Telerehabilitation After Brain Injuries: Its Efficacy and Role in Reducing Healthcare Burdens

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Abstract: Rehabilitation following brain injuries, such as stroke and other traumatic injuries, presents significant challenges for both patients and healthcare systems. Traditional in-person rehabilitation often requires regular visits to specialized facilities, which can be difficult for patients in remote areas or those with mobility and financial constraints. Telerehabilitation offers a promising solution by enabling patients to continue essential therapy at home, ensuring continuity of care while reducing the burden on healthcare providers. It can be effectively applied across various patient groups, including children, adults, the elderly, amputees, individuals with traumatic neurological injuries, and those with neurocognitive impairments such as dementia. Our telemedicine platform integrates advanced technologies, i.e., 3D motion analysis and Virtual Reality (VR) to enhance home-based physiotherapy. These tools enable precise monitoring, real-time feedback, and immersive therapy sessions, in order to improve coordination, fine motor skills, hand-eye coordination, and the vestibular system, which is crucial for balance. This platform also performs detailed offline data analysis, allowing healthcare professionals to adjust therapy plans based on individual needs. As the demand for rehabilitation services continues to grow, adopting these technologies will be crucial for sustainable, effective healthcare, ultimately *improving patient outcomes and shaping a more efficient and equitable future for healthcare systems.*

Keywords: Telerehabilitation; Virtual Reality (VR); 3D Motion Analysis; Stroke Recovery; Parkinson's Disease; Telemedicine

1 Introduction

Research on brain injuries leading to motor dysfunction is a significant area of focus. Acquired brain injury (ABI) and traumatic brain injury (TBI) resulting from accidents, stroke, or multiple sclerosis are among the leading causes of long-term disability.

The advantages and disadvantages of telemedicine in this field have been already discussed, with particular attention to the limitations of the technology [1]. Rehabilitation following brain injuries such as strokes, traumatic brain injuries, and other neurological events presents significant challenges for both patients and healthcare systems. These challenges are amplified by the fact that traditional in-person rehabilitation often requires regular visits to specialized facilities, which can be difficult to access for patients living in remote areas, persons with mobility problems, or those who are facing with financial constraints. The strain on healthcare systems is further compounded by the growing demand for rehabilitation services, particularly as populations' age and the incidence of neurological conditions increase. Telerehabilitation, which leverages modern telecommunication technologies, offers a promising solution to these challenges by enabling patients to continue their essential therapy from the comfort of their homes. It is also believed to support universal access to care through sustainability [2]. This approach not only ensures continuity of care but also allows for more flexible and personalized rehabilitation programs that can be tailored to the individual needs of each patient.

The integration of advanced technologies, such as 3D motion analysis and virtual reality (VR), into clinical programs further enhances the potential benefits, particularly in the domain of telemedicine. These technologies enable more precise monitoring of patient movements and provide immersive environments that can make rehabilitation exercises more engaging and effective. For example, 3D motion analysis allows for detailed tracking of a patient's physical progress, offering real-time feedback that can be used to adjust therapy on the fly. VR programs, on the other hand, can simulate real-world scenarios, helping patients to practice and improve their motor skills in a controlled and safe environment [2].

The use of telerehabilitation methods has increased recently due to technological advancements. It can enhance patients' functional abilities through systematic training and can be organized either synchronously or asynchronously in a home-based environment or within clinical settings. Telerehabilitation can serve as a complementary therapy or as an alternative to conventional treatment. However, further research is required to evaluate various telerehabilitation systems using larger patient samples [3-5]. Cognitive rehabilitation can also be conducted through a telerehabilitation modality, often in conjunction with VR. The cost-effectiveness of such systems could contribute to making healthcare more efficient, addressing both geographical and temporal limitations [6]. Despite the fact that more recently, the stricter regularization and standardization environment of digital medical devices have made it harder to develop innovative solutions to the market, continuous development is required to support a wider rage of patients [7, 8].

1.1 Effectivenes on Target Groups

Telerehabilitation within telemedicine can be effectively utilized across a wide range of patient groups, including children, adults, the elderly, amputees, individuals with traumatic neurological injuries, and those with neurocognitive impairments such as dementia. It is particularly valuable for stroke survivors and patients with other neurological conditions, supporting neurocognitive development and rehabilitation [9, 10]. Telerehabilitation can also be extended to preventive care for older adults, aiming to enhance and maintain cognitive and motor functions, thereby delaying age-related decline. The scope of telerehabilitation includes improving various physical and cognitive skills, such as coordination, fine motor skills, and hand-eye coordination, while also positively impacting the vestibular system, which is essential for balance and spatial orientation. By targeting these areas, telerehabilitation enhances overall functional abilities, enabling patients to achieve greater independence and quality of life. These targeted therapies can be customized to meet individual needs, making telerehabilitation a versatile and effective tool within telemedicine for supporting a diverse range of patient conditions and rehabilitation goals.

1.2 Methods and Systems

The effectiveness of telerehabilitation has been extensively evaluated through a variety of studies, focusing on its impact on motor function, balance, and overall quality of life at patients recovering from neurological conditions. The most well-known system for virtual reality in rehabilitation is the VRRS Evo. Classified as a Class I medical device, it uses virtual reality for rehabilitation and tele-rehabilitation in hospitals [11]. The system includes approximately 800 clinically tested exercises, sensors, a reporting system, customization options, and remote rehabilitation functions. Various USB peripheral devices can be connected to the hub. The system supports both immersive and non-immersive scenarios, enhanced by AI-driven evaluations and audiovisual/tactile feedback based on performance scores. An additional editor module allows for the creation of custom exercises.

The HomeKit, designed for home use, helps improve patients' cognitive, postural, facial, or respiratory conditions, and can be used both online and offline. Studies consistently demonstrate that telerehabilitation can be as effective as traditional in-person therapy, particularly when enhanced with advanced technologies such as 3D motion analysis and VR [11-14]. These technologies are pivotal in home-based rehabilitation programs, offering precise monitoring, engaging therapy sessions, and comprehensive data collection that enables both real-time feedback and offline analysis.

This paper explores the effectiveness of telerehabilitation for brain injury patients, its healthcare implications, and its role in reducing the burden on healthcare workers. Next, we introduce a novel telemedicine development focused on post-hospital rehabilitation for brain injuries, using 3D motion analysis and VR programs to enhance home-based physiotherapy.

2 System Development

We have developed an innovative and robust telemedicine solution specifically designed to support post-hospital rehabilitation for patients recovering from brain injuries for home-based physiotherapy [15]. Our solution leverages 3D motion analysis to monitor patients' movements with high precision, allowing for the detailed tracking of motor progress and ensuring exercises are performed correctly. This technology not only provides real-time feedback to patients, helping them to adjust their movements instantly, but it also collects data for offline analysis [16]. This analytical module enables healthcare professionals to review the patient's progress in depth, make data-driven adjustments to therapy plans, and provide more personalized care [17, 18].

The VR component of our platform engages patients in interactive and immersive exercises that promote neuroplasticity and motor recovery. For example, patients might participate in VR-based tasks such as collecting virtual coins from various heights and distances, or avoiding moving obstacles. These exercises are designed to improve the range of motion (ROM), enhance coordination, and build strength in both upper and lower extremities [19]. The immersive nature of VR helps keep patients motivated and engaged, which is critical for long-term rehabilitation success [20].

Our program also includes specialized VR exercises tailored for the rehabilitation of specific joints and muscles, as outlined in our protocols for range of motion and muscle activation. Exercises targeting, i.e., the shoulder, involve movements like flexion, extension, abduction, and rotation, all tracked and analyzed using 3D motion analysis [21]. This ensures that each rehabilitation session is effective and safely challenges the patient's abilities at the same time, progressively increasing in difficulty as the patient's capabilities improve [22].

This telemedicine platform was designed with flexibility and personalization in mind, allowing it to adapt to the individual needs of each patient [23]. By offering a blend of real-time and offline data analysis, it provides a comprehensive approach to monitoring and improving patient outcomes, making it a powerful tool in the field of neurorehabilitation [24]. Through continuous innovation and refinement, our goal is to set a new standard in the delivery of remote rehabilitation services, making high-quality care more accessible and effective for patients recovering from brain injuries [25].

2.1 Gaming Scenarios

The VRRehab application includes several games that involve various patient movements. These games were designed and selected by therapists and the medical staff. The Unity development environment was chosen for coding, as it supports both 2D and 3D scenarios, including first-party and third-party plug-ins for easy development on Quest 2 and Quest 3 headsets. Currently, the following minigames are available: obstacle course, ball throwing, basketball, whack-a-mole, target shooting, and button pressing for lightbulbs. Additionally, there are simpler games focused on shoulder movements, such as apple picking from a tree, catching stars overhead, and reaching for books on a shelf. Users interact with the system using the supplied controllers. Although we attempted to implement a solution for interaction based solely on hand recognition, issues arose when the hands were out of the headset's line-of-sight, leading to tracking problems. All games provide scores for motivation. Scores are recorded and can be accessed within the application, but they are not intended for medical evaluation. There is also the option to create personal gaming lists or just play randomly. All games are currently being tested by laboratory and development staff (no clinical trials yet). Figures 1-3 show screen shots of selected games and scenarios.

Figure 1
Opening screen of the telerehab software. Users can add games from the list on the left for a series of games

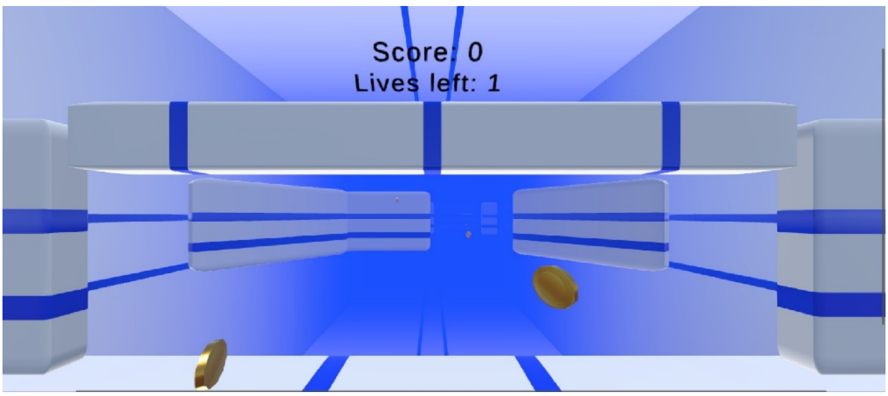

Figure 2
Screen shot of the game where coins are to be collected during navigation in a simplified 3D environment

Figure 3
VR scenario with enhanced graphic options. Coins can be collected during movement between obstacles

3 Discussion

Our team has been at the forefront of integrating advanced technologies within telerehabilitation. We employ these technologies in developing innovative solutions that offer superior outcomes compared to traditional rehabilitation methods. Several key factors contribute to the enhanced effectiveness, accessibility, and personalization of the care we provide [26-28].

A key component of telerehabilitation protocols is the use of interval-based therapy sessions to enhance patient outcomes and prevent adverse effects such as dizziness, which can occur during intensive rehabilitation exercises. Standard practice recommends incorporating breaks after every 20 minutes of continuous therapy to reduce the risk of vertigo, particularly in patients recovering from conditions such as stroke or benign paroxysmal positional vertigo (BPPV). For these patients, it is advisable to implement shorter breaks every 8 minutes to further mitigate symptoms. To ensure the effectiveness of the rehabilitation while safeguarding patient safety, the total duration of each session, including breaks, should not exceed 35 minutes. This structured approach not only enhances the therapeutic benefits of the intervention but also optimizes patient compliance and comfort, ultimately supporting better recovery outcomes in neurological rehabilitation.

One of the most significant advancements we have included into our programs is the use of real-time 3D motion analysis [29]. Recent studies have reported on TBI patients as well. In one study, ten patients participated in a telerehabilitation simulation during hospitalization using tablets [30]. It was found that patients with severe TBI could benefit from cognitive telerehabilitation performed in the pre-discharge phase, as this may lead to higher adherence to home-based tele-treatment. Another randomized trial focused on arm and hand function [31]. The training applied was found to be as effective as usual care in terms of clinical outcomes, with both therapists and patients expressing satisfaction with the intervention. A review of 13 eligible studies, including 10 randomized controlled trials and 3 pre-/postgroup studies, evaluated the feasibility and/or efficacy of telephone-based (10 studies) and Internet-based (3 studies) interventions [32]. Even telephone interventions were found to be effective. This technology allows for precise monitoring and feedback during rehabilitation exercises, providing detailed, moment-by-moment analysis of a patient's movements. Healthcare professionals can detect even subtle deviations from the desired motion patterns and intervene immediately with corrective guidance. This level of precision is crucial for patients recovering from neurological injuries, where the correct execution of exercises is essential for promoting neuroplasticity and motor recovery.

Our ability to dynamically adjust therapy based on real-time data is a major advantage over traditional rehabilitation methods, which often rely on periodic assessments that may not capture the nuances of a patient's daily progress. By continuously monitoring performance, our platform ensures that rehabilitation remains responsive to the patient's evolving needs. This approach is particularly beneficial for people with complex conditions such as stroke or multiple sclerosis (MS), helping prevent the development of compensatory movement patterns that could hinder recovery, and promoting more effective and lasting improvements in motor function.

In addition to physical rehabilitation, we also address the cognitive and psychological aspects of recovery through the use of VR in our programs. VR provides an immersive environment where patients can engage in tasks that simulate real-life challenges, such as navigating in a virtual kitchen or crossing a busy street. We incorporate the latest AR (Augmented Reality) and XR (Extended Reality) technologies as well, which are increasingly recognized for their effectiveness in rehabilitation. AR integrates virtual elements into real-world settings, enhancing exercises with real-time feedback and guidance, while XR provides a personalized and dynamic rehabilitation experience that adapts to individual needs. The use of AR and XR in rehabilitation has been increasingly recognized for its effectiveness, particularly in enhancing patient engagement and improving therapeutic outcomes. AR integrates virtual elements into real-world scenarios, enhancing exercises with real-time feedback, while XR offers a personalized and dynamic rehabilitation experience that adapts to individual needs, improving both cognitive and physical aspects of recovery [33-37].

For stroke survivors, in particular, these cognitive exercises are vital as they often experience deficits in these areas. The immersive nature of our VR applications also plays a significant role in maintaining the patients' motivation, which is a common challenge in long-term rehabilitation. Traditional rehabilitation exercises can become repetitive and monotonous, leading to decreased patient engagement over time. Our VR scenarios, however, offer a variety of interactive challenges that are tailored to the patient's interests and progress, making each session more engaging and enjoyable. The VR components we develop are designed to be adaptable, allowing for the difficulty of tasks to be adjusted based on the patient's performance. This ensures that patients are consistently challenged at an appropriate level, essential for continuous improvement. For instance, as a patient's balance improves, the VR exercises can introduce more dynamic and unpredictable environments, such as walking on uneven surfaces or reacting to sudden obstacles. This adaptability not only enhances the effectiveness of the rehabilitation but also helps build the patient's confidence in their abilities, which is crucial for their overall recovery and reintegration into daily life.

Beyond the immediate benefits of real-time monitoring and VR engagement, our platform's capacity for detailed offline analysis sets it apart from other rehabilitation solutions. By collecting and analyzing data from each session, our healthcare professionals can gain deeper insights into a patient's progress over time. This data-driven approach allows for the identification of trends and patterns that might not be immediately apparent during individual sessions. For example, a gradual improvement in a patient's range of motion or a consistent reduction in errors during VR tasks can inform adjustments to the rehabilitation plan, ensuring that it remains aligned with the patient's long-term recovery goals [38-41].

This level of personalization is often not feasible with traditional rehabilitation settings, where such detailed monitoring is typically limited to periodic assessments. By combining physical, cognitive, and psychological rehabilitation into an integrated system, we provide a comprehensive solution that addresses the multifaceted needs of patients recovering from neurological injuries. Our platform seamlessly blends real-time feedback, adaptive VR environments, and in-depth data analysis to ensure that patients receive the highest quality of care, tailored specifically to their unique recovery journey. By making these advanced technologies available, we are democratizing access to essential rehabilitation services, ensuring that more patients can engage in the therapy they need, regardless of their circumstances [42].

The advanced training provided through a non-immersive virtual reality rehabilitation system using the already mentioned VRRS HomeKit led to a statistically significant improvement in both general and motor outcomes, as well as psychological well-being, compared to a control group [43]. The VRRS proved to be a suitable alternative or complementary tool for improving motor and cognitive outcomes. Additionally, it had a beneficial impact on managing caregiver burden, reducing distress, and promoting the positive aspects of caregiving. Other studies also support the beneficial use of innovative technologies in motor and cognitive neurorehabilitation. However, the impact on motor rehabilitation remains limited and controversial [44]. The same applies to VR solutions. For instance, VR serious games have shown some efficacy in upper limb telerehabilitation after a stroke, but the strength of this evidence is still low. This is due to the limited number of randomized controlled trials, small participant groups, and heterogeneous samples [45]. Another issue is that while gamification elements are often used to enhance the experience, their descriptions frequently lack depth [46]. There are challenges in standardizing VR applications in rehabilitation, and there is a need for clear definitions of VR in clinical research. Only technologies that provide significant levels of presence and interaction should be classified as VR. Although many studies emphasize customization for an enhanced user experience, they often lack detailed reports on how stakeholder feedback was integrated. To improve reproducibility and patient engagement, detailed reporting of the participatory design process and clear definitions of VR and game design are necessary.

Generally, limitations include accessibility (access to the needed hardware and knowledge in use), security and privacy issues (sensible data), and the problems with performing large-scale clinical trials. Future works should address and focus on these problems, especially on the correct methodology and experimental procedure of double-blind trials.

Conclusion

Telerehabilitation has become a vital advancement in post-acute care for brain injury patients, addressing clinical and economic challenges in modern healthcare. With aging populations and rising neurological conditions, the need for accessible and effective rehabilitation services is growing rapidly. Traditional in-person rehabilitation requires significant resources, which are often limited, especially in remote or under served areas.

Our development and application of advanced technologies within a telemedicine framework represent a significant step forward to match these challenges. The integration of 3D motion analysis and VR into telerehabilitation programs has enhanced the effectiveness of home-based therapy. By enabling patients to engage in their rehabilitation from their home, our platform reduces the need for frequent, costly hospital visits and in-person therapy sessions. Former research has shown that maintenance programs, such as those incorporating VR and exergaming, are essential for sustaining the initial benefits of rehabilitation.

The data-driven approach facilitated by our platform's detailed offline analysis capabilities plays a significant role in enhancing the efficiency of healthcare delivery. By continuously collecting and analyzing patient data, healthcare professionals can make more informed decisions, optimizing therapy plans to improve outcomes and reduce the likelihood of complications or setbacks that could require additional, costly interventions. By reducing the burden on hospitals and clinics, releasing resources, and allowing for a more efficient distribution of care, telemedicine is positioned to play a central role in the future of healthcare.

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