Progress and Prospects of Human-Computer Interaction Technology Based on VR Mirror Therapy in Upper Limb Motor Function Rehabilitation of Stroke Patients

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Abstract. Stroke-induced motor dysfunction remains a major challenge in rehabilitation. Based on the fact that Virtual Reality (VR) mirror therapy can achieve better outcomes than other traditional techniques, we comprehensively summarized the study progress, clinical applications and its limitation through systematic analysis of relevant documents in database search. According to the following criteria, our study included articles focusing on VR-based mirror therapy. These kinds of articles covered Random Control Trial (RCT), feasibility study and technical development paper. The investigation of related literature demonstrated that VR mirror therapy showed the advantage of increased immersion and high patient compliance which could obviously benefit stroke patients' improvement of upper-limb motor function, balance and everyday life ability. However, the present research was restrained by small sample size, inconsistent interventions and unclarified mechanisms, which called for the need of designing more effective therapy regimens, elucidating underlying neurological mechanisms, implementing large-scale multi-center trials, so as to promote clinical translation of VR mirror therapy. Finally, we conclude this article based on in-depth critical analysis of the evidence available. And this review provides a whole account for clinicians and researchers on the current situation, implications, limitations and possible directions about the use of VR-based mirror therapy in stroke rehabilitation.

Keywords: Human-computer interaction technology, VR mirror therapy, Stroke rehabilitation, Limb motor function.

1. Introduction

Stroke is a kind of acute cerebrovascular disorder and characterized by high incidence, mortality, and disability rates—three major traits that shape how it affects patients clinically. Importantly, it's the second leading cause of death worldwide, representing roughly 11.6% of all deaths. The Global Burden of Disease Report says there are about 12.2 million new stroke cases worldwide each year. 143 million lost disability-adjusted life years and 6.55 million desths are caused by these cases each year [1].

It is common for stroke survivors to experience upper limb motor impairment as an after-effect. Nearly 80% of stroke patients have some level of upper limb motor problems during rehab, like limited arm movement, weaker grip, and poorer motor coordination [2]. Because this after-effect is so common and hits patients' quality of life hard, stroke rehabilitation is now a key challenge that healthcare providers around the world need to work on [3].

Currently, mirror therapy is widely used in clinical practice ton enhance upper-limb motor function. However, traditional mirror therapy relies on physical mirrors to achieve visual simulation, which has significant limitations: it cannot quantify key parameters, is difficult to design training tasks close to daily life, and the feedback only depends on a single visual modality. As a result, patients often abandon treatment due to "disconnection between training and needs" and "unperceivable progress" [4].

Recent studies have found that virtual reality (VR) is expected to be an effective auxiliary therapy for improving upper limb function. Its core mechanism lies in fully conforming to the principle of neuroplasticity by combining repetitive training, high-intensity practice of the impaired limb with targeted training, thereby promoting the remodeling and functional recovery of the nervous system [5]. The combination of VR technology and human-computer interaction also provides new possibilities for mirror therapy: VR can construct virtual mirror scenes, breaking through the spatial limitations of physical mirrors [6]; it can improve the activation imbalance between brain hemispheres, both the ipsilateral and contralateral primary motor cortexes are stimulated simultaneously and the mirror neuron system is widely activated, leading to the recovery of some motor neuron pathways on the affected side and ultimately promoting the reorganization and remodeling of brain functions [7].

This article focuses on the technical details related to human-computer interaction in VR mirror therapy, collects clinical research and technical development literatures in the past 10 years, and systematically sorts out its application status, efficacy evidence, and technical challenges in the recovery of upper limb motor function in stroke patients.

2. VR-related Technologies in Stroke Patients

2.1. Introduction of Basic Technology

2.1.1 VR and Human-Computer Interaction Technology

VR technology immerses individuals in a fictitious digital world through the use of head-mounted displays (HMD) and other kinds of equipment. When people are in the VR world they are cut off from seeing or hearing the actual world [8]. VR comprises of three main components: head-mounted displays, trackers and controllers. The head-mounted display is the component that shows images of the virtual world to users; the tracker acquires users' movements while the controller is how people interact within the virtual world.

To realize computer-human interaction (HCI) is very important in VR; the quality of user experience and immersion are greatly influenced by the degree of user-computer interaction. There are two types of main technologies used to realize HCI in VR: Head tracking can help track user head movement and allow the system to adjust in real time for a better immersive experience, gesture recognition, which can enable the user to communicate with their hands with the virtual world, and voice recognition, which can make the users directly issue voice commands on the VR system. Haptic feedback technologies can provide such cues by either utilizing gloves or armbands that can sense the user’s touch and thereby bring virtual sensations closer to real. Eye tracking technology tracks people’s eye movements so that the visual attention can be monitored.

In healthcare, VR is involved in psychological therapies or rehabilitation trainings; apart from that, human-computer interaction allows for personalized treatment plans as well [9].

2.1.2 VR Mirror Therapy

It is a new method for recovery in clinical settings, where it blends traditional mirror therapy with VR. It can help people recover from motor function disorders, reduce pain, and stimulate neuroplasticity. With traditional mirror therapy, a patient’s affected side is reflected in a mirror to fool the patient into thinking their unaffected side is working, thus activating corresponding areas of the brain. With VR mirror therapy, a headset provides a virtual reality environment, making the treatment much more impactful [10]. Studies have demonstrated that VR mirror therapy can improve neural plasticity, motor function recovery of the affected limb, and increase upper limb function, which is common after a stroke.

2.1.3 FMA

The Fugl-Meyer Upper Limb Functional Assessment Scale (FMA) is one keyway we assess motor function of the upper limb in stroke patients. Since it’s a standard part of neurological rehab evaluations, we use this scale a lot in clinical practice. It mainly helps us judge how well a patient's motor function is recovering—and we do that using the motor function scores it gives. Also, the FMA looks at several things during assessment, like motor function, sensory function, balance, joint range of motion (ROM), and how much pain the patient has [11].

2.1.4 Montreal Cognitive Assessment (MoCA)

The Fugl-Meyer Upper Limb Functional Assessment Scale (FMA) is one key way we evaluate upper limb motor function in stroke patients. When it comes to cognitive domains, it checks things like visuospatial skills, naming ability, memory, attention, and language skills. The MoCA is scored out of 30 total points, and it assesses seven distinct cognitive domains: visuospatial orientation, executive function, naming, attention, language ability, abstract reasoning, memory, and orientation. Clinically, if someone scores below 26 on the MoCA, that's usually a sign they might have cognitive impairment [12].

2.2. VR in Stroke

2.2.1 Improved Sensorimotor Hand Function in Chronic Stroke Patients through a Virtual Reality-Based Mirror Therapy Program: A Randomized Controlled Trial

Integrating mirror therapy into a virtual reality (VR) system might work better for motor recovery in people with chronic stroke [13]. This study aims to compare the effectiveness of three training methods, conventional occupational therapy (COT), mirror therapy (MT), and VR-based mirror therapy (VR-MT), in improving upper limb sensorimotor function in these patients. A single-blind randomized controlled trial design was utilized in the study, and fifty-four chronic stroke patients who were eligible were randomly assigned to one of three groups: the COT group, MT group, or VR-MT group. When it came to the intervention, all patients started with 20-minute task-specific training sessions twice a week. On top of that, each group got 30 minutes of their own assigned therapy during those same twice-a-week sessions—so the VR-MT group did VR-MT, the MT group did MT, and the COT group did COT—for 9 weeks total. To assess outcomes, we collected data on FM-UE(which served as our main outcome measure), the Semmes-Weinstein monofilament test (which tests touch sensitivity), the Motor Activity Log, the Modified Ashworth Scale (for checking muscle tone), and the Box and Block Test. We gathered this data at three times: before treatment, right after treatment, and when we followed up with them 12 weeks later. The findings indicated that VR-MT might facilitate the recovery of upper limb motor function in chronic stroke patients, especially when it comes to improving wrist function and hand grip. But this finding still needs to be confirmed with more high-quality studies.

2.2.2 Immersive Virtual Reality Mirror Therapy in Post-Stroke Upper Limb Recovery: A Pilot Study

This study was intended to assess the feasibility of virtual reality (VR)-based mirror therapy [14], which is used with a head-mounted display (HMD), for treating upper limb paresis in stroke patients, and to obtain preliminary evidence that it has been effective for some of these patients. The intervention involved 10 outpatients who'd had a stroke at least a year earlier, all of whom had physical examinations before starting treatment. VR systems projected moving images onto the patients' hemiparetic upper limb, and at the same time, their view of the unaffected limb was blocked. Over the course of the study, we tracked subjective measures closely—like how well patients stuck to the intervention and any adverse events that came up. The participants completed two surveys, one on the System Usability Scale and one on the Simulator Sickness Questionnaire. At the end of the study, The Fugl-Meyer Upper Extremity (FM-UE) and the Action Research Arm Test (ARAT) were used to measure their therapeutic outcomes. During the study, there was no simulator sickness or other adverse reactions, and patients stuck to the intervention well; for instance, 6 out of 10 didn't need a handheld controller to keep up. These findings give preliminary proof that VR-based mirror therapy is a feasible, effective way to boost rehab results for stroke survivors with long-term upper limb paresis.

2.2.3 Evaluating the Efficacy of Robot-Assisted Mirror Therapy with Virtual Reality for Post-Stroke Upper Limb Motor Dysfunction: Protocol of a Single-Center Randomized Controlled Clinical Trial

The purpose of this paper is to conduct a one-center, assessor-blinded, randomized controlled clinical study [15], which is designed to verify the clinical effectiveness of robot-assised virtual reality (VR)-based mirror therapy in easing upper limb motor impairment in stroke patients, and to explore the central nervous mechanism that drives its effects. Thirty-two patients meeting the eligibility criteria will be enrolled in the study, and then randomly assigned into two distinct groups. The intervention will be delivered once daily, over a total period of 4 weeks. When assessing outcomes, the primary measure is the Fugl-Meyer Motor Assessment for Upper Extremity (FMA-UE). Secondary measures, meanwhile, include the Montreal Cognitive Assessment (MoCA), assessments of activities of daily living (ADL) and quality of life (QOL), the Visual Analogue Scale for Pain (VAS-pain), and functional magnetic resonance imaging (fMRI). All adverse events will be documented systematically throughout the study; notably, severe adverse events will serve as the standard for discontinuing the intervention. The mirror neuron system and brain reward circuits are likely to be more effectively activated by combining robot-assisted therapy with VR-based mirror therapy than by single-modal therapies, according to theory. However, this proposed mechanism and its related therapeutic benefits still need to be confirmed by additional high-quality clinical research.

3. Discussion

3.1. Challenges and Limitations

3.1.1 Hardware and visual experience limitations

Currently, the performance of VR hardware is still quite limited. It will directly affect the immersive level and the realistic experience of the user in the process of using VR devices. At present, hand tracking is one of the key technical elements in the VR mirror therapy equipment, but there is still room for improvement. An exploratory trial about inexpensive low-cost VR mirror therapy for post-stroke patients, and despite being cost-effective, causes the hand tracking system to fail due to excessive head movements and incorrect hand positions, resulting in discontinuation of the rehabilitation training regimen [16]. The present promising eye tracking and optical hand tracking technologies might replace them in the future, but they still require further improvements in cost and ease of use before being useful enough to find widespread acceptance.

3.1.2 Limitations and Safety of Treatment Effects

While VR mirror therapy proves effective for certain patients, the beneficial impact of intervention varies greatly according to the specific condition of each patient, such as age, cognitive ability, etc. The usage of VR technology is likely to cause Cybersickness or simulator sickness – a range of distressing physical symptoms which may include nausea, headaches and/or dizziness. People's intolerance to Visual/Musculoskeletal environment mismatch makes them feel unpleasant when faced with the gap between what they visually perceive in the computer-generated world and the body movements actually performed; the incidence and severity differs for each individual, yet it represents a critical determinant affecting individuals' willingness to use it and adherence to the therapeutic regimen [17].

3.1.3 Research Methodology

A review of the extant literature reveals a preponderance of methodological shortcomings in contemporary VR research, including inadequate sample sizes, studies with deficient designs, the absence of effective control groups, and an insufficiency of long-term follow-up. The heterogeneity of studies (differences in technology used, assessment methods, and disease types) also makes it difficult to conduct meta-analyses to draw universal conclusions [18].

3.2. Future Prospects

3.2.1 Integration of Emerging Technologies and Technological Breakthroughs

The evolution of VR mirror therapy may move away from being a single piece of technology and more towards being a meeting of various technologies which are just starting to emerge. It will need artificial intelligence (AI). The use of AI for healthcare purposes can lead to analyses of a patient's performance data in real time which will subsequently enable the formulating of customised treatment regimens and alterations to the level of difficulty on a real-time basis; for example, an AI could anticipate a user's intentions or interact with the user, adjust the interaction and/or evaluate the user's emotional engagement or task engagement using biometric measures such as heart rate or skin conductance.

The integration of Augmented Reality (AR), the Internet of Things (IoT), and haptic feedback technology will create richer, more realistic therapeutic experiences. AR can place virtual rehab exercises in physical locations outside of a rehab centre. Devices used under the IoT contain a variety of items, including but not restricted to: smart wearables with heart rate monitoring or gait steps taken which are capable of continuously tracking data during home-based remote rehab with various kinds of devices. And products like haptic gloves use force feedback to add another layer of tactile sense onto interaction with VR content that enables the user to feel a virtual object even though it is just presented digitally on screen.

3.2.2 Treatment Optimization

The rehabilitation of homes and teletherapy are both especially important channels for advancing VR-based therapy. The decrease in cost and increase in usability for the general public in VR devices provide an excellent environment to implement therapy at home to train a larger amount of patients without many restrictions on the environment like previously present in traditional medical treatments such as physical therapy. Allowing treatments to be carried out in home settings instead of confining them to physically restrictive locations increases the availability of services offered and improves treatment adherence. Additionally, services are more easily accessible for patients on demand through teletherapy, cloud platforms can be used to enable therapists to check progress at a distance and make modifications in treatment plans.

3.2.3 Research Directions and Implementation Strategies

To promote the development and innovation in the field of VR mirror therapy, rigorous methods should be applied, among which multi-center, large-scale, randomized, controlled clinical trial is a feasible solution that can be adopted at present to gather enough high-quality data.

Furthermore, interdisciplinary collaboration is imperative for achieving success in this field. To ensure the efficacy of VR treatment protocols, a collaborative effort among engineers, clinicians, therapists, psychologists, and patients is essential. This collaborative effort involves the design, development, and evaluation of VR treatment protocols, ensuring that technological innovations align with clinical needs and ultimately benefit patients. Ongoing research, technological innovation, and multi-stakeholder collaboration have the potential to overcome the current limitations of VR mirror therapy and make it an indispensable tool in the future of medical rehabilitation.

4. Conclusion

In the field of upper limb rehabilitation for stroke patients, VR mirror therapy has demonstrated unique advantages through innovative human-computer interaction technologies. In clinical practice, it not only significantly improves the range of motion of the patient's joints but also specifically enhances grip strength and limb coordination, providing an intuitive solution to the "motor imagery impairment" that is difficult to overcome in traditional rehabilitation training and serving as an important supplementary means to physical therapy and occupational therapy. However, the further promotion of this technology still faces some core challenges. At the technical level, there is a lack of unified standards for parameters such as motion capture accuracy and delay control of different devices, making it difficult to compare treatment effects horizontally. In terms of individual adaptability, due to differences in patients' disease stages, injury degrees, and cognitive levels, existing systems are difficult to quickly adjust personalized plans. Looking forward to the future, with the optimization of AI algorithms to achieve accurate prediction of movement intentions, the reduction of wearing burden by lightweight VR devices, and the accumulation of more evidence-based medical evidence, VR mirror therapy is expected to break through the current bottlenecks. Its ultimate value is not only to become a routine intervention method for stroke rehabilitation but also to promote a fundamental transformation of the rehabilitation model—from the traditional "process-executing" standardized training to a "personalized, immersive and active participation" model adjusted based on the patient's real-time status. This allows patients to actively complete training in virtual tasks, ultimately achieving a qualitative change from "passive rehabilitation" to "active rehabilitation" and reshaping the self-care ability and rehabilitation confidence of stroke patients.

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All the authors contributed equally, and their names were listed in alphabetical order.

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