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Immersive Technology in Stroke Rehabilitation: A Scoping Review of Effectiveness, Challenges and Future Direction

Vanitha Jayaraj*, Keerthana A K, Sathya Siva, Daniel A, Santhana Lakshmi S, Vignesh Srinivasan, Prathap Suganthirababu
Saveetha College of Physiotherapy, Saveetha Institute of Medical and Technical Sciences, Chennai, India

Abstract

Stroke rehabilitation has traditionally relied on physical and occupational therapies to improve motor and cognitive functions. Recently, immersive technologies, including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), have emerged as innovative tools for enhancing recovery. These technologies offer engaging, tailored rehabilitation experiences, potentially improving stroke outcomes. This scoping review synthesizes recent studies on immersive technologies in stroke rehabilitation, focusing on clinical trials, pilot studies, and systematic reviews published in the past decade. Findings indicate that VR, AR, and MR interventions show promise in improving motor function, gait rehabilitation, and cognitive recovery. VR-based interventions, including treadmill training and mirror therapy, have demonstrated benefits such as increased walking speed and enhanced upper limb motor function. However, challenges remain, including participant selection bias, small sample sizes, and a lack of long-term follow-up. Additionally, issues such as physical discomfort, safety concerns, and the need for personalized therapy were noted. The diversity of stroke severity and patient heterogeneity further complicate generalizability. Immersive technologies hold significant potential in stroke rehabilitation by providing engaging and effective therapies. However, challenges such as safety, accessibility, and scalability must be addressed. Future research should focus on larger, multicenter trials with diverse patient populations, long-term follow-ups, and integrating advanced technologies like AI and motion tracking to optimize immersive interventions for stroke recovery.

Keywords: *Immersive Technology, Rehabilitation, Stroke, Virtual Reality.*

Introduction

Stroke, as defined by the World Health Organization (WHO), is the sudden onset of neurological dysfunction lasting more than 24 hours or leading to death, resulting from a vascular cause [1]. It remains a leading cause of long-term disability worldwide, with a complex interplay of modifiable and non-modifiable risk factors such as hypertension, diabetes, hyperlipidemia, atrial fibrillation, smoking, physical inactivity, and alcohol consumption contributing to its onset [2, 3]. Beyond the immediate medical emergency, stroke often results in profound physical, cognitive, and emotional impairments, severely diminishing quality of life for survivors and imposing a considerable burden on caregivers and healthcare systems alike [4, 5]. Optimal stroke management extends beyond acute interventions, requiring a comprehensive and sustained rehabilitation approach. Multidisciplinary rehabilitation, initiated early in the recovery process, has been associated with better functional outcomes, largely due to the brain’s capacity for neuroplasticity—the ability to reorganize neural pathways in response to injury [6, 9, 10]. Personalized rehabilitation plans tailored to the individual’s

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***Corresponding Author: vanithajayaraj29@gmail.com**

functional needs and recovery trajectory are critical for maximizing therapeutic benefits and enhancing long-term outcomes [11]. Traditional rehabilitation modalities—including physical, occupational, and speech therapies—have long served as the cornerstone of stroke recovery [12]. However, these interventions are often intensive, costly, and confined to clinical settings, which may limit access and reduce patient adherence over time [13]. Moreover, the repetitive nature of these therapies can lead to decreased engagement and motivation among patients, while also placing significant demands on rehabilitation professionals [14]. Although services are commonly delivered through interdisciplinary teams across inpatient, outpatient, and home-based settings [15, 16], they are frequently constrained by fixed schedules or predefined treatment durations that may not align with the individual pace of recovery [17]. These limitations underscore the pressing need for more adaptable, accessible, and patient-centered rehabilitation solutions. Emerging immersive technologies—including virtual reality (VR), augmented reality (AR), and mixed reality (MR)—offer promising avenues to address these challenges [19]. Immersive virtual reality (IVR), typically experienced through head-mounted displays (HMDs), creates engaging 3D environments that simulate real-world tasks, enabling patients to perform therapeutic activities in a controlled, interactive setting. These platforms also generate performance data, which can be used to tailor interventions and track progress [20]. The growing availability of commercial VR systems and supportive evidence from clinical trials further reinforces the viability of IVR in rehabilitation contexts [21]. Augmented reality (AR), by superimposing digital information onto the physical environment, facilitates real-time feedback and enhances motor learning, offering patients a more engaging and responsive therapeutic experience [22, 23]. Its ability to integrate seamlessly into physical spaces fosters a sense of embodiment and creates adaptable scenarios that reflect individual needs and capabilities [24, 25]. Mixed reality (MR), which blends the immersive qualities of VR with the contextual awareness of AR, enables complex interactions between virtual and real-world elements. This hybrid approach has shown particular promise in supporting motor skill acquisition, functional task training, and increased motivation [26, 27]. Recent advances in digital technologies and medical devices are revolutionizing stroke rehabilitation by empowering patients to take an active role in their recovery journey. These innovations are increasingly being tested in clinical settings, demonstrating potential to enhance functional outcomes and support sustained engagement. This scoping review aims to explore the role of immersive technologies in stroke rehabilitation. It critically examines current applications of VR, AR, and MR, identifies existing limitations, and discusses emerging directions for research and clinical practice. By evaluating the potential of these technologies to complement or transform traditional rehabilitation strategies, this review seeks to contribute to a more responsive and individualized approach to stroke recovery.

Methodology

The objective of this paper is to present a comprehensive analysis of the effectiveness of immersive technologies in stroke rehabilitation, while also highlighting their limitations (Table 1). A systematic search strategy was employed to identify relevant literature published in scholarly databases and peer-reviewed journals. Boolean operators were used to filter the search, incorporating keywords related to immersive virtual reality, augmented reality, mixed reality, stroke rehabilitation, and their respective synonyms. Key databases, including PubMed, Embase, Scopus, and Google Scholar, were thoroughly explored to retrieve pertinent studies (Figure 1) [28].

Studies were selected for inclusion based on the following criteria:

1. They investigated the use of immersive virtual reality, augmented reality, or mixed reality interventions in stroke rehabilitation.
2. Participants were adult stroke survivors aged 18 years and above.
3. Publications were written in English.
4. Studies assessed outcomes associated with motor and cognitive recovery following stroke.
5. The research design comprised clinical trials or randomized controlled trials (RCTs).
6. Only studies published within the last five years (from November 2023) were considered to ensure the inclusion of the most current evidence.

Studies that did not meet these criteria or were duplicate entries were excluded. A rigorous quality assessment was conducted on the shortlisted articles. Two independent reviewers evaluated each study, considering potential sources of bias, methodological robustness, and relevance to the research question. Articles that did not meet the predefined quality standards were excluded from the review. Following the quality assessment, data extraction commenced. Relevant data were systematically gathered from the selected studies by two independent reviewers. Any discrepancies arising during this process were resolved through discussion and consensus. Extracted data included sample characteristics, details of the intervention, outcome measures, as well as findings related to the effectiveness and limitations of the interventions in stroke rehabilitation.

In recent years, immersive technology-based therapies have emerged as promising tools in stroke rehabilitation, offering innovative ways to engage patients in interactive and enjoyable recovery activities. A growing body of research has investigated the efficacy and challenges of these interventions in enhancing motor and cognitive recovery among stroke survivors (Table 2).

Current Evidence on the Effectiveness of Immersive Technology in Stroke Rehabilitation

Immersive Virtual Reality in Stroke Rehabilitation

Immersive virtual reality (VR) is gaining momentum as an innovative tool in stroke rehabilitation, largely due to its ability to engage patients, enhance motivation, and deliver personalized, interactive therapeutic experiences. By simulating customizable environments, immersive VR supports neuroplasticity and aligns with rehabilitation goals across motor and cognitive domains. Clinical applications of immersive VR have yielded encouraging results. For instance, rhythm-based games such as Beat Saber have been effectively employed to motivate patients with chronic stroke, promoting both physical activity and psychological engagement through a state of "flow" [29]. Similarly, immersive VR-based treadmill training has shown promise in improving gait speed, demonstrating high usability and minimal adverse effects [30]. However, the use of head-mounted displays (HMDs) presents challenges such as user discomfort and visual occlusion, which may affect both safety and user experience [30]. Additional studies involving individuals with stroke and multiple sclerosis have found VR treadmill training to increase therapeutic engagement and walking speed. Nevertheless, short session durations, small sample sizes, and limited assessments of overground walking constrain the generalizability of these findings [31]. Patients with sensory impairments may also experience difficulty due to the high reliance on visual and proprioceptive input within immersive VR environments. In upper limb rehabilitation, platforms such as MNVR-Rehab—grounded in mirror neuron theory—have demonstrated the potential to enhance motor recovery through repetitive, goaloriented activities in patients recovering from subacute stroke [32]. These approaches activate neuroplastic mechanisms and offer early indications of efficacy. On a biological level, immersive VR has been associated with beneficial shifts in molecular biomarkers, including increased levels of brain-derived neurotrophic factor (BDNF) and reductions in oxidative stress markers such as HO-1 and 8-OHdG, suggesting a neurophysiological basis for recovery [33]. The cognitive benefits of immersive VR are also becoming more evident. In patients with acute post-stroke cognitive deficits, VR-based interventions have improved engagement and participation in therapy [34]. Although most studies report improvements in hand strength, dexterity, and coordination, translating into increased functional independence [35, 36], many are limited by small sample sizes and a lack of long-term outcome data. Moreover, few studies have incorporated objective attention metrics, compared different types of VR (e.g., 360-degree video versus computer-generated environments), or evaluated corresponding brain activation during therapy sessions [37]. Overall, immersive VR holds substantial promise in advancing stroke rehabilitation through adaptive, engaging, and patient-centered interventions. Nonetheless, addressing existing methodological limitations and evaluating long-term outcomes will be critical to validating its clinical effectiveness and scalability.

Immersive Augmented Reality in Stroke Rehabilitation

Immersive augmented reality (AR) is also emerging as a valuable adjunct in stroke rehabilitation, offering the potential to enhance therapeutic outcomes while easing therapist workload. A feasibility study conducted during the COVID-19 pandemic highlighted AR's ability to reduce in-person contact by enabling therapists to shift from repetitive physical assistance to more instructional and supervisory roles [38]. However, the evidence surrounding the clinical effectiveness of AR, particularly in patients with subacute and chronic stroke, remains mixed. For example, a comparative trial between treadmill-based C-Mill therapy and overground FALLS training found no significant differences in primary walking outcomes, though secondary outcomes—such as cardiovascular fitness and walking practice—favored the C-Mill group [39]. Emerging technologies like the RobExReha platform, which combines robotic-assisted arm therapy with AR-based gaming, have shown initial safety and usability in neurologically impaired patients with intact cognition. Similarly, devices like the Microsoft HoloLens have received favorable feedback from patients, reinforcing the feasibility and acceptability of AR in rehabilitation contexts [40]. While immersive AR appears to support patient engagement and facilitate autonomous training, evidence regarding its long-term efficacy and applicability across diverse stroke populations remains limited. Further research is needed to fully establish its therapeutic potential and define best practices for implementation.

Immersive Technology in Stroke Rehabilitation: Challenges and Future Directions

Despite the growing enthusiasm for immersive technologies in neurorehabilitation, several challenges continue to hinder their widespread clinical adoption. While increased motivation and engagement are frequently reported with VR interventions, selection bias is common, as participants are often self-selected and more likely to be technologically inclined [29]. Furthermore, heterogeneity in patient cohorts and the frequent exclusion of individuals with severe cognitive or communication impairments limit the external validity of many findings [36]. Although improvements in motor outcomes—such as increased walking speed—are commonly documented, many interventions rely heavily on visual input, posing challenges for patients with somatosensory deficits [32, 39]. Short intervention durations and a general lack of long-term follow-up data further constrain conclusions regarding sustained benefits [39–41]. Moreover, side effects such as dizziness and visual fatigue necessitate careful session structuring and regular breaks to ensure patient safety [34]. Recent innovations, such as the VIRTUE platform, offer low-cost, minimally supervised cognitive rehabilitation solutions, but challenges related to device compatibility and scalability—particularly with headsets like the Oculus Quest 2—remain unresolved [35]. Meanwhile, VR-based mirror therapy systems like BeSTEP show promise in chronic stroke populations, and could benefit from additional features such as EMG integration, eye/head tracking, and multiple camera angles to enhance exercise variability and therapeutic engagement [36]. However, methodological limitations persist across the literature. These include a lack of standardized outcome measures, limited personalization of interventions, high attrition rates, and insufficient use of control groups or blinded assessors. The logistical constraints introduced by the COVID-19 pandemic have only exacerbated these issues. To move the field forward, future studies must explore haptic feedback systems, advanced hand-tracking technologies, and secure home-based VR platforms that safeguard user privacy. Devices like RobExReha illustrate the potential for precision-targeted therapy, but also highlight current limitations in accessibility and adaptability for broader stroke populations [40]. Ultimately, addressing bias introduced by unblinded assessments and dual-role therapists requires well-designed, multicenter randomized controlled trials with larger, more diverse populations and extended follow-up periods. Such rigor will be crucial in establishing immersive technologies as evidence-based standards in stroke rehabilitation.

Limitations and Recommendations

This scoping review explored the effectiveness of immersive technologies in stroke rehabilitation but is not without its limitations. One key constraint was the exclusion of non-English language studies, which may have led to the omission of valuable research conducted in other parts of the world. This introduces a degree of linguistic bias and may limit the global relevance and comprehensiveness of the review's conclusions. Another limitation was the decision to include only studies published within the past five years. While this approach ensures that the review reflects recent advancements, it may have inadvertently excluded earlier, foundational research that could provide important historical context and insights into the trajectory of immersive technologies in neurorehabilitation. Although the findings highlight the growing promise of immersive technologies—such as virtual reality (VR), augmented reality (AR), and mixed reality (MR)—in supporting stroke recovery, several critical research gaps remain. Notably, there is a clear need for well-designed comparative studies that assess how these technologies perform relative to traditional rehabilitation methods. Such studies are essential not only for determining clinical effectiveness but also for evaluating cost-efficiency and practical feasibility, which are key considerations for widespread adoption in routine clinical settings. In addition, the long-term effects of immersive interventions on functional recovery and quality of life in stroke survivors are still underexplored. Longitudinal research is necessary to understand whether the benefits of these technologies are sustained over time and to what extent they contribute to meaningful, lasting improvements in patient outcomes. Beyond clinical measures, future studies should also investigate how immersive environments affect patient engagement, motivation, and social interaction—factors known to play a crucial role in the success of rehabilitation programs.

Finally, the temporal scope of the current review may limit its ability to fully capture the development and refinement of immersive technologies, particularly MR applications, over time. Expanding the timeframe and scope in future work will allow for a more nuanced understanding of both the evolution of these tools and the ongoing challenges in their implementation. As the field continues to evolve, sustained research and innovation will be vital to realizing the full potential of immersive technologies and advancing a more personalized, engaging, and effective model of stroke rehabilitation.

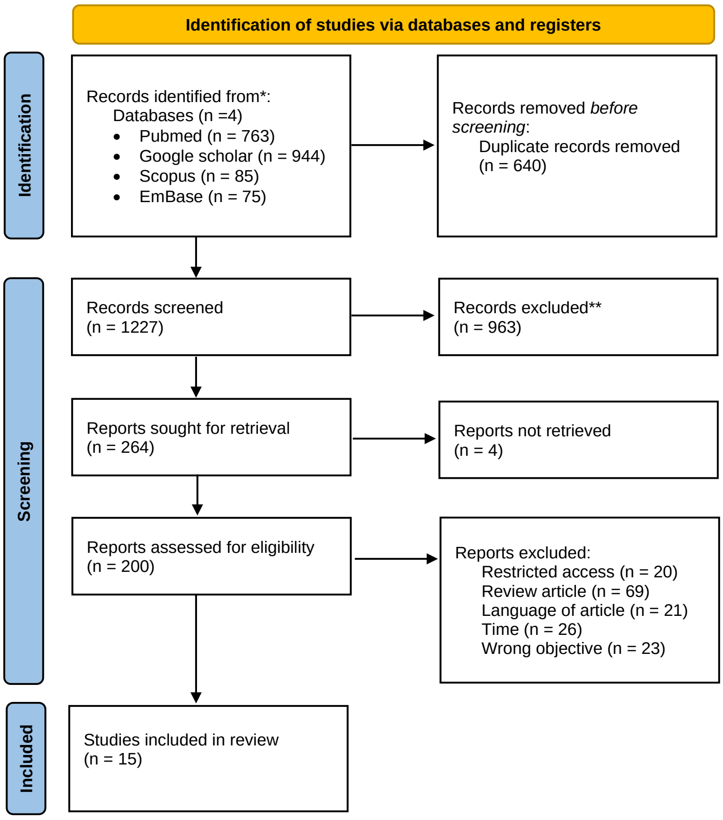

Figure 1. Literature search flowchart

Figure 1. Literature Search Flowchart

Table 1. Methodology

Methodology aspect	**Description**
Aim	To provide a comprehensive overview of the efficacy of immersive technology in stroke rehabilitation, focusing on its limitations.
Search Strategy	Employed a comprehensive search strategy using relevant terms related to immersive virtual reality, augmented reality, mixed reality, stroke rehabilitation and synonyms with Boolean operators.
Databases Searched	PubMed, Embase, Scopus, Google Scholar, and other relevant academic databases were searched for eligible articles.

Inclusion Criteria	Studies were considered for inclusion based on the following criteria: • They examined stroke rehabilitation using immersive virtual reality, augmented reality, or mixed reality interventions. • The participants were adult stroke survivors aged 18 years or older. • The studies were published in English. • They assessed outcomes related to motor and cognitive recovery in stroke rehabilitation. • The research design included clinical trials or randomized controlled trials (RCTs). • - Only studies published within the past five years (from November 2023) were included to ensure the review reflects the latest evidence.
Exclusion Criteria	Duplicate publications or studies that did not fit the predetermined criteria were not included.
Data Extraction	Information on the research design, sample characteristics, intervention details, outcome measures, and key results about stroke rehabilitation outcomes were extracted by two independent reviewers.
Data Analysis	Qualitatively compiled the results of several research, discovering themes, trends, or patterns pertaining to the results of stroke rehabilitation.

Conclusion

In conclusion, this review highlights the transformative potential of immersive technologies—including virtual reality (VR), augmented reality (AR), and mixed reality (MR)—in advancing stroke rehabilitation. These emerging tools offer a dynamic, interactive platform that can significantly enhance patient engagement by simulating task-specific activities and fostering a heightened sense of presence. Such features may help counteract the apathy and disengagement often observed in conventional rehabilitation, ultimately promoting greater motivation and participation among stroke survivors.

Despite their promise, the widespread adoption of immersive technologies in clinical settings is not without challenges. Issues such as cost, accessibility, patient variability, data privacy, and the need for training among both patients and healthcare professionals must be carefully navigated. However, the findings of this review underscore the importance of a patient-centred approach, informed implementation strategies, and strong interdisciplinary collaboration. With thoughtful integration, immersive technologies have the potential to not only complement traditional rehabilitation methods but also to reshape the future of stroke recovery by enhancing outcomes and enriching the rehabilitation experience.

Table 2. Study Characteristics

Title and author of the study	Immersive technology	Participants	Rehabilitation's goal	Intervention	Primary outcome measures	Conclusion	Limitations
Virtual reality gaming in rehabilitation after stroke - user experiences and perceptions Gustavsson, M et al., 2022	VR	N=7	Enhance motor function	The commercially available HTC Vive head-mounted VR system was used, featuring five different games: NVIDIA VR Funhouse, The Lab, Beat Saber, Climbey, and Pierhead Arcade.	Fugl-Meyer Assessment of Upper Extremity	Participants with chronic stroke found VR gaming to be engaging and motivating, reporting a positive experience and improvements in their daily activities.	The sample included participants of different genders, ages, and cultural backgrounds but excluded individuals with severe cognitive or communication impairments.
Immersive virtual reality during gait rehabilitation increases walking speed and motivation: a usability evaluation with healthy participants and patients with multiple sclerosis and stroke Winter C et al., 2021	VR	N= 4	Enhance motor function	Treadmill training without VR, while the second included two VR-based treadmill conditions in pseudo-randomized order, each lasting about 7.5 minutes.	Walking speed and heart rate	Increased walking speed demonstrated in gait rehabilitation.	Overground walking, was not assessed Within the study where they pooled findings from a heterogeneous and small group of patients with stroke.
Immersive virtual reality-based rehabilitation for subacute stroke: a randomized controlled trial Huang, Q et al., 2024	VR	N= 40	Enhance motor function	The imVR group activities: cooking in a virtual kitchen, popping balloons, punching dolls, shooting basketballs, collecting eggs, and tidying a virtual office.	Fugl-Meyer assessment (FMA-UE) and the Barthel Index (BI)	The imVR improves the recovery of UE functional capabilities.	No blinding of subjects. Not explored the mechanism for those significant brain regions.

A novel fully immersive virtual reality environment for upper extremity rehabilitation in patients with stroke Mekbib DB et al., 2021	VR	N= 28	Enhance motor function	VR rehabilitation tasks of reaching, grasping, and releasing-colored balls, tailored to each patient's abilities. After each session, the therapist adjusted task complexity based on the patient’s performance.	Fugl-Meyer Upper Extremity (FM-UE) and Barthel Index (BI)	The MNVR-Rehab improves the recovery of UE functional capabilities of subacute stroke patients with moderate-to-severe UE impairments.	The number of participants is relatively small. No follow-up evaluations The control group included were also the same stroke patients, although untreated using MNVR therapy.
Effects of virtual reality-based motor control training on inflammation, oxidative stress, neuroplasticity and upper limb motor function in patients with chronic stroke: a randomized controlled trial Huang, C. Y et al., 2022	VR	N= 30	Enhance motor function	HTC VIVE commercial VR headset, which includes an HMD, two controllers, and two infrared emitters.	Fugl-Meyer Assessment for upper extremity (FMA-UE) and active range of motion (AROM)	The application of immersive VR-based training improves upper extremity motor performance	A similar difference in serum biomarker level in healthy adults remains to be examined. Less sample size Not identified the biomarker sensitive to VRT at the chronic stage, at regular intervals across a longer period.
Immersive Virtual Reality for the Cognitive Rehabilitation of Stroke Survivors Chatterjee K et al., 2022	VR	N= 40	Enhance cognitive function	The Unity 3D game development platform in combination with the Virtual Reality Toolkit (VRTK) has been used to develop VIRTUE	Montreal Cognitive Assessment (MoCA) test and the Cognitive Assessment of Minnesota (CAM)	It helps those with severe cognitive impairment and reduce the duration of hospital stay.	The sample size is relatively small. The final assessment at three months is lag.

Feasibility and psychophysical effects of immersive virtual reality-based mirror therapy Heinrich C et al., 2022	VR	N= 11	Enhance cognitive function	Leap Motion hand tracking camera. Mitigating these by using black infrared absorbent cloth on the table and by limiting hand exercises to basic movements.	The Fugl-Meyer Assessment-Upper Extremity subset (FMA-UE), Modified Rankin Scale (MRS)	It enhanced motor recovery and psycho-physical effects such as tingling/paraesthesia during the interventions in stroke	Limited sample size and number of interventions.
Effectiveness of Immersive Virtual Reality-Based Hand Rehabilitation Games for Improving Hand Motor Functions in Subacute Stroke Patients F. Amin *et al.*, 2024	VR	N= 52	Enhance motor function	VR Based Game Intervention Plus Conventional Physical Therapy, (VRGI+CPT)) The patient played each game level twice in easy and difficulty levels.	Fugl-Meyer Assessment's- Upper Extremity (FMA-UE), Action Research Arm Test (ARAT), Box and Block Test (BBT), Modified Barthel Index (MBI) and Stroke-Specific Quality of Life (SSQOL)	It showed increased dexterity, improved range of motion, hand strength, and griping. Also improves the patient's ability to synchronize their hand motions with visual stimuli, cognitive engagement within visual training aspects was incorporated into the games.	Some additional clinical outcome measures may require to be considered for further assessment of VR-based hand games.
Effect of Leap Motion-based 3D Immersive Virtual Reality Usage on Upper Extremity Function in Ischemic Stroke Patients Ögün, M. N et al., 2021	VR	N= 65	Enhance motor function	The VR device featuring four games: a cube handling game for grip using Leap Motion; a tree decorating game for complex hand motions; a kitchen	Fugl-Meyer Upper Extremity (FMUE) assessment. The Action Research Arm Test (ARAT), Functional Independence Measure (FIM), Performance Assessment of Self-Care Skills—instrumental activities of daily living (PASS-IADL), and Performance	Immersive VR applications in rehabilitation has a positive impact on upper extremity function and daily life activities for stroke patients.	High dropout rates Single-center design.

				game for forearm movements; and a drumming game for upper extremity movements.	Assessment of Self-Care Skills—basic activities of daily living (PASS-BADL)		
The effect of balance training using touch controller-based fully immersive virtual reality devices on balance and walking ability in patients with stroke: A pilot RCT Kwak HD et al., 2024	VR	N=44	Enhance motor function	FIVR training utilized the Oculus Quest 2, a head-mounted display (HMD), with commercially available sports games on the device.	Timed up-and-go test, Berg balance scale, Gait velocity (km/h), Step length (cm), Stride length (cm), Single support time (sec)	Participants showed improvement in balance by performing goal-directed upper extremity movements while standing, inducing postural sway and anticipatory postural adjustments.	Not suitable and difficult for the patient to follow. All interventions were performed on a flat surface to mitigate the risk of falling during the intervention period.
360° immersive virtual reality-based mirror therapy for upper extremity function and satisfaction among stroke patients: a randomized controlled trial Jo, S et al., 2024	VR	N=45	Enhance motor function	The recorded videos were edited using Final Cut Pro (Apple, USA), where they were mirrored and adjusted for distance (X-axis -10° and Y-axis +10°), then displayed through a Pico G2 VR 4K head-mounted display (Pico, China).	Fugl-Meyer Assessment for upper extremity (FMA-UE)	The 360MT seems to be a more beneficial choice than TMT for upper extremity rehabilitation in stroke patients. This innovative approach provides an immersive and engaging therapy experience, potentially enhancing patient outcomes.	Follow-up assessments and comparisons between 360MT and VRMT using computer-generated graphics were not conducted. The duration of patients' concentration during the interventions was not measured.

Performing a shortened version of the Action Research Arm Test in immersive virtual reality to assess post-stroke upper limb activity Burton Q et al., 2022	VR	N=30	Enhance motor function	The immersive VR adaptation of the Action Research Arm Test (ARAT-VR) includes 19 tasks categorized into four subtests: grasp, grip, pinch, and gross movement.	Fugl-Meyer Assessment for upper extremity (FMA-UE)	ARAT-VR is a reliable, valid, and user-friendly tool for assessing upper limb activity in individuals with stroke, offering the potential to enhance assessment frequency, enable remote evaluations, and support neurorehabilitation.	The test was designed using hand-tracking technology, which did not allow for the provision of tactile feedback.
Augmented reality for stroke rehabilitation during COVID-19 Yang, Z. Q et al., 2022	AR	N=129	Enhance motor function	The AR uses a Microsoft Kinect V2 camera to track patient movements, a TV/monitor for instructions and real-time feedback, and AR software enhanced with AI for training.	Fugl-Meyer Assessment with Upper Extremity and Lower Extremity (FMA-UE and FMA-LE), Berg Balance Scale (BBS), Functional Ambulation Category (FAC).	The AR system automates monotonous practice tasks, allowing participants to practice independently, freeing trainers to focus on teaching	Requirement of training using specific equipment.
Walking-adaptability therapy after stroke: results of a randomized controlled trial Timmermans, C et al., 2023	AR	N=40	Enhance motor function	Treadmill-based C-Mill therapy (CT) and overground FALLS program (FP)	10MWT	C-Mill therapy improves the amount of walking practice an important ingredient of effective interventions of walking speed and walking adaptability after stroke.	No control group Assessors, neither physical therapists nor participants were blind to group allocation Only one center study

Robotic arm training in neurorehabilitation enhanced by augmented reality – a usability and feasibility study de Crignis AC et al., 2023	AR	N=18	Enhance motor and cognitive function	RobExReha, LBR iiwa robotic arm (KUKA AG, DE) further interfaced with a custom-made Unity application (Unity Technologies, US) for the HoloLens (Microsoft Inc., US)	Quebec User Evaluation of Satisfaction with assistive technology [QUEST], workload Raw Task Load Index [RTLX] and a questionnaire for rating visual perception of the gaming scenario	Robotic arm training improves upper extremity from neurological causes and good cognitive function. Notably, the good acceptance and perception of the game using the HoloLens is promising.	The Reference Group, contrarily, additionally included patients with left-sided impairments. Study does not reflect the wide variation of neurological patients potentially training with robotic devices. Not blinded the patients, therapists and assessors were aware of which system they were evaluating.

Conflict Of Interest

The authors declare that there is no conflict of interest regarding the publication of this study.

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References

[1]. Sacco, R. L., Kasner, S. E., Broderick, J. P., et al., 2013, An updated definition of stroke for the 21st century. *Stroke.*, 44(7):2064–2089. doi:10.1161/STR.0b013e318296aeca.

[2]. Maruvada, S. S., Sornavalli, V., Poonambalaganapathi, & Gowri Sankar, A., 2025. Mini mental state examination (MMSE) as a predictor of cognitive recovery in acute stroke. *Romanian Journal of Neurology*, 24(1):25–30. Doi:10.37897/RJN.2025.1.5.

[3]. O'Donnell, M. J., Xavier, D., Liu, L., et al., 2010, Risk factors for ischaemic and intracerebral haemorrhagic stroke in 22 countries (the INTERSTROKE study): a case-control study. *Lancet.*, 376(9735):112–123. doi:10.1016/S0140-6736(10)60834-3.

[4]. Roth, E. J., Harvey, R. L., Rehabilitation of stroke syndromes. In: Physical Medicine and Rehabilitation.

[5]. TP, A., 1990, Rehabilitation of patients with completed stroke. In: Krusen's Handbook of Physical Medicine and Rehabilitation., 656–673.

[6]. Herpich, F., Rincon, F., 2020, Management of acute ischemic stroke. *Crit Care Med.*, 48(11):1654–1663. doi:10.1097/CCM.0000000000004597.

[7]. Chen, X., Liu, F., Yan, Z., et al., 2018, Therapeutic effects of sensory input training on motor function rehabilitation after stroke. *Medicine.*, 97(48):e13387. doi:10.1097/MD.0000000000013387.

[8]. Joypriyanka, M., Surendran R., Sathish Kumar, P. J, Sivasangari A. Game therapy for specially-abled individuals with PPO reinforcement learning in VR-based educational games. In: *Proceedings of the 5th International Conference on Data Intelligence and Cognitive Informatics (ICDICI 2024).* 2024. Doi:10.1109/ICDICI62993.2024.10810847

[9]. Coleman, E. R., Moudgal, R., Lang, K., et al., 2017, Early rehabilitation after stroke: a literature review. *Curr Atheroscler Rep.*, 19(12):59. doi:10.1007/s11883-017-0686-6.

[10]. Puderbaugh, M., Emmady, P. D., 2023, Neuroplasticity. In: StatPearls. St. Petersburg (FL): *StatPearls Publishing.*

[11]. Cirstea, M. C., Levin, M. F., 2000, Compensatory strategies for reaching in stroke. *Brain.*, 123(5):940–953. doi:10.1093/brain/123.5.940.

[12]. Li, W., Luo, Z., Jiang, J., Li, K., Wu, C., 2023, The effects of exercise intervention on cognition and motor function in stroke survivors: a systematic review and meta-analysis. *Neurol Sci.*, 44(6):1891–1903. doi:10.1007/s10072-023-06636-9.

[13]. Teasell, R., Meyer, M. J., McClure, A., et al., 2009, Stroke rehabilitation: an international perspective. *Top Stroke Rehabil.*, 16(1):44–56. doi:10.1310/tsr1601-44.

[14]. Huang, Q., Wu, W., Chen, X., et al., 2019, Evaluating the effect and mechanism of upper limb motor function recovery induced by immersive virtual-reality-based rehabilitation for subacute stroke subjects: study protocol for a randomized controlled trial. *Trials.*, 20(1):104. doi:10.1186/s13063-019-3177-y.

[15]. Bhavani Sowndharya, B., Mathan Muthu, C. M., Vickram, A. S., Saravanan, A., 2025. Bio-ethical considerations in the application of artificial intelligence in spinal surgery. *Brain Spine Lett.*, 10:104161. doi:10.1016/j.bas.2024.104161.

[16]. Bonnyaud, C., Gallien, P., Decavel, P., et al., 2018, Effects of a 6-month self-rehabilitation programme in addition to botulinum toxin injections and conventional physiotherapy on limitations of patients with spastic hemiparesis following stroke (ADJU-TOX): protocol study for a randomised controlled, investigator blinded study. *BMJ Open.*, 8(8):e020915. doi:10.1136/bmjopen-2017-020915.

[17]. Nik Ramli, N. N., Asokan, A., Mayakrishnan, D., et al., 2021, Exploring stroke rehabilitation in Malaysia: are robots better than humans for stroke recuperation? *Malays J Med Sci.*, 28(4):14–23. doi:10.21315/mjms2021.28.4.3.

[18]. Rikhof, C. J. H., Leerskov, K. S., Prange-Lasonder, G. B., et al., 2024, Combining robotics and functional electrical stimulation for assist-as-needed support of leg movements in stroke patients: a feasibility study. *Med Eng Phys.*, 130:104216. doi:10.1016/j.medengphy.2024.104216.

[19]. Suh, A., Prophet, J., 2018, The state of immersive technology research: A literature analysis. *Comput Human Behav.*, 86:77–90. doi:10.1016/j.chb.2018.04.019.

[20]. Slater, M., Sanchez-Vives, M. V., 2016, Enhancing our lives with immersive virtual reality. *Front Robot AI.*, 3:74. doi:10.3389/frobt.2016.00074.

[21]. Diriba Kenea, C., Gemechu Abessa, T., Lamba, D., Bonnechère, B., 2024, Technological features of immersive virtual reality systems for upper limb stroke rehabilitation: a systematic review. *Sensors (Basel).*, 24(11):3546. doi:10.3390/s24113546.

[22]. Azuma, R., Baillot, Y., Behringer, R., et al., 2001, Recent advances in augmented reality. IEEE *Comput Graph Appl.*, 21(6):34–47. doi:10.1109/38.963459.

[23]. Sigrist, R., Rauter, G., Riener, R., Wolf, P., 2013, Augmented visual, auditory, haptic, and multimodal feedback in motor learning: a review. *Psychon Bull Rev.*, 20(1):21–53. doi:10.3758/s13423-012-0333-8.

[24]. Da Gama, A. E., Chaves, T. M., Figueiredo, L. S., et al., 2016, MirrARbilitation: A clinically-related gesture recognition interactive tool for an AR rehabilitation system. *Comput Methods Programs Biomed.*, 135:105–114. doi:10.1016/j.cmpb.2016.07.014.

[25]. Tang, A., Biocca, F., Lim, L., Comparing differences in presence during social interaction in augmented reality versus virtual reality environments: An exploratory study.

[26]. Phan, H. L., Le, T. H., Lim, J. M., Hwang, C. H., Koo, K.-I., 2022, Effectiveness of augmented reality in stroke rehabilitation: A meta-analysis. *Appl Sci.*, 12(4):1848. doi:10.3390/app12041848.

[27]. Cameirão, M. S., Badia, S. B., Duarte, E., Frisoli, A., Verschure, P. F., 2012, The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke. *Stroke.*, 43(10):2720–2728. doi:10.1161/STROKEAHA.112.653196.

[28]. Duff, M., Chen, Y., Cheng, L., Liu, S. M., Blake, P., Wolf, S. L., Rikakis, T., 2013, Adaptive mixed reality rehabilitation improves quality of reaching movements more than traditional reaching therapy following stroke. *Neurorehabil Neural Repair.*, 27(4):306–315. doi:10.1177/1545968312465195.

[29]. Page, M. J., McKenzie, J. E., Bossuyt, P. M., et al., 2021, The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ.*, 372:n71. doi:10.1136/bmj.n71.

[30]. Gustavsson, M., Kjörk, E. K., Erhardsson, M., et al., 2022, Virtual reality gaming in rehabilitation after stroke: user experiences and perceptions. *Disabil Rehabil.*, 44(22):6759–6765. doi:10.1080/09638288.2021.1972351.

[31]. Winter, C., Kern, F., Gall, D., Latoschik, M. E., Pauli, P., Käthner, I., 2021, Immersive virtual reality during gait rehabilitation increases walking speed and motivation: a usability evaluation with healthy participants and patients with multiple sclerosis and stroke. *J Neuroeng Rehabil.*, 18(1):68. doi:10.1186/s12984-021-00848-w.

[32]. Huang, Q., Jiang, X., Jin, Y., et al., 2024, Immersive virtual reality-based rehabilitation for subacute stroke: a randomized controlled trial. *J Neurol.*, 271(3):1256–1266. doi:10.1007/s00415-023-12060-y.

[33]. Mekbib, D. B., Debeli, D. K., Zhang, L., et al., 2021, A novel fully immersive virtual reality environment for upper extremity rehabilitation in patients with stroke. *Ann NY Acad Sci.*, 1493(1):75–89. doi:10.1111/nyas.14554.

[34]. Chatterjee, K., Buchanan, A., Cottrell, K., et al., 2022, Immersive virtual reality for the cognitive rehabilitation of stroke survivors. *IEEE Trans Neural Syst Rehabil Eng.*, 30:719–728. doi:10.1109/TNSRE.2022.3158731.

[35]. Heinrich, C., Morkisch, N., Langlotz, T., Regenbrecht, H., Dohle, C., 2022, Feasibility and psychophysical effects of immersive virtual reality-based mirror therapy. *J Neuroeng Rehabil.*, 19(1):107. doi:10.1186/s12984-022-01086-4.
[36]. Amin, F., Azad, A., Zubair, M., et al., 2024, Effectiveness of immersive virtual reality-based hand rehabilitation games for improving hand motor functions in subacute stroke patients. *IEEE Trans Neural Syst Rehabil Eng.*, 32:2060–2069. doi:10.1109/TNSRE.2024.3405852.
[37]. Li, P., Wang, Z., Zhang, J., et al., 2023, Virtual reality rehabilitation for stroke patients: a meta-analysis of randomized controlled trials. *Comput Methods Programs Biomed.*, 225:107037. doi:10.1016/j.cmpb.2023.107037.
[38]. Kwok, Y., Chen, L., Lee, W., et al., 2024, The impact of virtual reality therapy on cognitive and motor rehabilitation in stroke patients: A review of clinical studies. *J Clin Neurosci.*, 81:13–23. doi:10.1016/j.jocn.2024.04.017.
[39]. Serrano, F., Martínez, C., Sánchez, A., et al., 2023, Effectiveness of virtual reality in post-stroke rehabilitation: a comparative meta-analysis. *Arch Phys Med Rehabil.*, 104(6):1235–1245. doi:10.1016/j.apmr.2023.01.052.