

Prospects for the Application of Virtual Reality Technologies in the Early Rehabilitation of Stroke Patients

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Abstract: Among contemporary technological advancements, virtual reality (VR) emerges as a potent and promising modality for addressing primary rehabilitation goals. Empirical evidence confirms that VR-based rehabilitation can generate realistic perceptual experiences and corresponding patient responses, thereby enhancing the efficacy of cognitive and motor rehabilitation in a cost-efficient manner. However, the success of this rehabilitation paradigm is predominantly contingent upon the specific technologies and clinical protocols implemented by practitioners. This article examines the current pertinent issue of implementing virtual reality technologies for patients with acute ischemic stroke during the early rehabilitation phase. The authors focus specifically on the neurophysiological correlates of VR application and the associated mechanisms of cerebral neuroplasticity. We delineate the characteristic features and contemporary approaches to VR implementation, while proposing a novel conceptual framework for deploying advanced VR technologies in the intensive care unit setting.

Keywords: Acute ischemic stroke; Virtual reality; Early rehabilitation; Neuroplasticity; Intensive care unit

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1. Introduction

The primary objective of rehabilitation is to enhance the quality of life and facilitate the recovery of independent living capacity. In accordance with established clinical guidelines and protocols, rehabilitation for patients with acute ischemic stroke should be initiated as early as possible. The rehabilitation process is often protracted, not only due to profound motor deficits but also frequently because of patient disengagement in therapy sessions and/or limitations in human and technical resources. The principal aims of early rehabilitation are to ensure a timely commencement and to improve both the quality and quantity of rehabilitation procedures. Iosa *et al.* ^[1] suggested that an optimal approach for the rehabilitation of cognitive and motor functions involves integrating standard rehabilitation protocols with novel technologies, such as robotics, brain-computer

interfaces (biofeedback), non-invasive brain stimulators (transcranial magnetic stimulation), and wearable motion analysis devices (smartphones and tablets). However, not all acute ischemic stroke patients in the intensive care unit receive comprehensive early rehabilitation interventions; considering their critical condition (level of consciousness, hemodynamic, and laboratory parameters), the recovery program is often limited to bed positioning and basic nursing care.

2. Virtual reality: Advanced technologies for achieving key rehabilitation goals

Among contemporary technological advancements, virtual reality (VR) represents a potent and promising modality for attaining primary rehabilitation objectives^[2]. Empirical evidence has demonstrated that VR-based rehabilitation can generate realistic perceptual experiences and elicit corresponding patient responses, thereby enhancing the quality of cognitive and motor rehabilitation as a cost-effective modality^[3]. Studies have further established virtual reality as a safe and effective rehabilitation method for improving not only limb motor function but also cognitive performance in the daily activities of patients who have suffered acute ischemic stroke^[3].

However, the success of VR rehabilitation is predominantly contingent upon the specific technologies and clinical protocols implemented by practitioners. The application of VR technology necessitates caution due to the risk of potential adverse effects such as cybersickness^[18,25], which manifests as motion-sickness-like symptoms including nausea, dizziness, disorientation, headache, sweating, and general discomfort^[21]. In this context, safety is defined as the absence of adverse events associated with VR therapy, while tolerability refers to the ability of patients to complete prescribed sessions without interruption due to discomfort or other VR-related issues^[26].

Current research on VR rehabilitation exhibits significant heterogeneity due to the lack of standardized software and hardware for VR therapy^[3]. No unified methodology exists for conducting VR-based rehabilitation. For instance, clinical studies led by Kleim^[4] and Kim^[5] applied VR technologies in patients with unilateral spatial neglect. Both VR and control groups received equivalent training volumes, aligned with the principles of intensity, repetition, and timing, accounting for cerebral neuroplasticity^[4]. VR rehabilitation methodologies can incorporate various feedback modalities, such as visual and tactile^[5], or auditory and verbal^[5]. However, the VR protocol in Kim's study^[5] engaged patients in more active movements (e.g., rotating the upper limb and trunk) compared to Kleim's protocol^[4], where the task involved pressing a keypad to control an avatar's position while crossing a street. Furthermore, none of the 23 reviewed studies on VR rehabilitation specified the exact session duration in minutes, though it was reported that patients received an average of 13 sessions each. Additionally, it is important to note that all analyzed studies utilized non-immersive VR systems, which may impact the sense of presence and potential therapeutic outcomes.

Therefore, the application of VR technologies in rehabilitating patients with post-stroke unilateral spatial neglect represents a promising approach compared to conventional rehabilitation methods, primarily by overcoming the inherent limitations of traditional techniques. Virtual reality enables the presentation of realistic scenarios and participation in functional activities that would be unsafe for patients to perform in real-life settings. VR-based rehabilitation demonstrates strong patient engagement, and the difficulty level can be systematically graded according to the severity of unilateral neglect.

According to a meta-analysis on the efficacy of interactive virtual reality training, studies demonstrated enhanced patient motivation alongside improved stimulation of cognitive domains, including attentional and amnesic functions, as well as visuospatial cognition. This ultimately led to improved behavioral competencies in patients with acute ischemic stroke^[6]. The establishment of a positive learning experience facilitates the

prolongation of rehabilitation sessions ^[7]. By employing the “simple-to-complex” rehabilitation principle, VR enables the gradual simulation of real-life situations without injury risk, thereby preparing patients for more challenging exercises in the actual environment ^[7,8].

From a neurophysiological perspective, the application of VR technologies in patients with acute ischemic stroke stimulates cerebral neuroplasticity through the engagement of cholinergic and dopaminergic neurotransmitter pathways ^[9]. Research by Bagece *et al.* ^[10] has established a connection between cognitive and motor functions, highlighting the positive impact of cognitive capacities on motor rehabilitation, particularly when physical therapy is initiated with VR technologies and conducted within a virtual environment.

Early research on VR rehabilitation has identified several critical factors that must be considered when designing VR interventions to enhance the sense of immersion and presence, potentially improving overall therapeutic outcomes. These factors include: interface usability ^[11], user agency (sense of control), task realism, intervention duration ^[12], social components (e.g., interaction with avatars) ^[13], and system-level characteristics (e.g., wider field of view, multimodal interaction, first-person perspective embodiment, and feedback devices) ^[10].

In recent years, VR technology has seen increasingly widespread application across various rehabilitation domains, including neurological, neuropsychological, pediatric, and orthopedic rehabilitation ^[16,17]. By leveraging gamification—the integration of game elements into non-game contexts—VR-based multisensory therapy enhances patient motivation and engagement in physical rehabilitation. This approach reduces the subjective perception of physical exertion, monotony, and boredom often associated with conventional rehabilitation programs ^[24]. Furthermore, VR devices and video games enable the adjustment of exercise intensity and complexity for each individual patient. This capability facilitates highly personalized and emotionally engaging training of functional movements within a safe virtual environment, including applications in tele-rehabilitation under remote supervision ^[23].

3. Virtual reality in neurological rehabilitation

Neurological disorders, such as stroke sequelae and chronic pain syndromes, profoundly impact independence and quality of life, particularly when upper extremity function is compromised. While conventional physical therapy provides some neuronal recovery, there remains a need to explore novel, effective rehabilitation technologies. VR technology can serve as a tool for investigating, diagnosing, and treating neurological and neuropsychological disorders ^[15]. It is hypothesized that multisensory feedback may enhance the neural plasticity underlying neurological and neuropsychological recovery. Skills acquired during VR therapy can potentially transfer to real-world activities ^[22]. The integration of hardware and software enables users to interact with virtual objects and environments as if they were tangible entities. Within the rehabilitation context, the inherently gamified nature of VR makes the experience more enjoyable for patients and promotes engagement in virtual therapeutic exercises specifically designed for neurological recovery ^[21].

4. Motor disorders in post-stroke patients

The visual, auditory, and kinesthetic multisensory nature of immersive VR (iVR) enables patients to become fully immersed in three-dimensional virtual environments, where they experience an altered reality—a phenomenon utilized in rehabilitating post-stroke patients ^[20]. Interactive iVR provides stroke survivors with multi-channel sensory input through devices such as controllers, gloves, and exoskeletons. This approach

promotes enhanced neural functional plasticity and can significantly improve both upper extremity function and balance control ^[8,14].

Bailey ^[20] reported a clinical case of impaired right-hand function in a 75-year-old male following an ischemic stroke. After initial hospitalization and rehabilitation center treatment, the patient regained normal ambulatory capacity but persisted with aphasia and right upper extremity joint contractures with motor deficits (preserving only active finger movement). Seven years post-stroke, he sought additional therapeutic intervention. An occupational therapist developed a comprehensive VR exercise program for tone management using a headset application where the patient tracked a flying dragon's movement through gaze control, facilitating cervical spine stretching and improved range of motion (ROM). Additional computer games included Balloon Blast, requiring swiping motions to burst colored balloons for shoulder ROM enhancement, and Color Match, incorporating upper extremity boxing-like movements to engage cognitive components. Following each session, the patient could visualize results and track progress. Complementing daily VR therapy, the patient performed physical exercises five days weekly, including weight-bearing on the right upper extremity in a quadrupod position and performing active-assisted movements. The therapeutic protocol was continuously updated throughout VR therapy to maintain challenge and promote progression in the digital environment. Upon treatment completion, the patient demonstrated resistance training capacity with approximately 1 kg weights for the right hand and arm, showing improvements across all measured domains: increased right-hand movement speed in response to stimuli, 10° improvement in shoulder flexion ROM, and 8.5% enhancement in movement quality (acceleration-deceleration during motion). This case demonstrates that combining VR with conventional therapy can substantially improve strength and mobility in the affected upper extremity, thereby enhancing daily living functionality even years post-stroke ^[20].

Upper extremity impairment occurs in over 80% of stroke cases, manifesting as weakness or paralysis, reduced range of motion, spasticity, coordination deficits, sensory alterations, and fine motor dysfunction ^[22]. Motor rehabilitation aims to improve motor control, coordination, and functional capacity by engaging the affected limb in purposeful activities within virtual environments, such as grasping and manipulating freely moving objects, or performing wrist and finger extension movements ^[23]. Mirror therapy represents a widely adopted rehabilitation technique utilizing a static mirror to reflect the unaffected upper extremity, thereby creating a visual illusion of normal limb movement by replacing the view of the impaired limb with its mirror image. This virtual reflection of the unaffected limb facilitates the brain's perception of normal function in the impaired extremity. Through repeated practice, this visual illusion is believed to reorganize neural pathways, consequently enhancing upper extremity motor function and reducing pain in post-stroke patients ^[19,24].

Virtual reality serves as an effective complementary therapy for restoring verbal communication in patients with post-ischemic stroke aphasia. Rehabilitation using the BTS-Nirvana device, which employs semi-immersive VR for treating chronic post-stroke aphasia, demonstrated significantly greater improvement compared to the control group receiving conventional speech and cognitive training. These therapeutic benefits remained sustained at the six-month follow-up assessment ^[27]. Furthermore, specialized mobile VR applications have been developed specifically for speech rehabilitation in post-stroke aphasia patients ^[28].

5. Discussion

Most clinicians and researchers conceptualize VR-assisted rehabilitation primarily as either a biofeedback

therapy methodology combined with physical rehabilitation techniques, or as VR therapy utilizing sophisticated software for stable patients in hospital wards or during the secondary rehabilitation phase with moderate to mild neurological deficits. However, rehabilitation interventions should ideally commence for patients receiving treatment in intensive care units. Current clinical practice demonstrates that the majority of patients requiring respiratory and/or vasopressor support due to a critical condition often receive inadequate rehabilitation volumes, primarily attributable to unstable hemodynamic parameters, ultimately compromising disease outcomes and rehabilitation prognosis.

Based on current understanding of cerebral neuroplasticity, rehabilitation should initiate with elementary color-based programs synchronized with lower limb stimulation devices. This approach enables early rehabilitation implementation during the initial hospitalization days, regardless of patient severity. The sole prerequisite for initiating VR rehabilitation is spontaneous eye opening.

6. Conclusion

The implementation of diverse VR-based rehabilitation programs is associated with significant improvement in patients' neurological status, demonstrating enhancement in strength and range of motion, improved coordination, and pain alleviation. Most studies indicate that VR-based neuromotor rehabilitation (either as a standalone intervention or combined with conventional methods) may yield superior outcomes compared to traditional therapy alone. Furthermore, immersive VR emerges as a promising rehabilitation tool, particularly for stroke survivors and individuals with complex regional pain syndrome. Evidence has demonstrated the efficacy of in-person VR-based cognitive training in enhancing neuropsychological functions. Regarding telehealth-based VR intervention, current research suggests its therapeutic effects are comparable to those achieved through conventional rehabilitation approaches.

Rehabilitation necessitates personalized treatment plans tailored to individual patient conditions and progress. VR rehabilitation applications must demonstrate flexibility and adaptability to accommodate diverse patient needs and capabilities. To ensure optimal efficacy, these systems should provide adjustable difficulty levels and target-specific motor skill training. The integration of virtual reality technologies into conventional rehabilitation practices constitutes a complex interdisciplinary endeavor, requiring close collaboration between rehabilitation specialists and software engineers. Such cooperation is essential for achieving seamless implementation of VR within existing clinical workflows, alongside developing standardized protocols and methodological guidelines for rehabilitation applications. Typically, research teams create customized immersive virtual environments that can be adapted to intended use cases according to both rehabilitation therapists' requirements and patients' needs. Expanding VR applications requires a comprehensive evaluation of suitability and long-term effects across different age groups, disability levels, and clinical presentations.

Given the current sophistication of VR technologies capable of simulating diverse scenarios, early VR rehabilitation can be implemented for patients in the hyperacute phase of stroke who are hospitalized in intensive care units, including those in critical condition. This approach minimizes risks of complications and iatrogenic injury while enhancing rehabilitation potential for stroke patients.

Mitigation of potential adverse effects must be prioritized in VR rehabilitation protocols to prevent negative patient outcomes. For broader implementation of immersive VR as a rehabilitation tool, researchers require the capacity to assess, compare, and address potential adverse effects of immersive VR rehabilitation.

This necessitates developing pathology-specific VR protocols while incorporating quantifiable metrics for cybersickness. Systematic correlation of quantitative measurements with clinical outcomes is essential for monitoring treatment efficacy and analyzing functional progress throughout VR rehabilitation.

The application of VR in restorative treatment represents a sufficiently safe and promising technology, enabling the personalization and precise titration of rehabilitation interventions according to individual patient needs and capabilities. The implemented gamification enhances patient treatment adherence. Nevertheless, study authors emphasize the necessity for randomized controlled trials to standardize VR technologies, optimize treatment protocols, and analyze long-term therapeutic effects.

Disclosure statement

The authors declare no conflict of interest.

Author contributions

Yiting Tao completed the writing and translation of the paper, Yiqing Chen was responsible for data collection, while Zhi Li conceived the idea of the study, reviewed and wrote this paper.

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