

Review

Co-Design Approaches in Immersive Virtual Reality for Upper Limb Stroke Rehabilitation: A Narrative Review

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Abstract

Stroke-related upper-limb impairment is a leading cause of long-term disability, and immersive virtual reality (IVR) has emerged as a promising tool to enhance rehabilitation intensity and engagement. However, the effectiveness of IVR systems depends not only on technological features but also on how they are designed with end-user involvement. This narrative review examines co-design approaches used in the development of IVR systems for upper-limb stroke rehabilitation and evaluates how stakeholders contribute to system design and outcomes. A literature search was conducted in PubMed, Scopus, and IEEE Xplore, and studies involving IVR upper-limb rehabilitation with participatory, user-centered, or human-centered design were included. Thirteen studies met the inclusion criteria. Most studies demonstrated intermediate levels of participation, with seven classified as Level 4 (Collaborate), three as Level 3 (Involve), one as Level 2 (Consult), one as Level 1 (Inform), and one as Level 5 (Co-create). Common design principles included task-specific training, gamification, personalization, adaptive difficulty, meaningful activities, and clinician involvement. Despite positive findings regarding usability, motivation, and acceptability, most studies remained at feasibility or prototype stages, with limited evidence of clinical effectiveness. Recurring barriers included technological complexity, fatigue, cognitive demands, infrastructure limitations, and challenges in clinical integration. Overall, co-design is increasingly incorporated into IVR stroke rehabilitation development. However, sustained stakeholder partnership throughout the innovation lifecycle remains uncommon. Future research should prioritize longitudinal co-design processes and rigorous clinical evaluation to support the translation of IVR systems into routine rehabilitation practice.

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1. Introduction

Stroke is one of the leading causes of long-term disability worldwide, imposing substantial clinical, social, and economic burdens on survivors, families, and health systems [1]. Post-stroke disability often results from upper limb motor impairments, which are highly prevalent and profoundly affect participation in daily life [2]. These dysfunctions often persist long after a stroke, resulting in impairments of bodily functions (such as reaching,

grasping, and releasing objects) that are essential for performing activities of daily living (ADL) [3]. As a result, the overall quality of life of stroke survivors is affected [4].

Considering the substantial influence of upper limb disabilities on daily activities, understanding the mechanisms that facilitate rehabilitation, is crucial [5]. Neuroplasticity is one of the most significant mechanisms that enables the brain to reorganize after injury, making the first week to month post-stroke a critical window for rehabilitation, though the optimal timing and intensity of training remain uncertain [6]. There is evidence that the slower recovery of upper-limb motor function after stroke compared to the lower limb may be due to differences in usage frequency, neurophysiological factors, and spasticity, highlighting the need for high-intensity, repetitive interventions for upper-limb rehabilitation [7].

Since neuroplastic changes are driven by repetition and task-specific practice, effective recovery requires sustained, high-intensity training [8]. However, conventional therapy often provides insufficient repetition for meaningful, long-term motor recovery [9]. Also, stroke survivors' rehabilitation priorities evolve over time, shifting from an early focus on walking recovery to increasing importance of upper-limb function, especially after returning home. Despite these limitations, rehabilitation requires ongoing support and more collaborative, patient-centered approaches that enable individuals to actively manage their recovery [10]. In addition, client-centered Occupational Therapy (OT) enhances stroke patients' satisfaction with their occupational performance by actively involving them in therapy, even though it may not significantly improve overall daily functioning or caregiver burden [11].

In response to these limitations, emerging technologies such as virtual reality (VR) have been proposed as innovative tools to enhance the intensity, engagement, and accessibility of stroke rehabilitation [12]. VR is a computer-generated, interactive 3D environment that users can experience and interact with through devices like head-mounted displays (HMD) or screens [13]. VR systems vary in immersion levels (fully immersive, semi-immersive, and non-immersive) depending on how fully they surround and engage the user. While immersive VR (IVR) offers higher engagement and realism using HMDs such as the Meta Quest, HTC Vive, or Pico devices, often combined with controllers or motion tracking, semi- and non-immersive systems are more commonly used in clinical settings due to lower cost and easier implementation [14]. By minimizing external distractions, HMD-based IVR enables users to focus more effectively on therapeutic tasks and may better support neuroplasticity-driven motor learning than non-immersive approaches [15]. Evidence suggests that IVR can improve upper limb motor function, patient motivation, adherence to therapy, and quality of life following stroke, particularly when integrated with conventional OT or Physiotherapy (PT) interventions during the chronic phase of rehabilitation [16–20].

However, the effectiveness of VR rehabilitation is based not only on technological capability but also on design quality and alignment with end-user needs [21]. Qualitative research also shows that stroke survivors' experiences of VR rehabilitation are influenced by usability, motivation, and perceived match with personal needs [22], further underscoring the importance of design processes that consider user perspectives. Also, from OTs' perspective, it has been documented that there is a high potential for IVR in stroke rehabilitation, but it requires user-centered design, cultural adaptation, adequate training, and systemic support towards long-term implementation [23]. These principles provide a conceptual foundation for designing IVR interventions that are both therapeutically effective and engaging. However, the translation of these principles into functional systems requires participatory and co-design approaches, in which survivors, clinicians, and developers actively collaborate to ensure usability, clinical relevance, and personalization [24].

Human-Centered Design (HCD) is a design philosophy that prioritizes people's needs, abilities, and contexts throughout system development by incorporating iterative refinement and stakeholder involvement to facilitate meaningful integration within real-world environments [25]. User-Centered Design (UCD) applies these principles by emphasizing users' needs, preferences, and abilities during the development and evaluation of virtual reality rehabilitation systems [26]. Co-design represents the collaborative implementation of these approaches, actively involving end-users and other stakeholders through methods such as workshops, interviews, iterative prototyping, and generative activities [27]. These methods should be adapted to participants' cognitive, motor, and communication abilities, including those of individuals with aphasia, while addressing practical challenges related to accessibility, resource requirements, and iterative refinement [28].

In healthcare, co-design typically progresses through preparation, development, and evaluation stages. Preparation focuses on establishing relationships, clarifying expectations, and supporting meaningful patient participation. During development, stakeholders contribute through shared decision-making, iterative feedback, and integration of lived experience with clinical expertise. Evaluation involves refining the intervention based on participant input while reflecting on both the design process and its outcomes [29]. By engaging end-users throughout development, co-design seeks to improve the usability, acceptability, and clinical relevance of rehabilitation technologies.

Despite growing interest, there remains a lack of comprehensive synthesis describing how co-design has been applied specifically to IVR systems for upper-limb stroke rehabilitation and how different participatory approaches facilitate collaboration among stroke survivors, clinicians, and technology developers.

This narrative review aims to examine participatory design and co-design approaches in the development of IVR systems for upper-limb stroke rehabilitation. It specifically explores how stroke survivors, clinicians, and technology developers collaborate to co-create solutions that are usable, engaging, clinically meaningful, and aligned with established therapeutic principles. For the purposes of this review, co-design is defined broadly to include participatory design, co-creation, UCD, and HCD if end-users are actively involved in at least one stage of the system development process.

To ensure consistency during study selection and synthesis, operational definitions were established for these related concepts. Although they are frequently used interchangeably in the literature, they differ in the extent and continuity of stakeholder involvement. HCD refers to a broad design philosophy that considers human needs throughout development without requiring continuous user participation. UCD emphasizes iterative refinement informed by user feedback, with users primarily contributing through evaluation and usability testing. Participatory design involves stakeholder engagement during selected phases of development, such as requirements gathering or prototype evaluation, with meaningful but limited influence on design decisions. Co-design involves stakeholders as active contributors across multiple iterative design stages, whereas co-creation represents the highest level of participation, with stakeholders acting as equal partners throughout ideation, development, implementation, and evaluation.

2. Materials and Methods

This study employed a structured narrative review approach to synthesize the existing literature on co-design methods applied to IVR systems for upper-limb stroke rehabilitation. A PRISMA-style flow diagram [30] was used to transparently report the study selection process, without claiming full PRISMA 2020 systematic review compliance. To improve transparency and reproducibility, systematic search procedures were applied, including pre-defined eligibility criteria, database searching, duplicate removal, and structured screening

of titles, abstracts, and full texts. This methodology was selected due to the heterogeneity of study designs in this emerging interdisciplinary field, including qualitative studies, feasibility trials, technical prototypes, and pilot implementations. In contrast to systematic reviews, which are suited to narrowly defined questions and homogeneous datasets, narrative reviews allow for flexible synthesis, interpretation, and critical reflection across diverse sources, enabling integration of evidence across heterogeneous study designs, interpretive analysis, and the generation of new conceptual insights [31–33]. No review protocol was registered prior to conducting this narrative review.

A structured search was conducted in PubMed, Scopus, and IEEE Xplore, covering the period from each database's inception to the final search date of 1 May 2026. These databases were selected to ensure coverage of clinical rehabilitation research (PubMed), interdisciplinary scientific literature (Scopus), and engineering/technology-focused publications (IEEE Xplore), which collectively represent the core domains of IVR rehabilitation system development.

Eligible publication types were peer-reviewed journal articles and conference proceedings, published in English; conference abstracts without full text, editorials, opinion pieces, theses, and non-peer-reviewed preprints were excluded. Studies were considered relevant if they focused on IVR-based upper-limb rehabilitation after stroke and explicitly described participatory design approaches (including co-design, UCD, or HCD) involving stakeholders such as stroke survivors, clinicians, or developers. Studies focusing solely on non-immersive or semi-immersive VR, lower-limb rehabilitation without upper-limb relevance, or those without end-user involvement in the design process were excluded.

Study selection and data extraction were conducted in a structured and transparent manner following established recommendations for narrative reviews. Although this study is a narrative review, the reporting and methodological transparency were informed by principles described in Scale for the Assessment of Narrative Review Articles (SANRA) [34], particularly regarding clarity of literature search description, inclusion criteria, and structured synthesis. Title/abstract screening and full-text eligibility assessment were conducted by one reviewer, with ambiguous cases discussed and resolved through consensus within the research team. As a post-hoc reliability assessment, a second reviewer independently classified four randomly selected studies (31% of the included studies) using the proposed five-level co-design classification framework. Agreement between reviewers was assessed using Cohen's kappa coefficient.

An initial search strategy was developed by combining four core concept areas: stroke, virtual reality, co-design approaches, and upper limb rehabilitation. The following search string was applied:

("stroke" OR "post-stroke" OR "cerebrovascular accident" OR "hemiplegia" OR "hemiparesis") AND ("virtual reality" OR "immersive virtual reality" OR "head-mounted display" OR "head mounted display" OR "VR") AND ("participatory design" OR "co-design" OR "co creation" OR "co-creation" OR "user-centered design" OR "user centered design" OR "human-centered design" OR "human centered design" OR "design thinking") AND ("upper limb" OR "upper extremity" OR "arm rehabilitation" OR "motor recovery" OR "neuorehabilitation").

This highly specific search yielded a limited number of results. This was expected given the emerging and interdisciplinary nature of the field, where studies rarely integrate all four domains simultaneously. Given the interdisciplinary nature of IVR and co-design literature and the initially limited yield of a highly specific four-concept query, the search strategy was iteratively expanded using predefined principles, including (i) decoupling combined concept blocks, (ii) removing overly restrictive Boolean constraints, and (iii) adding synonymous terms for co-design and participatory design. Each iteration was

documented, and adjustments included expanding terms such as ‘co-design’ to include ‘participatory design’, co-creation’, and ‘user involvement’, and separating rehabilitation and VR concept blocks to improve sensitivity. Then they were grouped into 3 categories, and for each category, specific search terms were included (see Table 1). Full database-specific search strings, including adaptations for PubMed, Scopus, and IEEE Xplore, are provided in Supplementary Table S1 to facilitate reproducibility and future updating of the review.

Table 1. Search strategy terms used across databases.

Concept Groups	Search Terms
IVR and stroke rehabilitation (without co-design)	("stroke" OR "post-stroke" OR "cerebrovascular accident" OR "CVA" OR "hemiplegia" OR "hemiparesis") AND ("virtual reality" OR "immersive virtual reality" OR "VR" OR "head-mounted display" OR "HMD") AND ("upper limb" OR "upper extremity" OR "arm rehabilitation" OR "motor recovery" OR "hand rehabilitation")
Co-design in rehabilitation (without IVR)	("stroke" OR "neurorehabilitation") AND ("co-design" OR "participatory design" OR "human centered design" OR "user-centered design")
Co-design in VR (without stroke restriction)	("virtual reality" OR "immersive virtual reality") AND ("co-design" OR "participatory design" OR "human centered design" OR "user-centered design")

A co-design classification framework was designed and utilized during data gathering and synthesis to comprehensively examine and compare the variability of participatory approaches across the included research. The paradigm was essential due to the lack of standardized reporting in co-design processes within IVR rehabilitation research, where words like participatory design, UCD and HCD are frequently employed simultaneously without defined operational definitions. This framework is exploratory and not externally validated.

The development of the five-level co-design classification framework was informed by established participatory design and engagement models, particularly the IAP2 Spectrum of Public Participation [35]. This framework conceptualizes increasing levels of stakeholder involvement from passive consultation to active partnership. Building on these principles, we adapted a simplified five-level structure tailored to the context of IVR rehabilitation research, focusing on the degree and timing of end-user involvement in design and evaluation processes.

The suggested five-level co-design classification framework was further enriched by comprehensive theoretical frameworks of participation and collaborative design. Arnstein’s ladder of citizen participation outlines participation as a continuum from non-participation to citizen control, highlighting the correlation between engagement and authority to make decisions [36]. Sanders and Stappers characterize co-design as a continuum of creativity and cooperation, differentiating users as providers of information, participants in design activities, and active collaborators in knowledge creation [37]. Chamberlain et al. highlighted that co-design in Human–Computer Interaction (HCI) entails negotiated collaboration among stakeholders, with the allocation of expertise and authority impacting design results [38]. Although these frameworks offer significant theoretical foundations, they were not explicitly designed for immersive rehabilitation technology. The current paradigm applies these ideas to IVR stroke rehabilitation by highlighting the timing, continuity, and impact of stakeholder engagement throughout the technology development process.

The conceptual terminology and the five-level framework address complementary but distinct aspects of stakeholder involvement. HCD, UCD, participatory design, co-design, and co-creation describe the design philosophy or methodological approach reported by a study, whereas the five-level framework operationalizes the extent, continuity, and influence of stakeholder participation during the development process. Therefore, the terminology used by authors does not directly determine the assigned co-design level. For example, a study described as “co-design” may correspond to Level 2 or Level 3 if stakeholders primarily provide feedback or participate only during selected stages, whereas a study applying UCD principles may reach Level 4 if users are continuously engaged in iterative decision-making and refinement. Similarly, co-creation terminology does not automatically indicate Level 5 unless stakeholders demonstrate sustained partnership, shared ownership, and involvement throughout the complete innovation lifecycle.

The framework classifies studies based on the extent and continuity of stakeholder involvement across the system development lifecycle, from no involvement to completely embedded co-creation, rather than using design vocabulary for categorization. Five hierarchical levels were established:

Level 1 (Inform): End-user needs were derived indirectly from clinical expertise, literature, or retrospective data, without direct user participation in the design process.

Level 2 (Consult): Stakeholders provide feedback regarding system requirements, usability, or acceptability, but their contribution has limited influence on subsequent design decisions. Typical activities include interviews, surveys, questionnaires, focus groups, or isolated usability evaluations, where stakeholder perspectives are collected but are not integrated through iterative design modifications.

Level 3 (Involve): Stakeholders participate actively in selected stages of system development, such as requirements identification, prototype assessment, or usability testing, with recurring but constrained influence on specific design elements. Evidence for this level includes multiple stakeholder engagement activities where feedback contributes to refinement of system features, although stakeholders are not continuously involved throughout the entire development process.

Level 4 (Collaborate): Stakeholders are involved across multiple iterative design cycles and contribute to decision-making related to system refinement, functionality, and evaluation. Studies classified at this level demonstrate repeated collaboration through activities such as co-design workshops, iterative prototyping, and joint discussions between end-users, clinicians, and developers, with stakeholder input directly influencing system development.

Level 5 (Co-create): Stakeholders participate as equal partners throughout the complete innovation process, including ideation, development, implementation, and refinement. Studies at this level demonstrate continuous and longitudinal collaboration, shared ownership of design decisions, and integration of stakeholder expertise within real-world clinical or rehabilitation environments.

Importantly, the proposed levels should not be interpreted as indicators of methodological quality, effectiveness, or superiority of individual studies. Higher levels represent greater reported depth and continuity of stakeholder involvement, whereas lower levels may reflect different research objectives, development stages, or practical constraints. No formal risk-of-bias or quality appraisal was conducted, as the aim of this review was to map and synthesize co-design methodologies rather than evaluate intervention effectiveness. Therefore, the classification should be interpreted as exploratory.

3. Results

The study selection process is illustrated in the PRISMA flow diagram (see Figure 1). A total of 5957 records were identified through database searching across PubMed ($n = 1140$), IEEE Xplore ($n = 1187$), and Scopus ($n = 3630$). After removal of duplicates ($n = 1578$), 4379 records were screened based on title and abstract. Of these, 4246 records were excluded due to not meeting eligibility criteria, including wrong population, non- or semi-immersive VR, absence of co-design methodology, or inappropriate study design. Subsequently, 133 full-text articles were assessed for eligibility, with 120 studies excluded for reasons such as the wrong population, lack of co-design methods, or absence of upper-limb involvement. Ultimately, 13 studies met the inclusion criteria and were included in the final review (see Table 2).

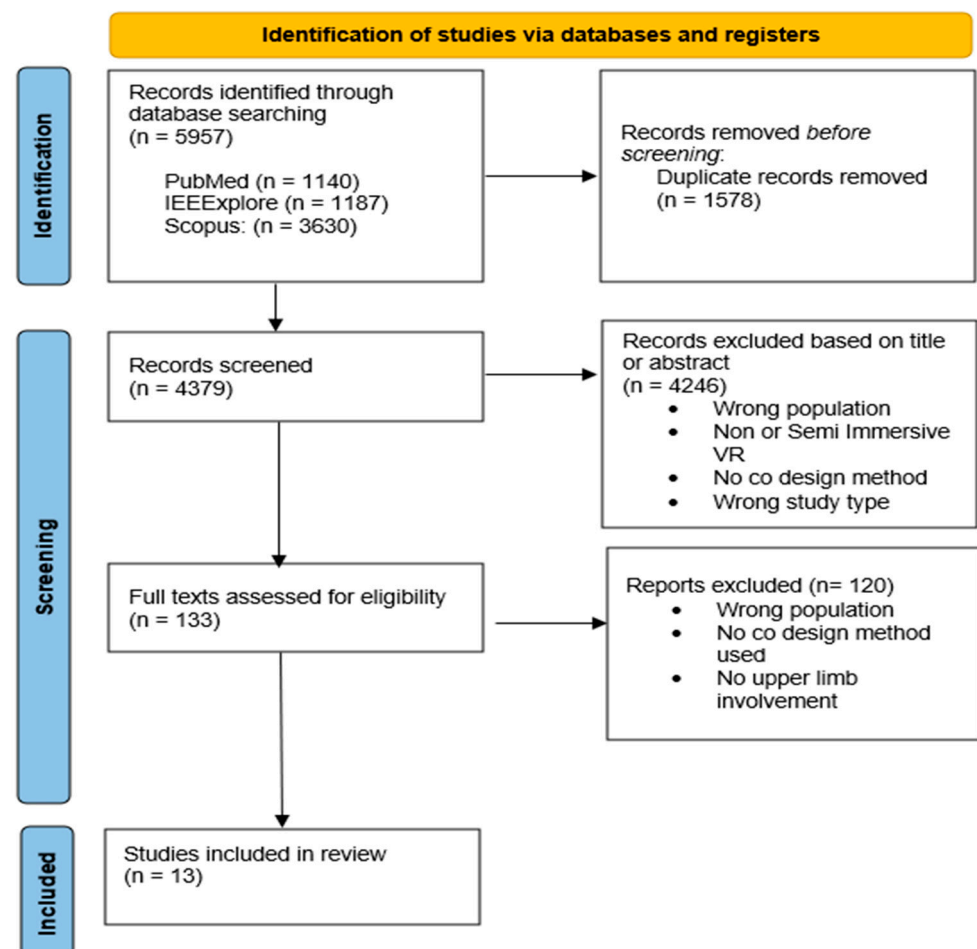


Figure 1. Flow diagram of the included studies.

Data was extracted using a standardized form that captured study characteristics, participant details, IVR system description, co-design methods, stages and level, key design factors identified, barriers encountered and reported outcomes. In line with SANRA guidance for narrative reviews [34], no formal risk-of-bias or methodological quality appraisal of included studies was conducted. Instead, the synthesis focused on a structured description of study characteristics, design types, and levels of evidence to ensure transparent and interpretive reporting rather than quantitative assessment of intervention effectiveness. A post-hoc reliability assessment was conducted on four randomly selected studies with A.T. The independent classifications demonstrated substantial agreement between reviewers (Cohen's $\kappa = 0.64$). Disagreements were minor and were resolved through discussion and consensus.

Table 2. Characteristics, Design Approaches, and Outcomes of Included Studies.

Study	Country	Design	Participants	IVR System	Co-Design Stage	Key Design Principles	Barriers	Outcomes	Evidence Stage	Co-Design Level
[39]	Portugal	Participatory design, prototype development, and usability study	20 stroke survivors (survey); 8 survivors, 1 physician, 3 engineers (focus group); 10 VR-experienced users (usability)	Oculus Quest 2; Unity-based serious game; hand tracking; “whac-a-mole” and mirror therapy modes	Survey → FG → requirements → iterative prototype design	Mirror therapy; positive reinforcement; gamified repetition (upper limb); adjustable difficulty; controller-free interaction; home usability; simple setup; real-world tasks	Limited stroke-user testing; mirror therapy cognitive load; adaptation difficulty; no longitudinal data; COVID-19 constraints	SUS: 87.8 (standard), 65.9 (mirror); high engagement and usability; increased mental effort in mirror mode	Early-stage feasibility (design and usability; no efficacy trial)	L3 Involve
[40]	Portugal	HCD with participatory approach; mixed-method user study (lab and clinical settings)	3 patients; 7 professionals	Multi-user collaborative VR drawing system (Meta Quest 2, Unity)	Interviews and observations → iterative refinement → rehabilitation center co-design	Social interaction; collaboration; gamified upper-limb training; real-time clinician monitoring; personalization; low cognitive load; motivation-driven design	Technical complexity; infrastructure constraints; accessibility issues; arm fatigue; need for personalization; motivation-focused interaction	High motivation; independence; increased engagement; low frustration; moderate physical effort	Early-stage clinical usability (feasibility; no efficacy trial)	L4 Collaborate
[41]	Portugal	HCD with iterative participatory design and clinical evaluation	>80 stroke survivors; 20 healthcare professionals	Collaborative VR serious games (Meta Quest 2 + PC monitoring system)	Continuous co-design with clinicians, researchers and patients	Personalization; adaptability; collaboration; clinician monitoring; meaningful content; data-driven adaptation; clinician-controlled parameters	High configuration burden; limited analytics; insufficient documentation tools; complex personalization workflows	High clinician satisfaction; strong perceived value; improved engagement potential	Early-stage clinical evaluation (formative usability; no controlled trial)	L4 Collaborate
[42]	Netherlands	Qualitative HCD (observations, interviews, questionnaire, workshop)	11 experts (interviews); 24 (questionnaire); 8 (workshop)	Conceptual IVR system (adaptive HMD environment)	Observation → interviews → questionnaire → workshop	Specificity; meaningfulness; versatility; educational value; safety; supportiveness; adjustable complexity; realism	Challenges in tailoring to cognitive diversity	Defined rehabilitation phases; design recommendations; scenario development	Exploratory qualitative design study (no clinical validation)	L3 Involve

Table 2. Cont.

Study	Country	Design	Participants	IVR System	Co-Design Stage	Key Design Principles	Barriers	Outcomes	Evidence Stage	Co-Design Level
[43]	Italy	Iterative UCD with engineering development and pilot feasibility study	Experts (therapists, clinicians, engineers, patients—FG) 4 stroke survivors (2 subacute, 2 chronic)	HTC Vive; EMG armband (Myo); adaptive mirror therapy (VVITA)	FG → iterative prototyping cycles (P0–P9) → pilot testing	Adaptive difficulty; bimanual training; embodiment; balance between realism and cognitive load; meaningful ADLs; therapist-in-the-loop; safety; personalization	Calibration complexity; visuo-proprioceptive mismatch; fatigue; trunk compensation; visual distractions; therapist expertise required	Improved usability; high engagement; enhanced performance; potential motor recovery	Early clinical feasibility (pilot validation)	L4 Collaborate
[44]	Finland	DSR and Design Thinking	68 participants (patients, relatives, clinicians, students)	Immersive VR Museum (HTC Vive, Leap Motion)	Empathize → Define → Ideate → Prototype → Test (continuous user feedback loops)	Gamification; immersion; experiential learning; low-cost home rehabilitation; object interaction; iterative UCD	Limited realism; lack of structured goals; motion smoothness issues; risk of reduced motivation; lack of long-term validation	SUS > 85; 78% motivation; high engagement; positive satisfaction	Prototype validation (usability; no clinical trial)	L4 Collaborate
[45]	UK	Participatory co-creation; longitudinal service design	100 stroke survivors (92 completed); therapists and engineers	Technology-Enriched Rehabilitation Gym (VR, robotics, FES, tablets)	Continuous co-creation throughout 8-week program	User-as-co-creator; intensive task-specific training; multimodal integration; peer support; gamification; clinical alignment	High resource requirements; scalability challenges; volunteer bias; legal/IP complexity	92% adherence; improved engagement; new technologies developed; implementation framework	Late-stage feasibility (translational; no RCT)	L5 Co-create
[46]	Norway	Qualitative participatory co-design with iterative prototyping (workshops, interviews)	Stroke survivors, clinicians, developers	Immersive VR prototypes (home-based scenarios—café, kitchen, painting)	Iterative co-design cycles (concept → refinement → gamification)	Adaptability; personalization; safety; goal-oriented therapy; real-life relevance; motivation; repetition intensity	Hemiparesis adaptation; cognitive load; hardware usability; safety concerns; supervision needs	Thematic insights (adaptability, safety/ease, goal orientation, motivation, complementary use); refined prototypes; improved user-centered concepts	Early-stage qualitative feasibility	L4 Collaborate

Table 2. Cont.

Study	Country	Design	Participants	IVR System	Co-Design Stage	Key Design Principles	Barriers	Outcomes	Evidence Stage	Co-Design Level
[47]	USA	RtD with iterative co-design and usability testing	14 clinicians (7 PTs, 3 OTs, 3 Rehab Clinicians)	Unreal Engine IVR system with gesture tracking	Clinician-only co-design → playtesting → iteration	Customizable gesture therapy; clinician authoring tools; multimodal feedback; gamification; telehealth integration	Lack of patient input due to COVID; time constraints; cost; usability challenges; safety concerns	Identified design requirements; telehealth needs; refined framework for post-stroke VR therapy	Pre-clinical design stage	L1 Inform
[48]	Mexico	Iterative UCD with usability evaluation	16 therapists (requirements); 5 therapists (evaluation); 10 healthy volunteers	VR rehab system with ADL-based games (Shapes, Supermarket, Fruit, Building) and haptic feedback; HTC Vive Pro)	Requirements → prototype → iterative evaluation	Gamified ADLs; structured difficulty; motor learning; multimodal feedback; ergonomic design; clinical scale integration	System complexity; usability issues; setup challenges; low aesthetic appeal	SUS improved (78→85+); increased usability and satisfaction; higher immersion with HMD	Pre-clinical feasibility	L2 Consult
[49]	Colombia	Iterative UCD with usability testing and pilot study	9 stroke survivors (testing); 10 (pilot)	Motion Health via Unity VR; Oculus Rift → Quest 2)	Participatory design with iterative playtesting cycles	Task-specific training; cultural relevance; adaptive difficulty; reduced complexity; rest integration	Small sample; COVID constraints; usability challenges; cybersickness risk	High usability (VRNQ 103.6); moderate immersion; strong engagement	Early-stage feasibility (proof-of-concept)	L4 Collaborate
[50]	Australia	Mixed methods (quantitative + qualitative interviews)	7 patients; 2 clinicians	Pico 3 VR system with ADL scenarios (apple, rowing, tea, painting, cannonball)	Clinician-led design → patient feedback	Task repetition; graded difficulty; multisensory engagement; adaptability; safety	Heterogeneous abilities; controller difficulty; discomfort; small sample; COVID delays; home safety concerns	High satisfaction (USEQ ~25.7); strong motivation; need for personalization	Exploratory feasibility	L3 Involve
[51]	Ethiopia	HCD with co-creation and pilot study	6 patients; 4 clinicians	AdaptRehab VR (Oculus Quest 2; Unity)	Iterative design thinking co-creation (empathize → define → ideate → prototype → test)	Cultural adaptation; gamification; real-time feedback; personalization; low-cost design	Infrastructure limitations; low technical expertise; funding constraints	6 games developed; Increased engagement; positive usability; feasible for LMIC settings	Feasibility (proof-of-concept)	L4 Collaborate

FG: Focus Groups; DSR: Design Science Research; RtD: Research through Design; LMIC: Low- and Middle-Income Countries; SUS: System Usability Scale; HMD: Head Mounted Display; VRNQ: Virtual Reality Neuroscience Questionnaire; USEQ: User Satisfaction Evaluation Questionnaire.

3.1. Geographic Distribution of Studies

The geographic distribution of the included studies demonstrates a broad international representation spanning multiple continents. Europe accounted for the largest proportion of studies (7/13, 53.8%), with studies conducted in Portugal [39–41], the Netherlands [42], Italy [43], Finland [44], the United Kingdom [45] and Norway [46]. North and South America contributed three studies (3/13, 23.1%), including the United States [47], Mexico [48] and Colombia [49]. In addition, the remaining studies were conducted in Oceania (Australia; [50]) and Africa (Ethiopia; [51]), with each country contributing one study (1/13, 7.7%) and highlight the global scope of the evidence base. Overall, while Europe appears as the dominant region in terms of study concentration and some geographic diversity is present, the evidence base remains insufficient to support strong claims of global external validity.

3.2. Models and Depth of Co-Design Participation

The studies reviewed have shown significant heterogeneity in the implementation and comprehensiveness of co-design methodologies. Utilizing the suggested five-level classification framework, only one study [45] obtained a complete co-creation level (Level 5), defined by continuous stakeholder engagement across the whole intervention lifetime in a real-world clinical setting. Most studies were categorized at intermediate levels, specifically Level 3 (Involve) [39,42,50] and Level 4 (Collaborate) [40,41,43,44,46,49,51], wherein stakeholders participated in selected or several iterative phases of development. A limited number of studies demonstrated reduced participation, encompassing consultative (Level 2) [48] or clinician-driven methodologies (Level 1) [47], wherein end-user input was either constrained or indirect.

Structured HCD frameworks with iterative cycles of observation, ideation, prototyping, and evaluation were used in several studies. For instance, to inform IVR neurorehabilitation environments customized to recovery phases and clinical demands, Ref. [42] implemented a multi-stage HCD process that included clinical observations, expert interviews, surveys, and participation workshops. Similarly to this, Ref. [46] refined home-based IVR rehabilitation scenarios across several cycles of improvement through iterative participative workshops and interviews with stroke survivors, clinicians, and developers.

Additionally, other studies explicitly included stakeholders throughout the empathize, define, ideate, prototype, and test cycles by implementing more structured design thinking or design science research frameworks. Both [44] and [51] showed how gamified IVR rehabilitation systems may be refined iteratively through full-cycle participatory design involving patients, clinicians, and developers. To facilitate real-time adaptation and system improvement, Refs. [40,41] expanded co-design into clinical settings by incorporating stroke survivors and medical professionals in rehabilitation facilities.

Although they lacked completely documented HCD or design thinking models, several studies used iterative user-centered or participatory design approaches that involved stakeholders in repeated cycles of prototyping and assessment in addition to these organized frameworks. For instance, Ref. [43] used several iterative development cycles (P0–P9) to improve an adaptive virtual mirror therapy system by incorporating feedback from therapists and stroke patients through focus groups and pilot testing. A complementary study [52] further evaluated the system in a larger cohort, confirming usability, acceptability, and key user-experience outcomes, thereby extending evidence from early feasibility to more robust evaluation. Like this, Ref. [49] carried out successive playtesting sessions with stroke survivors to gradually optimize usability, engagement, and task design, while [39] integrated surveys, focus groups, and usability testing to inform the iterative development of a home-based IVR rehabilitation game. Although there was no fully iterative

participatory design cycle, Ref. [50] described a more moderate degree of co-design in which clinicians guided the creation of the original scenario and patient input influenced later improvements.

Nevertheless, not every study included patients at every stage of development. Due to ethical and practical limitations, Ref. [47] provided an example of a clinician-driven early-stage co-design paradigm in which therapists informed system design before patient engagement. In the same way, Ref. [48] mostly relied on therapist-driven requirements collection, with iterative modification taking place prior to testing on healthy volunteers. The most established participatory model was demonstrated by [45], where co-creation was maintained over the course of an 8-week rehabilitation program including 100 stroke survivors and interdisciplinary teams.

3.3. Design Principles Underpinning IVR Rehabilitation Systems

The focus on task-specific, repetitive motor training in line with neuroplasticity mechanisms, carried out through gamified or functionally significant upper-limb activities, was a dominant approach [43,49,50]. These tasks were frequently based on motor learning concepts such as goal-oriented activity, repetition, and progression. In order to enable real-time task complexity adjustment based on user capability, performance, or recovery phase, several systems also included adaptive difficulty and customization methods [41,42,51]. In situations with limited resources, personalization also included cultural and contextual adaptation, such as language localization and context-specific content design [51].

To improve motor learning, body awareness, and immersion, it was also important to integrate multimodal feedback and embodiment, which included auditory, visual, and, in some situations, haptic or vibration inputs [43,47,48]. Thus, to facilitate contact with the affected limb, these systems often prioritize embodiment through mirrored movements, gesture-based interaction, or avatar representation.

Particularly in home-based or unsupervised rehabilitation environments, gamification and motivational design have been repeatedly included to enhance engagement, adherence, and user experience [39,44,49]. With the aim of maintaining motivation across several sessions, this incorporated interactive tasks, game narratives, score systems, and prizes.

With systems including familiar or real-world activities like cooking, painting, farming, or daily living activities, co-design approaches further highlighted ecological validity and meaningful task design [40,46,49]. To improve motivation and engagement, rehabilitation was sometimes expanded into social or collaborative settings that allowed for interaction with peers or therapists [40,41,45].

Furthermore, several studies [41,43,47] emphasized the significance of clinician engagement and system management, including therapist-in-the-loop design, adjustable workout parameters, and remote monitoring capabilities.

Moreover, all systems constantly prioritize accessibility, safety, and usability. According to [39,42,50], these included limiting cognitive load, simplifying interaction (e.g., reducing reliance on complex controllers), ensuring safe use in unsupervised or home settings, and accommodating a variety of physical and cognitive disabilities. Efforts to create affordable, scalable, and contextually suitable solutions, especially for home-based rehabilitation and low-resource settings, also demonstrated broader accessibility considerations [44,51].

3.4. Barriers to Implementation and Usability

Several recurring barriers were found in all the included studies, despite generally positive feasibility and usability results. Technical usability, user capacity, clinical integration, and contextual limitations were the main causes of these obstacles.

In the studies of [43,48,49], they noted that a significant obstacle was interaction complexity and motor limitations, specifically challenges with controllers or hand-tracking systems among people with hemiparesis, reduced dexterity, or impaired fine motor control. Embodiment and calibration problems, such as visuo-proprioceptive mismatch, trunk compensating movements, and challenges in precisely mapping impaired limb motion in immersive environments, were strongly correlated [43,47].

Physical fatigue, discomfort, and symptoms associated with cybersickness were also described in several studies, especially during extended or repetitive upper-limb movement activities in IVR settings [46,49,50]. These problems were particularly evident in elderly people and in systems that needed constant engagement or continuous arm extension.

In systems with adaptive difficulty, mirror therapy conditions, multi-user environments, or novel interaction paradigms, cognitive load and interface complexity were also commonly reported challenges [39,40,44]. Simplified interfaces were sometimes necessary in response to iterative feedback to increase usability and reduce cognitive strain.

Furthermore, infrastructure and technology limitations were prevalent, particularly in clinical or low-resource settings. Funding limitations, equipment availability, maintenance issues, and a lack of technical experience among clinical staff were some of these [45,51]. Cost and hardware accessibility were also identified as obstacles to wider implementation in actual rehabilitation settings [47,48].

For systems designed for autonomous home-based rehabilitation outside of hospital settings, concerns about patient safety, the absence of real-time supervision, monitoring limitations, and the uncertainty surrounding the transfer of training effects to real-world functional recovery were also reported [39,46,47]. Additionally, a few studies emphasized usability variability and heterogeneous user responses, where engagement, perceived competence, and satisfaction varied significantly based on task type, prior VR experience, and individual impairment level [39,49,50].

Clinical integration and workflow limitations, such as therapist time constraints, system configuration complexity, and difficulties incorporating VR tools into current rehabilitation pathways, were also identified as barriers [41,43,47].

Lastly, time-consuming participatory design cycles, coordination issues among interdisciplinary teams, and recruitment challenges, particularly during COVID-19-related disruptions, were identified constraints in the co-design and implementation process [45,49,50]. Sample size, iteration speed, and the generalizability of results across these studies were all impacted by these factors.

3.5. Outcomes and Levels of Evidence

Early-stage evaluation domains, such as usability, feasibility, engagement, satisfaction, and acceptability, reported as the main outcomes in the included studies. IVR systems were consistently linked to good usability scores, high user satisfaction, higher motivation, and positive engagement with rehabilitative tasks throughout the studies.

High usability and acceptance ratings were reported in several studies. For instance, Refs. [44,48] reported SUS scores exceeding established usability thresholds, indicating strong system acceptance and perceived usefulness, while [49] demonstrated high usability, immersion, and positive user experience in a VR exergame system. In the same way, Ref. [39] reported that both normal and mirror therapy modes had good usability and positive motivational responses, despite requiring higher cognitive effort. Additionally, significant levels of involvement, satisfaction, and perceived value of immersive and collaborative rehabilitation tasks were reported by [40,50].

Several pilot and prototype evaluations showed favorable outcomes for acceptability and feasibility. While [47] exhibited excellent physician acceptance and support for cus-

tomized gesture-based VR rehabilitation systems, Ref. [43] demonstrated increased use, engagement, and feasibility of an adaptive virtual mirror therapy system. Similarly, formative data confirming the viability of immersive environments customized to rehabilitation phases and user demands was presented by [42,46].

The potential for contextual scalability was highlighted by [51], who found positive usability and acceptance outcomes for culturally tailored VR rehabilitation games in a low-resource setting. Strong clinician satisfaction and perceived utility of collaborative VR systems in rehabilitation settings were also discovered by [41], especially about personalization and monitoring capabilities.

Despite these consistently favorable early results, most research stayed in the early stages of technology maturity estimation, concentrating more on pilot feasibility, usability testing, or prototype validation than on controlled clinical efficacy [39–44,46–51]. Only [45] demonstrated high adherence, sustained engagement, and successful integration of multiple rehabilitation technologies within a clinical service delivery model in a large-scale, real-world implementation model involving 100 stroke survivors within an 8-week structured rehabilitation program.

4. Discussion

This narrative review integrated knowledge about co-design methodologies in IVR systems for upper-limb stroke rehabilitation, indicating a rapidly growing, although methodologically and clinically immature, evidence base. The five-level classification framework used in this review is exploratory and intended as an interpretive tool to describe variability in stakeholder involvement rather than as a validated metric of methodological quality or research maturity. Therefore, the categorization should be interpreted as a descriptive synthesis of co-design depth rather than a hierarchical evaluation of study rigor or effectiveness. Importantly, higher co-design levels should not be interpreted as indicating superior study quality or effectiveness: they reflect greater reported depth, continuity, and influence of stakeholder involvement within the development process. Also, given the heterogeneity of study designs and the absence of controlled comparisons isolating co-design as an independent variable, findings should be interpreted as descriptive associations rather than evidence of causal effects.

The greater part of research adopted collaborative co-design methodologies (L4), but just one study accomplished complete co-creation (L5), suggesting that despite the prevalent use of participatory methods, lasting and integrated co-design throughout the whole development lifecycle is rare. Lower-intensity methodologies (L1–L3) correlated with diminished stakeholder influence on system architecture, frequently constraining end-user effect to the final review phase. This distribution suggests that although co-design is widely referenced in IVR rehabilitation research, it is rarely implemented as a continuous, embedded process throughout system development.

A central finding of this review is the lack of conceptual consistency in how co-design is defined and implemented. Across studies, terms such as HCD, UCD, participatory design, and co-creation are used interchangeably, frequently lacking obvious distinctions in scope or stakeholder involvement. The classification analysis suggests that numerous research studies designated as “co-design” more accurately align with consultation-based or evaluative participation (Level 1–2), wherein users predominantly engage through interviews, surveys, or usability testing, rather than through active design decision-making. This suggests that co-design is often utilized as a methodological label rather than a systematically implemented framework, so constraining comparability among studies and undermining the advancement of cumulative knowledge in the discipline.

Furthermore, stakeholder engagement is often unequal. Although healthcare professionals are often included, the extent of participation of stroke survivors varies considerably, with certain research primarily involving users in late-stage usability testing or evaluation rather than in early-stage conceptual design. This discrepancy raises concerns about the degree to which advanced systems authentically reflect user-generated needs, rather than simply confirming researcher-driven hypotheses post hoc. Due to the complex and diverse characteristics of post-stroke impairments, the significant involvement of patients during the design process is crucial for ensuring ecological validity, accessibility, and customization.

Another important conclusion of this review is that stated outcomes predominantly focus on usability, acceptance, and engagement. Improvements in usability were observed at all levels of co-design involvement, indicating that these outcomes may be influenced by both the depth of participation and the fundamental characteristics of IVR systems, such as immersion and gamification. Specifically, novelty effects and game-based interaction may foster temporary engagement without guaranteeing enduring behavioral change or clinically significant enhancement. This distinction is crucial, as participation must be regarded as a required yet insufficient prerequisite for the effectiveness of rehabilitation. Current literature highlights the limited standardization of user experience evaluation approaches for stroke rehabilitation technologies and emphasizes participatory co-design involving patients and carers to improve accessibility and engagement [53]. In this context, IVR systems are used across the included studies as complements to conventional therapy, offering engaging and personalized rehabilitation experiences. However, maximizing their effectiveness requires improved usability evaluation through more consistent frameworks, as well as addressing technical and accessibility barriers and ensuring adaptability to individual patient needs [54].

This analysis identifies a significant gap in the insufficient advancement from feasibility and usability assessment to thorough clinical validation. The majority of IVR systems are still in the prototype or pilot phase, marked by limited sample sizes, brief intervention periods, and regulated experimental settings. Only a single study exhibited extensive application within a structured rehabilitation program, underscoring the infrequency of sophisticated translational initiatives. Moreover, there is less evidence of incorporation into established rehabilitation treatments.

Consistent with the findings of the present review, recent investigations rarely incorporate explicit co-design methodologies involving stroke survivors, clinicians, and developers throughout the technology development process [55,56]. These studies have evaluated feasibility and patient perceptions of immersive upper-limb rehabilitation systems, while recent proposals have also begun incorporating stakeholder-informed design approaches, involving stroke survivors and healthcare professionals during early requirement-gathering and conceptual development phases [57]. Finally, since completion of the literature search, a series of studies has further explored participatory immersive VR for stroke rehabilitation through ecologically valid rehabilitation tasks, collaborative virtual environments, and clinician-facing monitoring tools. Although these studies were not included in the formal review and therefore did not contribute to the synthesis, they are broadly consistent with the trends identified here, demonstrating increasingly sophisticated stakeholder involvement while remaining primarily focused on feasibility, usability, and implementation rather than robust clinical effectiveness [58–61].

4.1. Limitations

The included studies were predominantly early-stage investigations, including prototype evaluations, pilot studies, and usability assessments, with generally small sample sizes

and limited follow-up durations. Most focused on feasibility and user experience rather than controlled comparisons, which limits the ability to draw causal or effectiveness-based conclusions regarding the impact of co-design on clinical or user outcomes. The included studies were also highly heterogeneous in design, intervention maturity, study settings, outcome measures, and reporting quality, which limits direct comparison between studies and reduces the ability to draw broad generalizations.

Although a post-hoc reliability assessment was conducted, involving independent classification of four randomly selected studies, the limited number of double-coded studies does not constitute a formal validation of the framework. Future research should evaluate the framework using larger samples and independent double-coding procedures to establish reliability and reproducibility. Also, as the framework is an exploratory interpretive tool rather than a psychometrically validated instrument, classification of studies into co-design levels may be subject to a degree of subjective judgment, particularly in cases where reporting of stakeholder involvement was ambiguous or incomplete. Future work should establish inter-rater reliability and seek external validation of the framework, for example through independent double-coding of included studies, to strengthen its reproducibility and broader. The search strategy was also restricted to three databases (PubMed, Scopus, and IEEE Xplore) and to English-language publications, which may have resulted in the omission of relevant studies indexed elsewhere, such as ACM Digital Library, Embase, PsycINFO, or Cochrane Library, or published in other languages, including HCI-focused co-design studies not well represented in the databases searched. These constraints may have introduced selection bias and should be considered when interpreting the findings.

Despite the use of iterative co-design approaches, the review revealed persistent and recurring challenges spanning technological, clinical, user, and infrastructural domains. Calibration problems, tracking inconsistencies, cognitive strain, fatigue, and usability challenges were frequently documented across multiple studies, including advanced prototypes and pilot systems. This suggests that iterative co-design alone does not fully address the intrinsic limits of human–technology interaction in post-stroke populations.

Notably, these obstacles relate not solely to system architecture but also to real-world implementation conditions, including restrictions on home-based use, inadequate clinical integration, and, in some contexts, insufficient technological infrastructure. These findings underscore an important gap between laboratory-based system development and the realities of rehabilitation in real-world settings. The persistence of these obstacles across geographically diverse studies suggests that they are systemic rather than specific to individual studies.

4.2. Implications for Practice

The findings of this review have several implications for clinical practice, design practice, and interdisciplinary collaboration in stroke rehabilitation.

First, clinicians and developers should recognize that IVR systems have consistent evidence supporting improved engagement. Therefore, IVR should be positioned as an adjunct to conventional rehabilitation rather than a replacement, particularly in upper-limb motor recovery where evidence of long-term functional gains remains limited.

Second, effective implementation requires early and sustained involvement of end-users, including stroke survivors and therapists, not only during testing phases but also during system definition and iterative redesign.

Third, actual implementation must consider real-world limits such as fatigue, cognitive load, accessibility requirements, and infrastructural constraints. Technologically advanced systems that lack contextual sensitivity may have diminished adoption, especially in home environments or limited-resource situations.

Finally, clinical teams should be aware that successful IVR integration depends not only on technology but also on workflow compatibility, training requirements, and long-term support structures.

5. Conclusions

This narrative study analyzed the adoption of co-design methodologies in the development of IVR systems for upper-limb stroke rehabilitation. The findings indicate that the area is marked by swift international expansion and significant methodological variation, while it remains in a juvenile and only partially integrated phase. Development initiatives are mostly prototype-driven, employing HCD and UCD participatory design, and engineering-oriented methodologies in adaptable but inconsistently operationalized frameworks.

Despite comprehensive records of stakeholder involvement, its intensity, timing, and consistency exhibit significant variation. In most of the studies, user involvement is predominantly observed during initial requirement elicitation and/or final usability evaluation, but continuous, comprehensive co-design throughout the whole development lifecycle is limited. This leads to slightly integrated rather than fully embedded participatory design processes.

For rehabilitation technology developers, these findings suggest that future IVR stroke rehabilitation projects should aim for meaningful stakeholder involvement beyond usability testing, ideally incorporating at least iterative Level 3 involvement during early development. Developers should also proactively address recurring implementation barriers, including cognitive load, hardware usability, therapist workflow integration, accessibility, and scalability, to facilitate successful translation into clinical practice.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/mti10080081/s1>, Table S1: Iterative search strategy and query modifications.

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Abbreviations

The following abbreviations are used in this manuscript:

ADL	Activities of Daily Living
HCD	Human Centred Design
UCD	User Centred Design
VR	Virtual Reality
IVR	Immersive Virtual Reality
HMD	Head Mounted Display

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