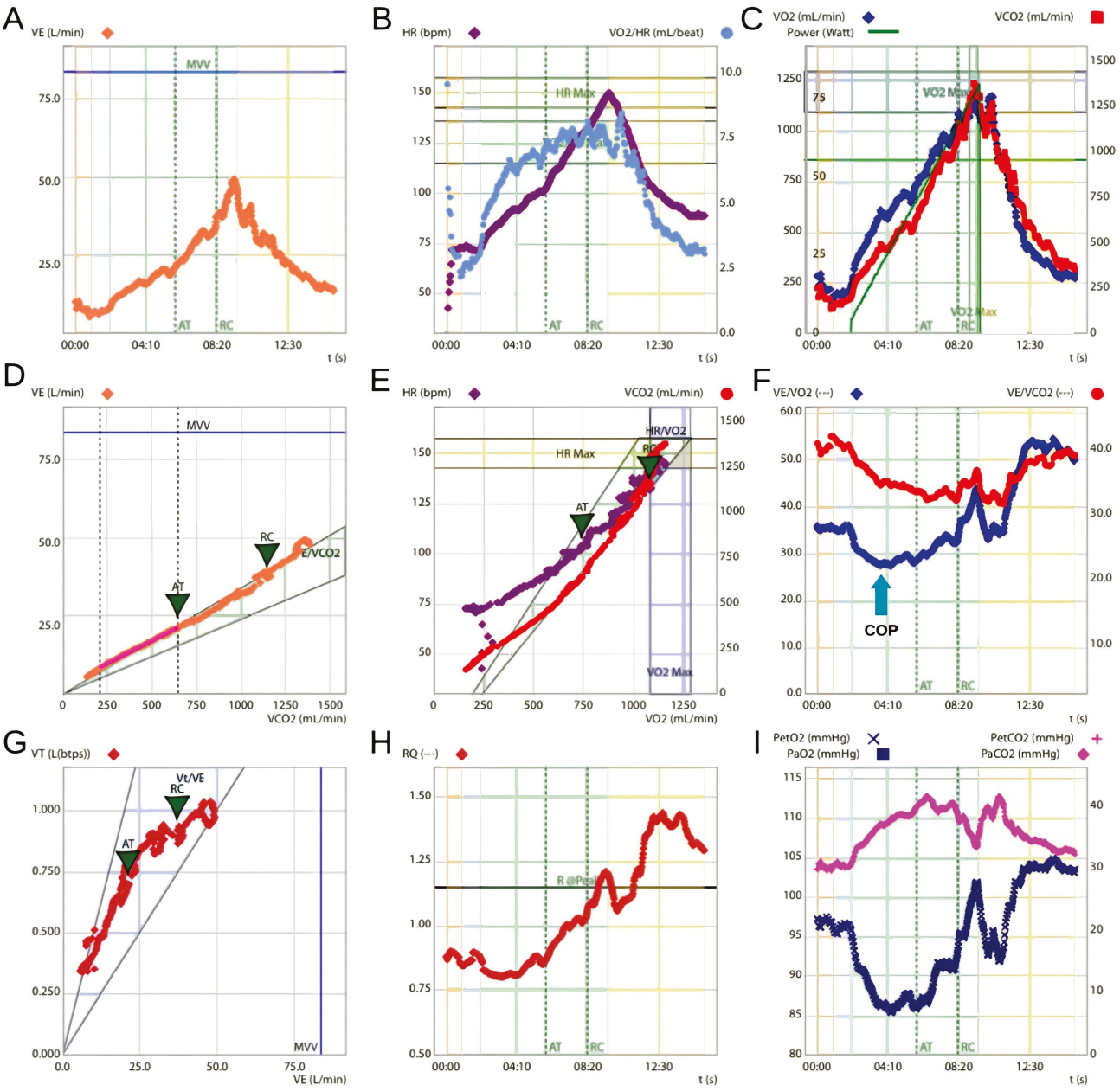

Figure 3. Illustrative examples of cardiopulmonary exercise test responses in patients with HF without IMW. A multi-panel graphic display to represent metabolic (**C**,**E**), cardiovascular response (**B**,**E**), ventilatory (**A**,**D**,**F**), gas exchange (**F**,**H**,**I**), and breathing pattern (**G**) variables during an incremental CPET. In a 56-year-old heart failure patient with inspiratory muscle strength preserved (PImax = 98 cmH_2O), with a severely reduced ejection fraction.

4. Does COP Have Independent Prognostic Value?

Several studies have evaluated the prognostic relevance of the COP for adverse cardiovascular disease outcomes and mortality [17,18,21,23–25,29]. A study of healthy individuals found that the COP was associated with fatal mortality outcomes and that high COP values were associated with a higher risk of mortality [29]. The authors demonstrated a strong and independent association between the COP and coronary disease, general cardiovascular disease, and all-cause mortality when the COP was greater than 25, following a dose–response relationship. Laukkanen et al. [23], in a prospective study with a mean follow-up of 28 years, demonstrated the existence of a linear relationship between the COP and the risk of sudden cardiac death following a dose–response relationship in middle-aged men.

The authors further stated that the COP could potentially be used to predict the established cardiovascular disease risk factors.

Consequently, these studies posited that the COP is a variable capable of detecting cardiovascular risk and mortality in both healthy individuals and those with HF, as previously noted. However, they did not compare its predictive capacity for mortality with those of other variables commonly used in the literature. This constitutes a critical consideration because, while the COP may demonstrate significant values in a univariate analysis model, its performance may differ in a multivariate logistic regression model, implying that it may not independently influence mortality. In contrast, Ramos et al. [18] have incorporated several variables into the multivariate model, such as age, smoking status, history of type 2 diabetes, systolic blood pressure, total cholesterol, high-density lipoprotein cholesterol, low-density lipoprotein cholesterol, body mass index, fasting plasma glucose, alcohol consumption, prevalent coronary heart disease, family history of coronary heart disease, use of cholesterol medication, total physical activity, and socioeconomic status, highlighting the crucial role of the COP as a predictor of mortality.

We analyzed the data collected by our group on patients with HF [36], examining the ROC curve behavior of various non-invasive prognostic variables such as the COP, $V'O_2$, PImax, $V'E$-$V'CO_2$ slope, 6 min walk test, OUES, and circulatory power (Table 3). The COP had the lowest area under the ROC curve, demonstrating a lower sensitivity than the other variables (Figure 4). The OUES significantly outperformed the reference line, exhibiting a larger area than all other variables. This appears to be a unique finding, suggesting that the OUES variable may be a better predictor of mortality than the COP. However, further studies are required to confirm these results.

Table 3. Receiver operating characteristic area under the curve (AUC).

Variables	AUC
COP	0.371
$V'O_{2p}$	0.859
PImax	0.769
$V'E$-$V'CO_2$ slope	0.386
6 MWT	0.731
OUES	0.976
Circulatory power	0.511

COP = cardiopulmonary optimal point; $V'O_{2p}$ = oxygen uptake; PImax = inspiratory muscle pressure; $V'E$-$V'CO_2$ = ventilatory response to carbon dioxide output; 6 MWT = 6 min walk test; and OUES = oxygen-uptake-efficiency slope.

Consequently, the COP may represent an essential index for the risk of mortality, demonstrating an inverse and dose-dependent relationship. The higher the COP value, the greater the risk of mortality from cardiovascular disease and all-cause mortality. Finally, the determination of the COP could also have prognostic utility, being relevant when a test of maximum effort is not feasible or desirable. However, further research is needed to confirm its prognostic relevance, with more comprehensive studies in different populations, particularly in patients with HF.

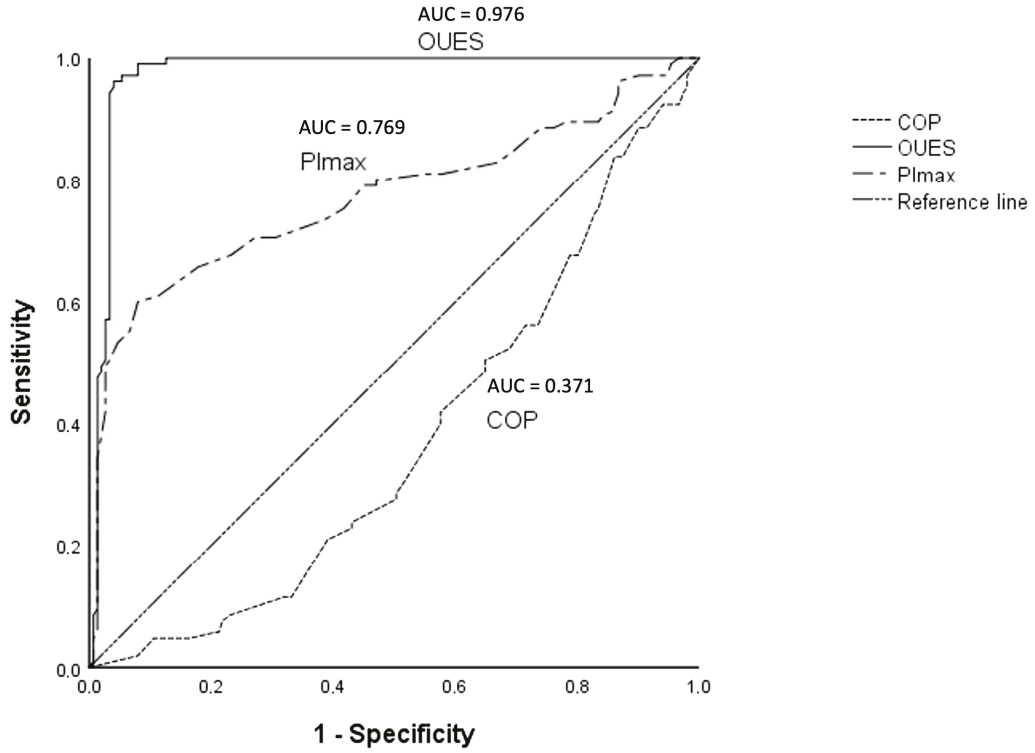

Figure 4. The figure presents ROC (receiver operating characteristic) curves comparing the prognostic capacity of different variables obtained from cardiopulmonary tests. The area under the curve (AUC) indicates the predictive accuracy of each parameter. The OUES (oxygen-uptake-efficiency slope) demonstrated the highest accuracy (AUC = 0.976), followed by PImax (maximum inspiratory pressure) with an AUC of 0.769. In contrast, COP (cardiorespiratory optimal point) exhibited lower performance (AUC = 0.371), indicating reduced sensitivity and specificity in predicting adverse clinical outcomes. The reference line represents a random prediction model (AUC = 0.5). This comparison highlights the potential of an OUES as a robust marker for clinical decision-making in HF patients.

5. Is the COP Concept Comparable to That of the Oxygen-Uptake-Efficiency Slope?

The concept of the COP is not similar to that of an OUES. These are distinct concepts in the field of cardiopulmonary physiology. On the one hand, the COP refers to the ideal balance between the cardiovascular and pulmonary systems during exercise, representing the optimal level of oxygen uptake, ventilation, and other physiological variables that maximize exercise efficiency.

In contrast, the OUES is a measurement of functional cardiopulmonary reserve derived from the submaximal values of oxygen uptake obtained during CPX [37,38]. It involves plotting oxygen uptake ($V'O_2$) against the logarithm of minute ventilation ($V'E$) at submaximal work rates and calculating the slope of the line using the following equation:

$$[V'O_2 = a \times \log V'E + b]$$

where "a" denotes the OUES value. A higher "a" value indicates a steeper slope and superior oxygen-uptake efficiency during exercise [39]. The OUES value represents the steepness of the slope, which reflects oxygen-uptake efficiency during exercise.

A general interpretation is that a higher OUES is associated with greater efficiency in oxygen uptake during exercise. This means that an individual can achieve a higher level of $V'O_2$ relative to ventilation, indicating better cardiopulmonary performance. Furthermore, the OUES has been used as an indicator of cardiopulmonary function in diverse popula-

tions [40–42], such as patients with HF [38,43,44] and coronary artery disease [45,46]. A lower OUES value has been associated with worse clinical outcomes and prognoses for patients with these conditions [47,48], whereas a higher OUES value is associated with a better prognosis and response to therapeutic interventions.

However, it is important to note that the specific interpretation of the OUES may vary depending on the clinical context, study population, and other variables assessed. In this context, it is crucial to comprehensively consider the clinical information and results of other cardiopulmonary function tests in conjunction with the OUES to understand an individual's functional capacity. We evaluated 256 patients with HF and categorized them into two groups: COP < 36 (n = 105) and COP $\geq$ 36 (n = 151). We assessed the OUES (2775 $\pm$ 574 vs. 1760 $\pm$ 664 and $p < 0.001$), $V'O_2$ (19.70 $\pm$ 5.6 vs. 16.93 $\pm$ 6.0 mL/kg.min^{-1} and $p < 0.001$), and PImax (68 $\pm$ 16 vs. 53 $\pm$ 11 cmH_2O and $p < 0.001$) [36]. These data suggest that low OUES values result in higher COP values, further supporting the notion that the COP may have a significant clinical utility as an independent prognostic marker.

6. Clinical and Prognostic Applications

The COP holds significant promise as a prognostic and clinical marker, offering non-invasive insights into cardiorespiratory efficiency that can be applied across various patient populations [19,22,49]. Its submaximal nature makes it particularly advantageous for evaluating individuals who may not tolerate maximal exercise testing, including older adults, patients with HF, and individuals with respiratory limitations [50].

As a measure that reflects the efficiency of oxygen uptake at low intensity, the COP can provide valuable information about a patient's cardiorespiratory health without imposing the physical demands associated with maximal exertion. For instance, evidence suggests that COP values exceeding 26 significantly influence mortality rates and lead to a worse prognosis in patients with HF due to a pronounced imbalance between ventilatory demand and cardiac function, following a dose-dependent relationship [24]. That is, individuals with a COP > 30 had approximately six times greater risk of mortality (17.1%) than those with a COP < 22 [18]. This characteristic has spurred growing interest in its application as a prognostic marker for assessing and monitoring patients at risk of cardiovascular and respiratory conditions. In populations undergoing rehabilitation, such as post-myocardial infarction patients or those recovering from HF, a COP reduction may demonstrate improvements in response to rehabilitation interventions. Therefore, it is important to emphasize that submaximal exercise testing is less expensive, easier to perform or repeat to observe changes in clinical status or treatment options, and less burdensome for patients compared with maximal exercise testing [51,52].

However, despite its potential, we realize that, to date, the COP should not be seen as a marker that will replace CPET (VO_{2peak}), but rather as a complementary variable, with greater applicability when it comes to clinical monitoring. Finally, longitudinal follow-up studies in different populations and across different levels of clinical severity are needed to identify the effects of different types of cardiovascular rehabilitation on COP behavior.

7. Future Studies

There is still a lack of information in the literature regarding the effects of interventions on the COP. However, some studies have shown associations between the COP and those cardiopulmonary variables that can be used to determine athletic performance [19]. Nevertheless, Silva et al. [20] did not find the same association when evaluating 198 professional soccer players according to their different positions on the field, demonstrating that the COP is a distinct variable, although complementary to the analyzed variables ($V'O_2$max and anaerobic threshold). Similarly, more recently, Charitonidis et al. [27] found no asso-

ciation between the COP and $V'O_2$max or ventilatory threshold in adolescent male and female volleyball players, corroborating the findings of Silva et al. [20].

Additionally, there is still a lack of studies addressing the influence of the type of ergometer used, type of exercise, type of protocol, body position (prone, supine, reclined, sitting, or standing), diet (high in carbohydrates versus high fat), menstrual cycle, and medications on the COP, and/or the influence of ergogenic resources, and mechanistic and physiological studies.

Finally, a clear advantage of the COP is that it does not require elevated levels of exertion during CPET, making it beneficial for individuals who are exercise intolerant or unable to perform the test. As a result, the COP serves as a valuable and applicable index, particularly for groups that require specialized expertise. In this regard, it is important to consider that individuals with panic disorder may experience compromised results during CPET because of phobic anxiety, which can consequently affect their breathing capacity [28,53,54]. Ramos et al. [28] sought to test the hypothesis that exercise-related respiratory symptoms in patients with panic disorder are not abnormalities in cardiorespiratory interactions. To this end, the authors compared the COPs of patients with panic disorder with those of healthy individuals matched by sex and age. The results showed no significant difference in the COP between the patients with panic disorder and healthy individuals (21.9 ± 0.47 versus 23.4 ± 0.65 and $p = 0.067$).

Ferreira Reis et al. [25] tested 442 individuals with HF and reduced ejection fraction to evaluate and compare the prognostic power of several parameters during submaximal CPET for risk stratification and found that the COP had the greatest prognostic power among all analyzed parameters, even being superior to $V'O_2$max. Furthermore, a COP value ≥ 36 achieved 100% sensitivity and 89% specificity for predicting death and heart transplantation outcomes. Another interesting point was that the COP maintained its high predictive power regardless of sex, age, disease etiology (ischemic or non-ischemic), baseline heart rate (sinus rhythm or atrial fibrillation), and the presence of chronic kidney disease.

In older adults, Cofre-Bolados et al. [49] found that after 18 months of detraining due to the limitations inherent to the SARS-CoV-2 pandemic, octogenarian older adults demonstrated changes in different submaximal parameters obtained from CPET when compared to the cutoff values existing in the literature, including the COP; 32% of the evaluated cases had values greater than 30, indicating a worse prognosis, according to a previously published study [25]. In summary, few studies have evaluated the COP in vulnerable populations, and there is an emerging need for new studies in special populations, particularly given that the COP is an index with prognostic potential.

Recently, Kroesen et al. [22] demonstrated that the COP is a robust and promising tool for risk stratification in patients with HF. Through detailed analyses, the COP exhibited high sensitivity (100%) and specificity (89%) in predicting critical outcomes, such as death and heart transplantation, in patients with HF and reduced ejection fraction. Moreover, the COP stood out as the parameter with the greatest prognostic power during submaximal testing, surpassing VO_2max in predictive efficacy. These findings highlight the COP's potential as a practical and reliable alternative for assessment in vulnerable populations, particularly those with exercise intolerance or an inability to perform maximal tests. Thus, the COP has emerged as a valuable tool for guiding clinical decisions in specialized settings while underscoring the need for further studies in specific populations and diverse clinical scenarios.

8. Perspectives and Limitations

This literature review focuses on the COP as an emerging prognostic marker that has garnered increasing attention in diverse populations. Recent research suggests that the COP may serve as a greater indicator of mortality risk than conventional measures, such as $V'O_2$max and maximum heart rate, because this marker considers cardiovascular and pulmonary capacity and the interplay between these systems.

With advances in technology, novel tools and devices may be developed to measure and monitor the COP more accurately and efficiently, facilitating a deeper understanding of how the COP is related to mortality in different populations. Furthermore, investigating this marker could enhance our understanding of the underlying mechanisms linking cardiorespiratory fitness and health, thereby aiding in the identification of strategies for preventing and treating chronic diseases associated with physical inactivity and sedentary lifestyles.

So far, it is worth noting that the COP does not have a scientifically robust basis; there is a lack of mechanistic studies that demonstrate the potential and originality of the COP as an independent index, despite some existing work illustrating some possible prognostic value, especially in clinically impaired individuals. For instance, individuals with cardiorespiratory complications commonly present high basal levels of ventilation at rest, which, in turn, predisposes these individuals to a high probability of demonstrating an elevated COP. In addition, it is unclear what additional clinical and prognostic information is gained by examining the COP metric because elevations in $V'E$-$V'CO_2$ at the VT1 point and $V'E$-$V'CO_2$ slope would provide obvious prognostic information that is sought when ordering a CPET. In this way, this substantial oversight is concerning because a large number of studies published by the Wasserman and Whipp group clearly detail the significance of gas exchange and ventilatory response during the part of the exercise that is being proposed in these more modern studies, such as the COP. Another point that requires attention concerns the heterogeneity of the studies reviewed, especially in terms of the subtypes of HF, sex, age group, type of ergometer used, and level of physical conditioning. Additionally, it is worth noting that the COP has poor performance in multivariate models, some of the reasons being the complexity of the data and the interaction between multiple variables, as demonstrated by a study that used different adjustment models for conventional risk factors and found important reductions in COP prediction after multivariate analyses [23,24]. For example, collinearity can lead to instability problems in the model coefficients and make it difficult to identify the real impact of the COP on predictions or relationships between variables. Furthermore, in some cases, the COP alone may not be sufficient to represent all aspects of cardiorespiratory health or disease severity. Subgroup analyses can provide a more detailed and accurate view, adjusting the interpretation of the COP according to the specific characteristics of the patients.

Finally, additional studies are required to gain a deeper understanding of the potential of the COP as an independent marker in both healthy and cardiovascular patient populations.

9. Conclusions

The COP is a dimensionless and easily obtainable variable that requires only the $V'E$ and $V'O_2$max data extracted during CPET at a reasonably low intensity before the first ventilatory threshold. The strong association between the COP and classic ergospirometric variables, such as maximum oxygen consumption (VO_2max) and ventilatory efficiency ($V'E$-$V'CO_2$ slope), indicates that its application can add value to clinical practice. Studies highlight the COP as a prognostic marker, offering a new perspective on physical fitness, chronic disease risk, and mortality. The COP can signal declining ventilatory efficiency in patients with inspiratory muscle weakness, with values above 26 being associated with

higher mortality and leading to a worse prognosis in patients with HF due to a ventilatory–cardiac imbalance. Studies are required to fill gaps in the scientific literature and provide an understanding of the potential uses of the COP, mainly in patients with HF.

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