Virtual Reality in Cerebrovascular Rehabilitation: A Mini Review on Clinical Efficacy and Neurological Impacts

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Abstract: The application of virtual reality (VR) technology in both upper and lower limb rehabilitation represents a significant advancement in the field of medicine. VR-based therapies provide patients with the opportunity to engage in intensive, repetitive, and targeted exercises that promote neuroplasticity and improve the motor skills necessary for daily life. VR has long been recommended for the rehabilitation of conditions such as in case of ischemic stroke, Parkinson's disease, and multiple sclerosis, further underscoring its versatility and therapeutic potential. In our study, we evaluated the effectiveness of VR therapy focusing on stroke rehabilitation. The reviewed VR systems provided motion analysis, tracking, feedback reinforcement, and realistic environments to facilitate the restoration of motor functions. Furthermore, we developed a VR-based therapy aimed at both upper and lower limb motor functions, combined with traditional rehabilitation. The application of VR technology not only promotes the improvement of motor functions but also offers economic advantages by reducing the burden on healthcare workers and increasing rehabilitation capacity. Further research is needed to determine the optimal conditions for applying VR therapy in clinical practice.

Keywords: virtual reality; stroke; ischaemic; subacute; virtual; exercise; training; intensity

1 Introduction

In recent years, technology-enhanced rehabilitation, particularly through the use of virtual reality (VR), augmented reality (AR), and robotics, has revolutionized therapeutic approaches in medicine [1]. VR technology allows patients to engage in immersive, interactive environments that simulate real-world scenarios, enhancing the rehabilitation process by providing repetitive, task-oriented, and personalized exercises. These simulations are critical for promoting neuroplasticity and motor learning, which involve sustained changes in motor behavior critical for recovery [2-3]. VR-based rehabilitation offers several key benefits over traditional rehabilitation methods. It provides real-time feedback, allowing patients to immediately adjust their movements, which enhances motor learning and accuracy. The engaging nature of VR can significantly improve patient motivation, adherence to therapy, and overall outcomes, which are often challenging in conventional rehabilitation settings. Studies have shown that VR interventions can substantially enhance, i.e., arm motor recovery in stroke patients compared to traditional methods, demonstrating a significant impact on motor impairment improvements [4, 5].

The integration of VR technology in rehabilitation facilitates precise tracking of patient progress and enables therapists to tailor exercises specifically to individual patient needs, thereby improving the effectiveness of therapy. By incorporating game-like elements, VR transforms repetitive exercises into more engaging activities, which is a critical factor for maintaining long-term patient motivation and adherence to therapy [6]. The use of VR in rehabilitation, particularly for post-stroke patients and those with other neurological impairments, marks a significant advancement in the field. VR enables the restoration of motor, cognitive, and sensory functions in both upper and lower limbs, which are crucial for daily activities and overall quality of life [7]. Traditional rehabilitation methods often lack the necessary intensity and individualized approach. Furthermore, the repetitive and monotonous nature of conventional therapies can lead to decreased patient motivation, slowing down recovery and negatively affecting therapeutic outcomes. Exercises with real-time feedback promote neuroplasticity—the brain's ability to reorganize itself by forming new neural connections, which is essential for recovering lost functions.

One of the most significant advantages of VR is its ability to maintain patient engagement and motivation throughout the rehabilitation process. The dynamic, game-like nature of VR tasks encourages patients to participate actively and consistently. This technology also allows for the personalization of rehabilitation programs, enabling therapists to select exercises that are specifically tailored to the needs and capabilities of each patient. VR therapy can be extended into the home environment, offering an economically viable solution that reduces the burden on healthcare facilities while providing high-quality professional supervision. VR-based rehabilitation has also shown promise in managing chronic conditions such as Parkinson's disease and multiple sclerosis. As VR technology continues to evolve, its role in personalized and effective rehabilitation is likely to expand, offering new hope for patients with a wide range of neurological and physical impairments [8].

VR-based therapy offers distinct benefits categorized into technical, medical, and economic aspects, enhancing the overall effectiveness of rehabilitation.

Technical Advantages: VR technology provides a highly controlled, customizable environment that enables patients to engage in intensive, repetitive, and targeted exercises.

Medical Advantages: The simulated environments in VR therapy promote neuroplasticity, which is essential for the recovery of brain-damaged areas. These technologies allow for targeted exercises that can improve motor, cognitive, and sensory functions, thereby helping patients regain skills more effectively. Remote virtual rehabilitation, including VR, AR, and gamification, offers physical improvements comparable to traditional face-to-face therapy [9].

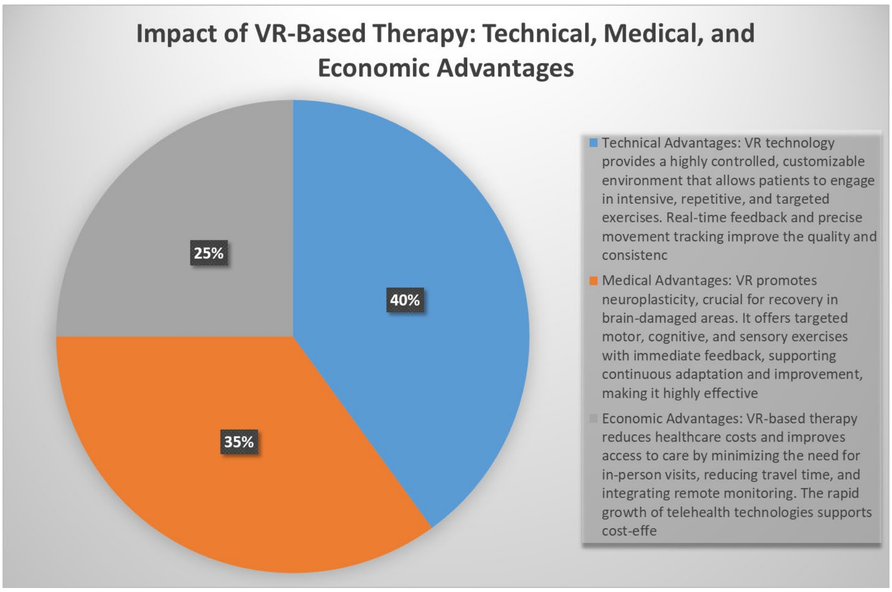

Figure 1
Distribution of technical, medical, and economic advantages of VR-based therapy

Economic Advantages: VR-based therapy, similar to other telemedicine applications, has the potential to significantly reduce healthcare costs and improve access to care. The ongoing expansion of telemedicine capabilities indicates a strong potential for cost savings and improved accessibility, especially for populations with limited access to specialized care [10-13]. Furthermore, this technology allows for more patients to be treated by the same number of personnel. Figure 1 shows summarized assumptions about the impact based on literature review. Numbers were averaged from papers dealing with this issue [14-20].

Our analytical research indicates that VR-based rehabilitation may be more effective than traditional therapeutic methods, particularly in improving upper and lower limb motor functions, gait performance, balance, and range of motion [21, 22]. For example, the use of VR technology enables exercises aimed at increasing the range of motion and muscle activation in the shoulder, elbow, and wrist for the upper limbs, while in lower limbs' rehabilitation, the focus is on improving the range of motion in the hip, knee, and ankle. VR-based exercises offer the opportunity to combine movements of the upper and lower limbs, which are critical for improving functional movement patterns, such as walking and balance [23, 24].

All these aspects of VR technology significantly contribute to improving long-term outcomes and increasing patients' independence [25, 26]. As VR technology continues to evolve, its role in personalized and effective rehabilitation is likely to expand, offering new hope for patients with a wide range of neurological and physical impairments. [27-30]. This paper presents a current development targeting VR-based rehabilitation and future perspectives based on literature review.

2 Methods

In our study, we will focus on the efficacy of VR therapy in both upper and lower limbs' rehabilitation following a stroke. The patients will receive a combination of VR-based and traditional therapies, which will be applied together to optimize rehabilitation outcomes.

2.1 System Description

The developed VR system provides precise motion analysis and real-time feedback throughout the therapy. The methods employed include:

- *Motion Analysis and Tracking:* Xsens and Qualisys systems for motion tracking are used, enabling accurate three-dimensional (3D) analysis of full-body movements. These systems employ advanced motion capture technology, including inertial sensors and optical cameras to precisely track joint positions and body segments in real-time. Xsens uses wearable sensors attached to various body parts to capture data on angular velocity, acceleration, and joint orientation. This data is essential for identifying dynamic parameters like body posture, balance, and coordination during movement, offering a comprehensive view of the kinematic chain. Qualisys, on the other hand, is an optical motion capture system that uses high-speed cameras and reflective markers placed on the body to accurately record the spatial position and trajectory of each body segment. This setup allows for detailed analysis of joint angles, velocities, accelerations, and ranges of motion (ROM) across different tasks and exercises. The integration of these two technologies enables precise monitoring of movement disorders, asymmetries, and coordination issues, which are critical for developing personalized rehabilitation strategies.

- *Interactive VR Exercises:* During rehabilitation, patients will perform various VR-based exercises aimed at improving motor functions in both upper and lower limbs. Games are designed with a simple user interface and virtual environment. Later, more sofisticated scenarios can be added using enhanced graphical options.
    - *Collecting Coins:* Patients collect virtual coins placed at different heights and distances, which increase the range of motion of the shoulders and improve muscle control (Fig. 2).

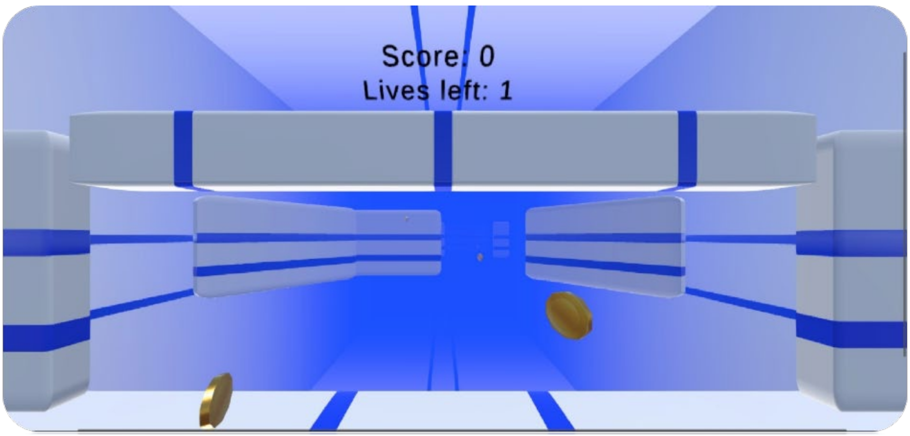

Figure 2
Screen-shot of the Interactive VR Exercises Program. Patients have to collect randomly organized coins while navigating through the virtual space.

    - *Avoiding Obstacles:* In the exercise of avoiding moving obstacles, patients improve their reaction time and overall mobility by moving their arms, which also enhances the stability of their lower limbs (Fig. 3). This dynamic task challenges coordination and motor skills, making it an effective rehabilitation tool for improving functional agility and body awareness.

- *Squatting and Balance Tests:* These exercises focus on maintaining balance in various postures, with the VR system monitoring the movement of the patients' center of pressure (COP). Patients perform movements such as squatting or standing up from a chair, which are essential for everyday activities. The continuous feedback from the VR system helps patients refine their posture and balance, resulting in improved functional movement patterns and a reduced risk of falls.
- *Whack-a-Mole:* An interactive game that challenges patients' speed, accuracy, and reaction time as they aim to "hit" virtual targets.

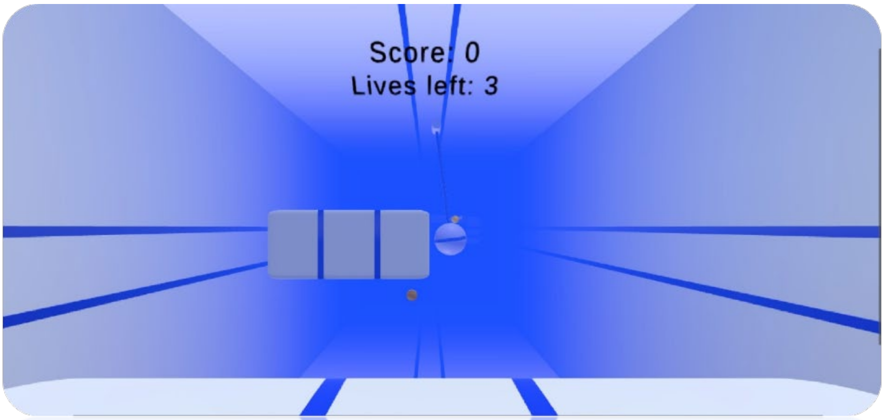

Figure 3
Screen-shot fo the Interactive VR Exercises Program. Patients have to avoid incoming obstacles by moving left or right.

- *Real-Time Feedback and Correction:* One of the most significant benefits of VR-based rehabilitation is the immediate feedback provided to patients. Our system delivers real-time corrections on movement accuracy, which allows patients to adjust their actions instantly. Visual and auditory cues will further motivate patients, making the therapy more engaging and effective.
- *Personalized Rehabilitation:* VR programs are highly adaptable, allowing therapists to tailor exercises according to individual patient needs and capabilities. The developed system can adjust the difficulty of tasks based on the patient's progress, ensuring that each session is challenging but achievable. This personalized approach promotes gradual improvement and helps them progress at their own pace, leading to more effective rehabilitation outcomes.

- *Home-Based Rehabilitation:* VR technology allows patients to continue their rehabilitation exercises in the comfort of their homes. This is particularly beneficial for those who have difficulty attending regular hospital sessions or find traditional rehabilitation methods less effective. The VR system provides real-time feedback and tracks progress, making home-based rehabilitation both accessible and efficient.

2.2 Experimental Setup

Our planned experiment will include patients diagnosed with stroke. They will be allocated into three groups: VR-based therapy, traditional rehabilitation (control group), and combined therapy. The VR therapy will be conducted in a clinical setting. Performance scores, such as the Wolf Motor Function Test (WMFT) for upper limbs and the Timed Up and Go Test (TUGT) for lower limbs, will be systematically collected to assess the impact on motor recovery [31, 32].

For upper limb assessment we intend to evaluate limb functions using the WMFT. It is anticipated that patients receiving VR therapy will demonstrate significant improvements in the range of motion and muscle strength, particularly in the shoulder, elbow, and wrist areas. Planned VR exercises will include tasks such as coin collection, object manipulation, and obstacle avoidance. The engaging and immersive nature of the VR environment is to increase patient motivation and adherence to the rehabilitation protocol, thereby facilitating active participation and improved recovery outcomes.

For lower limb assessment the TUGT will be used to evaluate improvements in gait performance and balance. VR-based exercises, including squatting, balance challenges, and gait training, are expected to significantly enhance stability and range of motion in the hips, knees, and ankles, aiding in the performance of daily activities. Continuous monitoring of the center of pressure (COP) during sessions will provide real-time feedback on balance, contributing to the development of proprioceptive skills and overall motor coordination, thus offering a dynamic approach to lower limb rehabilitation [33]. We anticipate that the immersive VR sessions will help reduce dizziness, a common barrier in traditional rehabilitation, thereby enhancing the comfort and effectiveness of the therapeutic process.

By leveraging the immersive nature of VR we aim to promote brain plasticity in ways that traditional methods cannot achieve. Cognitive stimulation is expected to support long-term neuroplasticity and improve adherence rates, which are critical to successful neurorehabilitation. Our study will also incorporate home-based VR therapy sessions supported by periodic telehealth consultations. This approach is intended to create a flexible and motivating rehabilitation framework that not only supports motor recovery but also addresses psychological factors by offering a supportive environment conducive to patient empowerment and sustained engagement with therapeutic exercises.

The combined use of VR-based therapy with traditional rehabilitation is anticipated to yield significant improvements in both upper and lower limb motor functions. It is expected that patients participating in VR therapy will perform a higher volume of repetitions and engage in more intensive practice compared to those receiving conventional rehabilitation alone, potentially leading to faster and more effective recovery. The integration of VR into clinical settings aims to provide a comprehensive rehabilitation approach, addressing the physical, cognitive, and psychological needs of patients.

3 Discussion

Former results support that VR-based therapy offers significant advantages in the rehabilitation of upper and lower limbs following a stroke, particularly when combined with traditional rehabilitation methods. The application of VR technology allows for patients to perform more repetitions and to engage in more intensive practice.

VR-based exercises significantly enhance the process of neuroplasticity, which refers to the brain's ability to form new neural connections and restore damaged areas. This adaptability is particularly crucial in stroke rehabilitation, where promoting neuroplasticity can help improve motor, sensory, and cognitive functions. Studies show that VR therapy not only improves motor function but also induces significant neuroplastic changes at the molecular level, evidenced by increased levels of brain-derived neurotrophic factor (BDNF), a key marker of neuroplasticity.

Innovative therapies, such as VR and brain-computer interfaces (BCIs), leverage the principles of neuroplasticity by creating immersive and adaptive training environments that promote synaptic plasticity and neural reorganization [34-36]. Further research supports the integration of VR with other neuroplasticity-based interventions, such as transcranial magnetic stimulation (TMS) and cognitive training, to maximize therapeutic outcomes. These combined approaches offer potential pathways to refine individualized treatment plans that cater to the specific neuroplasticity needs of patients, thus optimizing recovery and functional gains.

In lower limbs' rehabilitation, VR technology facilitated balance tests and squatting exercises, leading to notable improvements in gait ability and balance maintenance [37-40]. The monitoring of the COP movement provided patients with feedback on their balance, contributing to the development of proprioceptive abilities. The range of motion in the lower limbs, particularly in the hips, knees, and ankles, also improved significantly, aiding in the easier implementation of daily activities [41-46].

The VR therapy's effectiveness is amplified by its ability to offer real-time feedback and precise tracking of exercises, allowing patients to refine their movement patterns continuously [47, 48]. VR therapy can overcome common challenges in conventional rehabilitation, such as low patient motivation and compliance, significantly boosting adherence and therapy outcomes [49-51].

Further research is needed to determine how this technology can be optimally integrated into clinical practice and to explore its long-term effects on the restoration of motor and cognitive functions [52-57].

Conclusion

VR-based therapy is an effective tool for post-stroke rehabilitation of both upper and lower limbs. Additionally, VR therapy provides opportunities for the personalization of rehabilitation programs, contributing to faster recovery and improved quality of life for patients.

The real-time feedback provided by VR, the increased intensity of exercises, and the potential for tele-rehabilitation are factors that are challenging to achieve with traditional rehabilitation methods. Prelminary testa with our system support that VR therapy may be more effective than traditional methods, particularly in promoting neuroplasticity and restoring motor functions.

Further research is necessary to determine how VR therapy can be optimally integrated into clinical practice, with special attention to the long-term effects and the specific needs of different patient groups. It is also crucial to conduct detailed studies on the economic impact of VR technology to ensure its widespread applicability and sustainability within healthcare systems.

Acknowledgments

Authors thank the staff working at the Neurology Department of the Somogy County Mór Kaposi Teaching Hospital, especially the staff of the Neurorehabilitation Unit, who participated in the research.

T. Haidegger is a Consolidator Researcher, receiving financial support from the Distinguished Researcher program of Óbuda University. His work has been partially supported by the National Research, Development, and Innovation Fund of Hungary, financed under the TKP2021-NKTA-36 funding scheme, at Óbuda University.

The authors report no conflict of interest.

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