Harnessing Virtual Reality for Cognitive and Functional Rehabilitation in Brain Injury Patients

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Abstract

The growing incidence of brain injuries highlights the need for advancements in rehabilitation techniques. Virtual reality (VR) is emerging as a promising tool to complement traditional rehabilitation by addressing cognitive and functional deficits associated with brain damage. While initial research has focused on VR's role in cognitive assessments, there is a notable shift toward using VR for rehabilitation training. This paper reviews studies that explore the application of VR in mitigating impairments such as executive dysfunction, memory loss, spatial disorientation, attention deficits, and unilateral neglect. Additionally, it examines VR's potential in improving the quality of life by overcoming post-injury limitations. As VR technology continues to evolve, its integration into brain injury rehabilitation is expected to become a cornerstone for cognitive recovery and functional improvement.

Key phrase: *Brain injury recovery, Virtual reality, Cognitive impairment, Functional rehabilitation, Executive dysfunction, Memory loss, Spatial impairment, Attention deficits, Visual neglect, VR-based rehabilitation.*

Introduction:

Acquired brain injury (ABI) is a major cause of death and disability in young adults, occurring after birth and leading to significant changes in neuronal function, physical structure, and metabolic processes. Traumatic brain injury (TBI), a primary form of ABI, often arises from accidents, such as falls and vehicle collisions, and affects over 57 million people worldwide.

Brain injuries fall into two categories: traumatic and non-traumatic. Traumatic injuries stem from external forces, while non-traumatic injuries result from infections, tumours, strokes, or surgical complications. TBI is particularly prevalent in individuals under 45, with an enduring risk of mortality and long-term disability that can impact survivors and their caregivers for years post-injury.

ABI is a chronic condition marked by ongoing processes like cell death and network reorganization, which can have unpredictable effects on recovery. Psychological factors, including personality traits, also play a crucial role in healing. TBI severity is typically assessed using the Glasgow Coma Scale (GCS), which measures consciousness impairment through eye, verbal, and motor responses. The range of scores—from 3 (severe impairment) to 15 (full consciousness)—indicates the extent of brain dysfunction. Despite the cognitive and emotional challenges associated with TBI, neuroplasticity allows for potential recovery, particularly through innovative rehabilitation approaches such as virtual reality (VR).

Objective:

This study aims to perform a two-part systematic review cantered on therapeutic virtual reality (VR) applications in the rehabilitation of acquired brain injury (ABI), with a focus on traumatic brain injury (TBI). The specific objectives are:

1. Gather and Analyse Guidelines: To compile and examine existing frameworks and recommendations for designing and implementing therapeutic VR in ABI rehabilitation, emphasizing critical technological elements and collaborative design considerations. This will support the structured development of VR applications specifically aimed at enhancing rehabilitation outcomes.

2. Assess Existing Evidence: To review the current body of literature on the application of immersive VR for assessing and treating TBI. This assessment will involve comparing the identified studies with the synthesized recommendations to pinpoint strengths and weaknesses, ultimately suggesting enhancements for future research and practical applications of VR in ABI rehabilitation.

Literature Review:

Virtual Reality (VR) is revolutionizing healthcare by creating immersive simulations that enhance training for healthcare professionals and improve patient care. It enables safe anatomical studies and assessments (Adamovich et al., 2019) while effectively addressing mental health issues like PTSD and anxiety, and it shows promise in cognitive and physical rehabilitation.

- **VR-Based Cognitive Rehabilitation**: Researchers have explored the use of Virtual Reality (VR) in cognitive rehabilitation for patients with brain injuries. VR environments allow patients to practice real-world tasks in a safe, controlled setting, which can improve cognitive functions such as memory, attention, and visuospatial skills. These simulations provide the patient with an immersive experience that enhances engagement and motivation, key factors for successful rehabilitation. Studies suggest that VR-based cognitive therapies yield faster recovery times and better outcomes compared to traditional rehabilitation methods (Horan et al., 2020).

- **Functional Rehabilitation and VR**: Several studies highlight VR's effectiveness in functional rehabilitation for motor skills. For instance, VR systems, when combined with physical therapy, can enhance upper limb mobility and strength in patients recovering from stroke or traumatic brain injuries. The immersive environment motivates patients to participate in repetitive tasks that are essential for functional recovery, helping improve balance, coordination, and motor skills. VR applications in stroke rehabilitation have shown marked improvements in motor function and patient satisfaction, demonstrating its effectiveness in post-injury care (Assis et al., 2019; Janeh et al., 2021).

- **VR for Home-Based Rehabilitation**: The portability of VR systems has opened opportunities for home-based rehabilitation, reducing the need for frequent clinic visits. Home-based VR interventions allow patients to perform tailored exercises and monitor progress in a familiar environment. This approach not only makes rehabilitation more accessible but also reduces costs and improves patient compliance, especially for those with mobility limitations. Recent studies show significant functional improvements in patients using VR platforms at home, particularly for motor recovery (Lange et al., 2020).

- **Advances in VR Platforms**: Innovations in VR technology have led to the development of specialized platforms tailored for rehabilitation. Systems such as Saebo-VR and NeuronUP are designed to enhance cognitive and physical functions, offering real-time feedback and adaptive tasks based on the patient's progress. These platforms focus on improving day-to-day functional tasks, like dressing and meal preparation, to better integrate rehabilitation into daily life (Carroll et al., 2019).

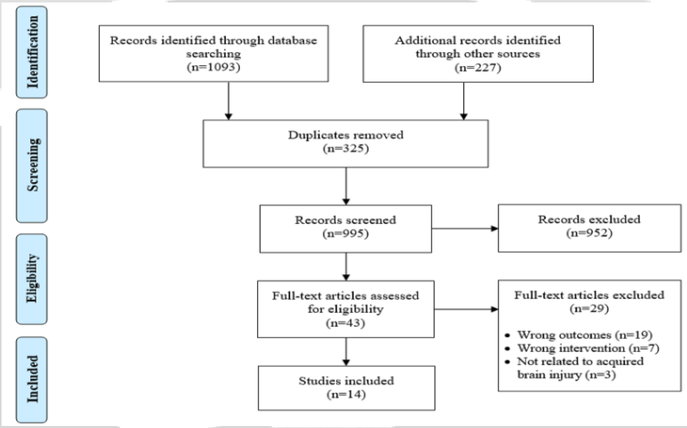
- **Safety and Personalization in VR Rehabilitation**: The integration of VR into rehabilitation programs requires careful consideration of safety and personalization. Cognitive impairments in brain injury patients necessitate specific safety protocols to avoid disorientation or overexertion. Moreover, personalized treatment plans tailored to the individual needs and abilities of the patient can significantly enhance the effectiveness of VR-based rehabilitation. Adaptive VR environments that adjust in difficulty based on patient performance are becoming increasingly important to create a balanced, user-friendly experience (Botella et al., 2020; Massetti et al., 2024).

- **Wearable Devices and VR in Rehabilitation**: The combination of wearable health technology with VR has revolutionized rehabilitation. Wearable sensors monitor physiological responses during VR sessions, providing real-time data that helps adjust the therapy based on patient needs. This continuous monitoring aids in early detection of any health issues, enabling proactive adjustments to the rehabilitation protocol. Wearables integrated with VR have demonstrated increased accuracy in detecting motor improvements and cognitive engagement, resulting in more precise rehabilitation outcomes (The Lancet Digital Health, 2022).

- **Challenges in VR-Based Rehabilitation**: Despite its potential, there are challenges in standardizing VR rehabilitation protocols, ensuring data accuracy, and addressing ethical concerns, such as patient privacy. There is also a need for more research to validate VR's long-term efficacy in cognitive and functional rehabilitation for brain injury patients. Continuous advancements in technology and methodologies will be crucial for overcoming these hurdles and fully realizing VR's potential in rehabilitation (IEEE Transactions on Biomedical Engineering).

Methodology

This study employed an international, single-blind, multicenter randomized controlled trial design across four rehabilitation centres in Korea and China, with ethical approval and informed consent obtained from participants and guardians. Eighty children (mean age: 5 years 8 months) with cerebral palsy or acquired brain injuries were recruited, meeting specific inclusion criteria.
Participants were randomized into an intervention group receiving 30 minutes of VR rehabilitation combined with conventional therapy, or a control group receiving only conventional therapy.
A systematic literature review was conducted using databases like PubMed, Cochrane Library, and Web of Science to identify relevant studies on VR interventions. Data extraction focused on study characteristics, participant demographics, and outcomes, with qualitative synthesis of recommendations for VR design.
The quality of the included studies was assessed using the Oxford Centre of Evidence-Based Medicine framework, with discrepancies resolved through discussion



1. **Study Design**
   This international, single-blind, multicentre randomized controlled trial was carried out across four rehabilitation centres in Korea and China, approved by their respective institutional review boards. Written informed consent was obtained from all participants and/or their guardians. The trial was registered with the Clinical Research Information Service (identifier no. KCT0002395).
2. **Participants**
   Eighty children (39 males, 41 females; mean age: 5 years 8 months) diagnosed with cerebral palsy (CP) or other acquired brain injuries (ABI) participated, with inclusion criteria including ages 3 to 18 years and at least 12 months post-onset. Exclusions were made for severe intellectual disabilities, visual impairments, and recent treatments like botulinum toxin injections.
3. **Interventions**
   Participants were randomized into an intervention group (n=40) receiving 30 minutes of VR rehabilitation using the RAPAEL Smart Kids system, combined with an additional 30 minutes of conventional occupational therapy, or a control group (n=40) undergoing two daily sessions of conventional occupational therapy. Both groups received identical amounts of total therapy time (1 hour daily for 4 weeks).
4. **Search Strategy**
   A systematic review of literature using VR for ABI rehabilitation was performed via PubMed, Cochrane Library, and Web of Science. Studies were included if they detailed VR interventions in ABI patients, while systematic reviews and non-English articles were excluded.
5. **Screening and Data Extraction**
   Search results were managed using EndNote and Covalence for duplicate removal and eligibility assessment. Data extraction was performed by the first author, focusing on study characteristics, participant details, VR systems used, and outcomes.

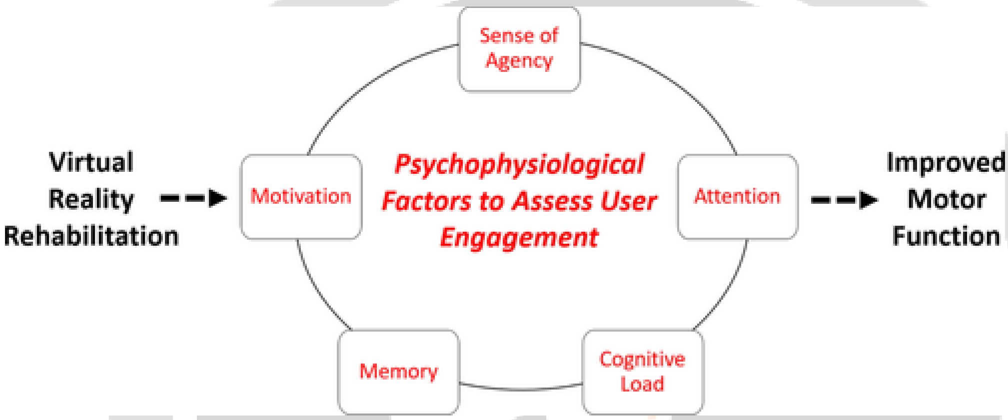
6. **Data Synthesis**
   Data from the first part were qualitatively synthesized into a comprehensive list of VR design and

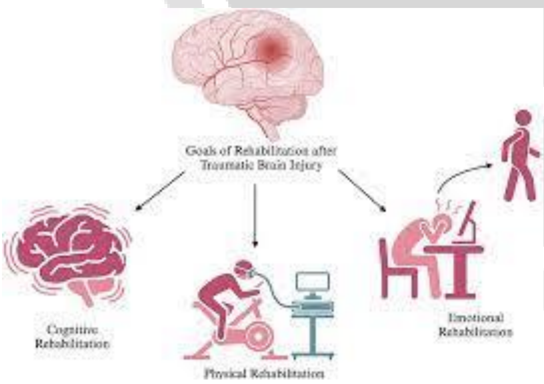
implementation recommendations. The second part's findings were presented descriptively, given the heterogeneity of included studies.

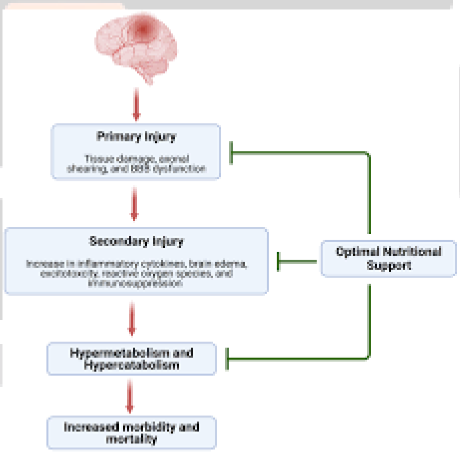
7. **Quality Assessment**
The Oxford Centre of Evidence-Based Medicine Levels of Evidence were used for classification, alongside relevant quality assessment tools. Discrepancies in quality ratings were resolved through consensus.

Populations and Participants
Studies investigating virtual reality (VR) in brain injury rehabilitation involved a variety of patient populations. The majority (57%) focused on acquired brain injuries (ABIs), while others centered on stroke rehabilitation (29%) or a mix of medical conditions involving ABIs (14%).

VR Systems
Different VR systems with varying levels of immersion were used in these studies, ranging from non-immersive to fully immersive systems. Half of the studies explored a combination of these VR systems, while immersive-only or semi-immersive environments were examined in others. Some studies specifically investigated immersive VR without using robotic devices.







Key Phases of VR Development
VR research in healthcare follows three key phases:

1. **Content development**, including user feedback and iterative testing,
2. **Feasibility and efficacy testing**, and
3. **Randomized controlled trials** (RCTs) comparing VR interventions with control groups. Researchers recommend ensuring safety, usability, and validity in early trials before scaling up.

User Involvement and Participant Factors
User-cantered design was emphasized in many studies, suggesting that therapists and patients should co-design VR systems to ensure the technology meets rehabilitation needs. Participant factors such as physical and cognitive

impairments must also be considered when developing VR therapies, ensuring that systems are accessible and tailored to individual needs.

Adverse Effects and Safety

VR use may cause adverse effects such as nausea, dizziness, and anxiety. Studies recommend measuring these effects to establish safety standards and avoid contraindications for use in neurological patients.

Barriers and Facilitators

Barriers to VR implementation, including technology limitations and user discomfort, should be identified and addressed early in the development process. This helps optimize VR systems for therapeutic settings.

Technological Design and Rehabilitation Principles

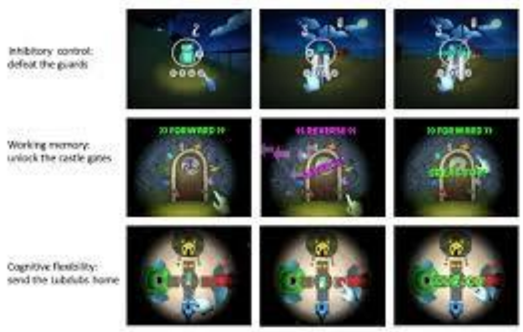
Collaborating with game developers and engineers was recommended to design effective VR rehabilitation tasks. Systems should allow for adequate movement and provide real-time feedback to engage and motivate patients. Rehabilitation principles, such as motor learning, should guide the development of VR tasks to ensure therapeutic benefits.

Supporting Implementation

Effective implementation of VR in clinical settings requires proper training for therapists and clear instructions for patients. VR systems should be accessible for both clinic and home-based rehabilitation, and patient progress should be monitored closely.

Study Design and Analysis

Methodological rigor is critical in clinical VR research, including proper randomization in trials, use of standardized outcome measures, and detailed reporting of VR task components. Researchers are encouraged to assess both short- and long-term effects of VR interventions in rehabilitation.



Results

VR as a Transformative Tool in Neuroscience

Comparing Traditional and Virtual Research Methods

Neuropsychology is essential for understanding brain behaviour, with virtual reality (VR) emerging as a transformative tool in this domain. Traditional neuropsychological tests often lack ecological validity and real-world relevance, leading to the adoption of virtual environments (VEs) that mimic daily activities. These immersive assessments effectively evaluate executive functions and sensorimotor skills, offering a more engaging alternative to conventional methods. Researchers believe that VR has the potential to set new standards in neuropsychological evaluations by enabling multisensory interactions that enhance both diagnosis and therapy.

Advantages of Virtual Environments

The diagnostic capabilities of VEs are noteworthy. Research indicates that VR-based training can yield better neurophysiological and psychological outcomes than traditional methods. Unlike standard tests, which may not accurately reflect real-life scenarios, VEs have high ecological validity, allowing findings to translate effectively into everyday behaviour. Additionally, VR reduces biases present in self-reported data, as it simulates genuine social interactions, enabling therapists to tailor treatment plans to individual needs.

Influence of VEs on Neurological Health

As digital technologies advance, their health implications are increasingly critical. Research investigates VR's role in precise diagnostics and therapeutic interventions for neurological disorders. Advanced VR models enhance our understanding of brain dynamics, including neuroplasticity and mirror neuron functions. Recent studies focus on personalized rehabilitation strategies utilizing biomarkers to meet the diverse needs of patient populations, including those with autism and schizophrenia.

Technical Considerations and Side Effects of VR

Immersion Levels in VR

VR systems vary in immersion levels, from non-immersive to fully immersive experiences. Our research employed the Neuroforma system, designed to limit adverse effects. Fully immersive setups often include head-mounted displays (HMDs) and advanced tracking technologies, greatly enhancing user engagement. However, the interplay between immersion, emotional responses, and the sense of presence requires further investigation.

Managing Cyber sickness

Cyber sickness, a frequent challenge in immersive VR, arises from mismatches between virtual and real-world movements, resulting in symptoms like dizziness and nausea. Younger users and specific technical conditions may exacerbate these effects. Ongoing research aims to develop effective strategies for mitigating cybersickness and assessing associated risk factors.

Challenges of Standardization and Validation

A key challenge in VR research is the absence of standardized validation procedures, complicating study replication and compromising comparative reliability. The effectiveness of VR training is also influenced by participants' cognitive abilities and motivation. Therefore, these factors must be carefully considered when interpreting results across clinical and non-clinical VR studies.

Discussion

Principal Findings

This systematic review highlights that the research surrounding virtual reality (VR) for rehabilitating individuals with acquired brain injury (ABI), particularly traumatic brain injury (TBI), is still developing. It synthesizes key recommendations for creating effective VR interventions while systematically assessing current evidence related to immersive VR in TBI recovery.

Part 1

The review first identifies essential recommendations for designing therapeutic VR applications for ABI rehabilitation. By applying established frameworks, we uncovered crucial technological factors and co-design considerations. A framework by Birckhead et al. presents three phases for VR implementation, culminating in nine categories of recommendations that prioritize participant involvement, thoughtful design, and adherence to rehabilitation principles.

Engaging end users in co-design and feasibility studies prior to larger trials is essential for successful VR interventions. Although this practice is gaining traction in pediatric research, it remains underutilized in adult TBI studies. Utilizing reporting guidelines and education is vital for fostering effective VR adoption and improving research quality.

Part 2

The second section evaluates existing studies on immersive VR for TBI rehabilitation, revealing five relevant studies. While these studies suggest VR's promise in addressing cognitive impairments, limitations arise from small sample sizes and methodological inconsistencies. The variety of VR systems employed highlights the need for adaptable technologies suited to different brain injury challenges.

Though adverse effects were minimally reported, ongoing monitoring for safety is necessary. While promising outcomes emerged, generalizability and methodological quality challenges hinder definitive effectiveness conclusions. Future research should enhance user engagement and adhere to co-design principles while ensuring comprehensive reporting.

Study Limitations

This review encountered limitations, including potential exclusions of relevant studies due to language barriers and varying definitions of VR immersion. The quality of evidence remains low, indicative of the nascent stage of VR technology in ABI rehabilitation.

Recommendations for Future Research

Future studies should implement the identified recommendations to refine VR applications for ABI rehabilitation, particularly for TBI patients. Emphasizing user co-design and iterative testing is crucial for ensuring the safety and effectiveness of VR interventions before larger-scale trials. Establishing specific guidelines for TBI will further strengthen therapeutic VR research and broaden the evidence base for addressing related impairments.

Conclusions

This review highlights the growing role of virtual reality (VR) as an intervention technique in the clinical rehabilitation of patients with acquired brain injury (ABI). VR technology offers the potential to partially restore cognitive, motor, and psychological functions by creating immersive simulated environments that can positively influence daily activities. Rehabilitation is evolving beyond traditional methods, integrating VR as a valuable tool for enhancing recovery outcomes.

Despite the promising applications of VR, our analysis reveals a relatively small body of research focused on its use for ABI patients experiencing cognitive or neurological impairments, with only 13 relevant studies identified among over 300 articles reviewed. This scarcity may indicate a gap in research concerning the targeted application of VR technologies in rehabilitation, especially given the increasing prevalence of ABI.

Future advancements in VR technology could lead to the development of more diverse simulated environments, thereby expanding rehabilitation possibilities for ABI patients. Moreover, further research examining the impacts of VR rehabilitation on brain plasticity and the learning processes involved could enhance our understanding of cognitive reserves in individuals recovering from traumatic brain injuries (TBI). By exploring these avenues, we can better harness VR's potential to improve rehabilitation practices for brain injury patients.

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