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The Use of Virtual Reality in Neurological Rehabilitation After Stroke: A Review

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ABSTRACT

Background: Stroke frequently causes motor, balance, cognitive, and psychological impairments that require individualized and multidisciplinary rehabilitation. Virtual reality (VR) has emerged as a complementary technology capable of providing interactive, task-oriented training with immediate feedback.

Objective: This review examines the applications, potential benefits, and limitations of VR in post-stroke rehabilitation, with particular attention to motor and cognitive outcomes.

Methods: Publications were identified through searches of PubMed and Google Scholar, with supplementary case material retrieved from ResearchGate. Recent systematic reviews, meta-analyses, randomized clinical trials, and selected clinical studies were narratively synthesized.

Results: The reviewed literature included immersive, semi-immersive, and non-immersive VR systems, customized rehabilitation platforms, commercial gaming devices, and home-based interventions. Reported benefits included improvements in upper-limb function, balance, gait, coordination, activities of daily living, cognitive performance, motivation, and quality of life. Repetitive task practice, adjustable difficulty, multisensory feedback, and engaging virtual environments may support motor learning and neuroplasticity. BCI-based interventions using

motor imagery, motor attempts, EEG, EMG, or fNIRS may complement VR-based rehabilitation but should be considered distinct technologies. However, the evidence remains heterogeneous because of differences in intervention protocols, patient characteristics, outcome measures, and follow-up periods.

Conclusions:VR appears to be a promising adjunct to conventional post-stroke rehabilitation. Its use should be individualized, supervised, and integrated into multidisciplinary care. Larger randomized controlled trials with standardized protocols, longer follow-up, and evaluation of safety, cost-effectiveness, adherence, and home-based applications are needed.

KEYWORDS: virtual reality," "stroke rehabilitation," "post-stroke rehabilitation," "cognitive rehabilitation," and "post-stroke cognitive rehabilitation.

INTRODUCTION

Virtual reality (VR) is a modern technology that has gained increasing attention in recent years and is now being applied in a range of fields, including medicine and rehabilitation. It involves the creation of computer-generated environments that enable users to participate actively and interact with simulated settings. By reproducing situations and tasks similar to those encountered in everyday life, VR creates new possibilities for supporting the rehabilitation process. Despite its rapid development and growing use in medicine, the full potential of VR has not yet been fully explored or evaluated.

VR may be particularly relevant to the rehabilitation of patients following stroke. Stroke can result in varying degrees of motor impairment, balance and coordination disorders, reduced manual dexterity, and cognitive dysfunction, all of which may significantly affect a patient's ability to function independently. Effective rehabilitation therefore requires an individualized approach that considers the patient's current abilities and specific needs. VR systems, including head-mounted displays, can provide a range of therapeutic exercises whose difficulty, intensity, and scope can be modified according to the patient's condition and progress. The use of VR may support improvements in balance, motor coordination, muscle strength, and limb function [1,2].

An important advantage of this technology is its ability to recreate activities and situations that resemble everyday tasks, such as climbing stairs, reaching for objects, or performing specific movements. This allows patients to train in controlled and safe conditions while preparing to

perform similar activities in real-life environments. VR may also increase patient engagement in the rehabilitation process. The interactive nature of the exercises, the possibility of receiving immediate feedback, and the ability to observe one's own progress may improve motivation and adherence to therapy. Furthermore, VR enables therapists to monitor task performance and adjust exercises to the patient's current abilities [3]. In some cases, VR-based exercises may also be performed outside healthcare facilities, including in the patient's home, thereby supplementing traditional rehabilitation.

Despite its potential benefits, the use of VR in rehabilitation also has limitations. This technology may not be suitable or recommended for every patient. Prolonged exposure to a virtual environment may cause dizziness, nausea, visual discomfort, or other unpleasant symptoms in some users. Therefore, VR should be appropriately adapted to the patient's health status and used with consideration of individual needs and abilities.

The aim of this paper is to present the potential applications of VR headsets and related systems in the rehabilitation of patients following stroke, as well as to discuss the possible benefits and limitations associated with this technology. Particular attention is paid to the use of VR as a complement to traditional rehabilitation methods and to its potential impact on the recovery of motor, cognitive, and functional abilities. VR should not be regarded as a replacement for conventional therapy, but rather as a potential complement to it. Combining technological innovations with traditional rehabilitation methods may provide valuable support throughout the therapeutic process and contribute to its effectiveness [4,5].

MATERIALS AND METHODS

This review was based on publications identified through searches of PubMed and Google Scholar. A supplementary case study was retrieved from ResearchGate. The search focused on recent systematic reviews, meta-analyses, and clinical trials investigating the use of virtual reality in post-stroke rehabilitation, with particular attention to motor and cognitive outcomes. The databases were searched using combinations of the following keywords: "virtual reality," "stroke rehabilitation," "post-stroke rehabilitation," "cognitive rehabilitation," and "post-stroke cognitive rehabilitation." Identified records were screened according to the selection criteria established for the review, and relevant findings were synthesized narratively.

WHAT IS VIRTUAL REALITY

The rapid development of digital technologies has transformed societies worldwide. Access to electronic devices and the internet exposes individuals to computer-generated virtual environments that influence many aspects of daily life. Digital technologies facilitate the generation, storage, and processing of large amounts of information and enable rapid interaction between individuals. When used in support of long-term personal goals, digital technologies may contribute to the well-being of healthy individuals [6,7].

In this review, VR is considered a multidisciplinary technology that creates a computer-simulated digital environment and provides complex, realistic, and immediate feedback through software and hardware devices, including headphones, head-mounted displays, glasses, gloves, and vests. These systems can provide users with a sense of immersion and presence. In recent years, VR has increasingly been introduced into medicine, particularly in the field of rehabilitation [8,9].

VIRTUAL REALITY IN POST-STROKE REHABILITATION

Stroke is one of the leading causes of mortality and long-term disability worldwide, accounting for an estimated 116 million disability-adjusted life years (DALYs). Arterial hypertension is the most common modifiable risk factor and the leading contributor to stroke onset. Outcomes after stroke are influenced by several factors, particularly the location and extent of the brain injury and the degree of neurological recovery achieved during rehabilitation.

Stroke survivors may experience a broad range of impairments affecting both physical and cognitive functioning. Motor deficits are among the most common consequences, occurring in up to 80% of patients. Stroke may also cause disturbances in language, sensory processing, vision, and behavior, as well as swallowing difficulties such as dysphagia. Cognitive impairments are also frequent and may involve difficulties with memory, attention, orientation, awareness, and overall intellectual functioning. The combination and severity of these deficits can substantially reduce patients' independence and ability to perform activities of daily living [10,11].

These disabilities can profoundly affect patients' lives, limiting their ability to work and participate in social activities. Consequently, stroke rehabilitation is a complex, multidisciplinary process associated with substantial personal, family, and societal costs.

Effective management requires well-trained multidisciplinary teams. Therefore, combining conventional rehabilitation techniques with emerging technologies, guided by current scientific evidence, has become an important component of contemporary stroke care [12,13].

VIRTUAL REALITY IN MOTOR REHABILITATION

A six-week pilot randomized clinical trial showed that combining neurological physiotherapy with VR and video games was more effective for patients recovering from stroke than neurological physiotherapy alone. Significant improvements were observed in the Motricity Index, Trunk Control Test, Tinetti Balance Scale, Berg Balance Scale, and Functional Ambulation Classification among patients treated at the Hospital of Sagunto [14].

A meta-analysis demonstrated that the benefits of VR in post-stroke rehabilitation may depend not only on the use of VR itself but also on the level of immersion. VR can be fully immersive, completely blocking perception of the real world; semi-immersive, using screens or headsets to provide partial immersion; or non-immersive, allowing patients to perceive the real and virtual environments simultaneously. The analyzed studies evaluated various VR modalities delivered through either customized software or commercial gaming devices. Some platforms included standardized tasks assessing object manipulation, manual dexterity, and fine motor coordination, such as lifting and transporting small objects, stacking checkers, and controlled pouring of liquids. These tasks provided timed assessments of proximal and distal upper-limb function relevant to activities of daily living. Control groups received conventional occupational or physical therapy matched to the VR interventions in duration and intensity. Outcomes included validated measures of upper-limb motor function, activities of daily living, dexterity, spasticity, quality of life, and patient-reported functional use. Moreover, initiating VR-based interventions within the first six months after stroke, when neuroplasticity may be particularly enhanced, and continuing therapy for more than six weeks appeared to be important for achieving greater therapeutic benefits [15,16,17].

Another study used a pretest–posttest control-group design. Outcomes were assessed in two groups at two time points: before and after six weeks of intervention. The VR training sessions lasted 15 minutes and were conducted in a well-equipped room. The equipment included a PlayStation console, VR goggles that immersed patients in the virtual environment, and controllers for interacting with the game. A screen allowed the examiner to observe what the patient saw and provide feedback. The results supported the hypothesis that VR-based

rehabilitation may provide additional benefits. This may be explained by practicing upper-limb movements in an engaging environment with immediate visual and auditory feedback. The training also encouraged participants to complete each session and was well accepted. Repeated practice in this environment may enhance motor performance and promote neuroplasticity, as suggested by electroencephalography findings, particularly in brain regions involved in motor planning.

Notably, repetitive bilateral training using VR controllers required participants to strike virtual paddles with varying levels of force. The statistically significant improvements observed in the study may therefore be attributed to the combined effects of symmetric and asymmetric bilateral upper-limb movements. These activities may have helped patients remain interactive, responsive, and motivated compared with routine functional tasks included in the prescribed task-oriented training program [18,19,20].

A related neurotechnology discussed in the literature is the brain–computer interface (BCI). BCI technology represents a promising adjunct to conventional stroke rehabilitation. Non-invasive BCI systems based on motor imagery (MI) or motor attempts (MA) can activate sensorimotor brain regions in patterns that partially resemble those associated with actual movement, potentially supporting motor recovery. These systems acquire electroencephalographic (EEG) signals associated with the patient's MI or MA, decode the underlying brain activity using computational algorithms, and use external devices to assist or reinforce limb movements. Randomized controlled trials have reported significant improvements in motor-function outcomes in more than 60% of patients with stroke, suggesting that MI- and MA-based BCI rehabilitation may promote activity-dependent neuroplasticity [21,22,23].

A randomized, double-blind, controlled clinical trial was conducted in patients with MRI-confirmed subcortical ischemic stroke accompanied by hemiplegia who were receiving treatment at a rehabilitation center. Outcomes were assessed using electromyography (EMG) and functional near-infrared spectroscopy (fNIRS). EMG analysis demonstrated greater muscle recruitment and compensatory activation of adjacent muscles in the BCI group. Significant increases in root mean square (RMS), integrated EMG (iEMG), and average EMG (aEMG) values were observed during shoulder and elbow flexion compared with baseline. No significant changes in any EMG parameters were observed in the control group. In particular, biceps activity on the paretic side increased significantly in the BCI group but not in the control

group. fNIRS imaging revealed greater activation of the ipsilesional motor cortex and enhanced functional connectivity with the prefrontal cortex, supplementary motor area, sensory cortex, and contralateral hemisphere in the BCI group after treatment. These findings suggest that a BCI rehabilitation system combining motor imagery and motor attempts may enhance activity in cognitive and motor regions, support interhemispheric and intrahemispheric compensation, and promote motor recovery after stroke [24].

Taken together, the available meta-analyses and clinical trials suggest that VR may improve motor rehabilitation outcomes after stroke. However, the results vary according to the type of system, level of immersion, intervention dose, stroke phase, and patient characteristics. The current evidence therefore supports the use of VR as a complementary intervention rather than as a universal replacement for conventional rehabilitation.

VIRTUAL REALITY IN COGNITIVE FUNCTION REHABILITATION

Rehabilitation after stroke should address not only physical function but also cognitive function. Post-stroke cognitive impairment (PSCI) has been reported in 25% to 80% of patients, and a study conducted in a Chinese cohort found that 57.8% of 963 stroke patients exhibited depressive symptoms [25,26]. Although this section focuses on cognitive rehabilitation, much of the evidence discussed below concerns BCI-based neurofeedback rather than VR alone; these technologies should therefore be distinguished in the final synthesis.

BCI technology has considerable potential to support cognitive rehabilitation in patients with stroke, particularly through neurofeedback-based cognitive assessment and memory training. Studies suggest that BCI systems using theta- and alpha-band activity, together with precise control of item presentation, may improve memory performance [27,28]. Stroke can affect attention, memory, executive function, and language processing. These deficits are typically a consequence of disrupted neural networks or functional impairment in specific brain regions. For example, dysfunction of the frontal and parietal lobes may lead to attention deficits and executive dysfunction, whereas hippocampal atrophy is strongly associated with memory decline. BCI systems offer dynamic assessment of these impairments by decoding EEG patterns and other neural markers. By modulating these signals, BCI systems may target specific cognitive impairments and provide tailored therapeutic interventions [26,29,30,31].

Neurofeedback training provides real-time feedback that allows patients to consciously regulate abnormal neural activity. Evidence suggests that this approach may improve attention and

memory in stroke populations. For example, neurofeedback interventions have resulted in measurable improvements in short- and long-term verbal memory in patients and healthy controls. In a proof-of-principle study, stroke survivors were able to modulate their own brain activity through neurofeedback training as successfully as healthy controls. Moreover, the positive effects on memory were observed in both stroke patients and healthy controls and were stronger than the effects of traditional cognitive rehabilitation in the stroke group [32]. These findings highlight the potential of BCI-based neurofeedback for supporting cognitive recovery. Aphasia, or the loss or impairment of language caused by brain damage, is one of the most disabling cognitive and communication impairments following stroke. Its clinical manifestations depend on the location of the brain lesion. Expressive aphasia is commonly associated with lesions involving Broca's area, whereas damage to Wernicke's area may result in difficulties with language comprehension. BCI-supported rehabilitation can capture and decode neural signals associated with language processing, providing real-time feedback intended to strengthen relevant neural activity and connectivity. Interestingly, neurofeedback targeting relative alpha-wave power in the occipital lobe produced moderate improvements in naming, image and color recognition, sentence completion, and language fluency. These findings came from an experiment involving two patients with chronic stroke, each of whom had experienced a stroke more than six months earlier. Each participant completed 15 sessions, with two sessions per week, at home using a computer. The study suggested that alpha neurofeedback may induce neuroplastic changes in chronic stroke and may be associated with improvements in emotional state, cognitive function, and motor performance [26,33,34].

It is also important to recognize that stroke survivors frequently experience mental-health disturbances. Post-stroke depression (PSD) and anxiety may reduce motivation, adherence, and overall quality of life and may negatively affect rehabilitation outcomes. Patients may become less engaged in the training process and may perceive it as ineffective or pointless. According to the cited studies, approximately 25% to 50% of patients experience depression during the acute phase, and about 30% continue to experience depressive symptoms during the chronic phase. Similarly, post-stroke anxiety (PSA) affects approximately 18% to 34% of survivors during the first year, with rates remaining relatively stable for up to five years after stroke. Patients with PSA may experience excessive concern about their prognosis, including fear of recurrence, returning to work, falling, or losing independence. This anxiety may exacerbate depression and cognitive impairment, further worsening rehabilitation outcomes. Nevertheless,

a review published in 2012 concluded that post-stroke anxiety had received substantially less attention than other psychological problems after stroke [35,36,37,38].

Mental-health rehabilitation in this population may also incorporate VR. BCI technology can monitor a patient's emotional state in real time by decoding relevant patterns of brain activity. EEG signals can be used to track emotional changes through frequency-specific features. BCI models may also integrate multimodal signals, such as EEG, heart-rate variability, and electrodermal activity. This integrative approach can provide a more comprehensive assessment of emotional dynamics. BCI systems with affective closed-loop interactions may offer a useful approach to emotional regulation. For example, participants have successfully modulated musical feedback by recalling emotionally salient memories, illustrating the potential of BCI-assisted emotional self-regulation. Closed-loop systems may also detect negative emotional states and trigger real-time interventions, such as mood-regulating music, VR-based meditation environments, or neurofeedback training, to support emotional balance.

Randomized controlled trials have reported that immersive or combined VR-based interventions may improve cognitive function, with particularly positive effects observed when VR is combined with robotics and personalized feedback. Secondary outcomes, including mental health, quality of life, and functional independence, have also shown positive trends following VR-based therapy. One single-blind randomized controlled trial included 54 patients with stroke who attended the Robotic and Behavioral Neurorehabilitation Unit of the IRCCS Centro Neurolesi "Bonino Pulejo" in Messina, Italy. The study aimed to evaluate the effects of VR rehabilitation on motivation, cognitive function, and emotional state in post-stroke survivors compared with conventional cognitive rehabilitation. It was conducted between October 2023 and December 2024.

The researchers used several scales to assess the main outcomes. Motivation was evaluated using the McClelland test, which is designed to identify the predominant motivational need influencing an individual's behavior. It includes three primary subscales: ACH, which measures the drive to excel and succeed in challenging tasks; AFF, which assesses the desire for relationships and social connections; and POW, which reflects the motivation to influence others and exert control over their environment. Cognitive function was assessed using the Montreal Cognitive Assessment (MoCA), which evaluates several domains, including attention, memory, and executive function. Emotional state was assessed using the Hamilton Anxiety

Rating Scale (HAM-A) and the Hamilton Depression Rating Scale (HAM-D), which provide information about anxiety and depressive symptoms.

The substantial improvements in cognitive performance observed in the experimental group suggest that immersive environments may support cognitive recovery following stroke. Positive trends were also observed in secondary outcomes, including mental health, quality of life, and functional independence. These findings support the multidimensional potential of VR-based rehabilitation [39,40,41,42].

DISCUSSION

The present review analyzed studies involving stroke survivors with both ischemic and hemorrhagic stroke. Overall, the available meta-analyses and randomized clinical trials suggest that VR-based rehabilitation may provide benefits beyond conventional therapy. However, the magnitude and consistency of these effects vary according to the type of intervention, level of immersion, treatment dose, and individual patient characteristics.

Emerging technologies, including brain–computer interfaces and VR systems with different levels of immersion, make it possible to adapt therapeutic tasks to patients' individual needs. VR hardware and interactive interfaces allow patients to practice a wide range of activities, from simple to more complex tasks, in a controlled and safe environment. Neurofeedback may further support the monitoring of patients' progress and enable therapists to adjust tasks according to their current abilities.

VR may support both motor and cognitive rehabilitation. However, effective post-stroke care should be holistic and delivered by a multidisciplinary team. Attention to mental health is particularly important, as stroke survivors may experience fear about their future, reduced motivation, anxiety, and post-stroke depression. In addition, stroke-related cognitive impairments may affect attention, memory, executive function, and language processing. Addressing these physical, cognitive, and psychological consequences is essential for achieving optimal rehabilitation outcomes.

CONCLUSION

Virtual reality is a promising complementary tool in post-stroke rehabilitation. The reviewed evidence suggests that VR-based interventions may support recovery of motor function,

balance, coordination, upper-limb dexterity, mobility, activities of daily living, and selected cognitive functions. Immersive, semi-immersive, and non-immersive systems can provide repetitive, task-oriented, and engaging exercises with immediate feedback. Their flexibility allows rehabilitation tasks to be adapted to the patient's abilities, treatment goals, and stage of recovery.

VR should be integrated into individualized, multidisciplinary rehabilitation rather than used as a replacement for conventional therapy. Its potential advantages include increased patient engagement, safe practice of functional activities, objective monitoring of performance, and the possibility of extending rehabilitation into the home environment. However, the current evidence remains heterogeneous because studies differ in patient characteristics, VR systems, treatment intensity, outcome measures, and follow-up duration. In addition, BCI-based interventions should be distinguished from VR-based rehabilitation, although the two technologies may be combined.

Further research should include larger, well-designed randomized controlled trials with standardized intervention protocols and outcome measures. Long-term effectiveness, safety, cost-effectiveness, patient selection, adherence, and the effects of home-based treatment also require further investigation. At present, VR appears to be most valuable when carefully selected, supervised, and combined with evidence-based conventional rehabilitation.

Disclosure

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