Evaluation of immersive virtual reality applications for the rehabilitation of patients with rotator cuff tears

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ABSTRACT

This study explores the growing role of immersive virtual reality (VR) applications for the rehabilitation of patients with rotator cuff (RC) tears. VR is increasingly integrated into shoulder musculoskeletal rehabilitation, offering a personalized and interactive approach to restoring joint function. VR can enhance patient motivation, engagement, and adherence to therapy by providing feedback and customizable exercises tailored to individual recovery needs. However, challenges such as needing specialized equipment, potential discomfort from prolonged use, and issues like "cybersickness" must be considered. Despite these limitations, the ability of VR to track movement and adapt exercises to the patient's recovery stage makes it a promising tool in shoulder rehabilitation. Future research is essential to assess the long-term clinical efficacy of immersive VR applications in traditional rehabilitation protocols. The potential for home-based VR therapy, under remote supervision, could enhance accessibility, particularly for patients who face challenges attending in-person sessions. As VR technology continues to evolve, its ability to improve rehabilitation outcomes for RC injury patients is expected to expand, offering both supervised and unsupervised treatment options.

KEYWORDS

Rotator cuff tear, shoulder, virtual reality, rehabilitation, orthopedics.

Introduction

Virtual reality (VR) is a human-machine interface that immerses users in a virtual environment (VE), creating an interactive and immersive experience [1,2]. Over the years, VR has gained recognition as a versatile tool with a broad range of applications, including education, entertainment, and industry, as well as a growing role in clinical settings, particularly in the rehabilitation field [1,2]. Given its potential, VR is increasingly being integrated into musculoskeletal rehabilitation, essential for restoring compromised anatomical functions following trauma or surgical procedures [3].

Rotator cuff (RC) tears are common musculoskeletal disorders, affecting between 16% and 21% of the adult population [3,4]. RC injuries are particularly common among individuals with an active lifestyle, and are influenced by a combination of genetic and environmental factors that significantly contribute to their development and progression [5-8].

Shoulder rehabilitation following RC repair focuses on restoring full and painless shoulder range of motion (ROM), progressively incorporating muscle-strengthening exercises [9-11]. Traditionally, the rehabilitation process for patients with RC injury involves different phases [12]. After a period of shoulder immobilization in a sling, passive ROM exercises are typically performed up to the sixth post-operative week (phase 1). This is followed by the introduction of active-assistive ROM exercises in low-load environments (phase 2), with gradual inclusion of light resistance activities performed using elastic bands and small hand-weights. From week 12 onward (phase 3), structured strengthening begins, with a progressive increase in resistance as tolerated. This strengthening program culminates, beyond week 20 (phase 4), in advanced strengthening tailored to the patient's functional demands [12].

Immersive VR technologies are emerging as complementary tools to traditional techniques, especially during the active phases of rehabilitation [13]. Compared with traditional rehabilitation, immersive VR physical therapy has the potential to enhance patient motivation and engagement, enable objective assessment of rehabilitation exercises, and increase adherence to the rehabilitation process [2,13,14].

Additionally, VR devices can offer the advantages of rehabilitation performed remotely, under the supervision of a physical therapist [15].

Generally, VR devices include head-mounted displays (HMDs) and controllers, enabling simulation of real-world sce-

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narios within a VE and tracking of the position and orientation (pose) of the controllers [14,16,17].

While the use of VR in shoulder rehabilitation following stroke, neuromuscular disorders, and brain injury has been extensively discussed in the literature, its application after RC repair is still under exploration [18,19]. However, a few studies have begun to investigate this promising approach [20,21]. In a recent study, a custom immersive VR application implemented on Oculus Quest 2 and designed for patients following RC repair enabled users to perform rehabilitation exercises with real-time feedback, achieving movements within the prescribed ROM with minimal errors [20]. Similarly, a VR game-based rehabilitation system integrating robotic assistance was developed, showing positive results in terms of patient engagement and adherence to therapy [21].

This study examines the latest research focusing on immersive VR applications for the rehabilitation of patients with RC tears, aiming to identify both the potential benefits and the limitations of integrating this approach into rehabilitation practices.

Immersive virtual reality for shoulder rehabilitation

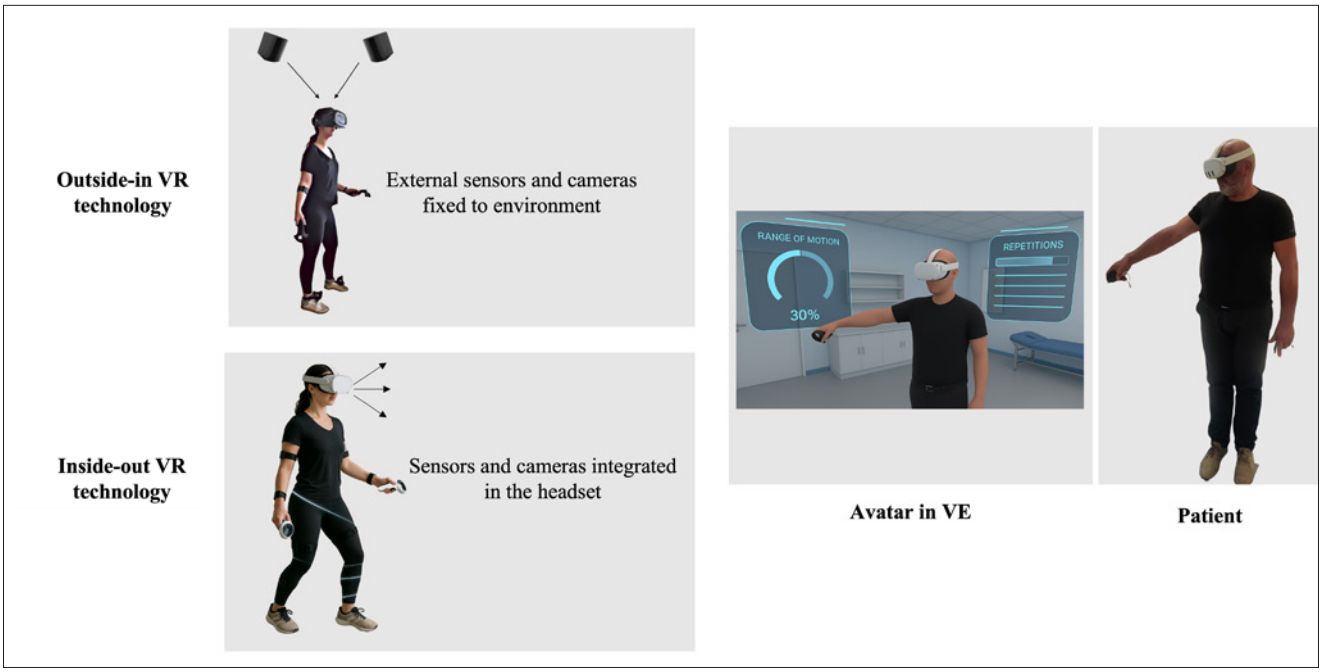
Cutting-edge VR technologies enable the manipulation of complex data, allowing the generation of immersive experiences that can simulate real-world scenarios [22]. As such, VR is a valuable tool for assessing and rehabilitating cognitive and functional abilities, offering interactive tasks that can be customized to address the specific needs of each user [22,23]. One of the first major successes of VR devices was achieved with the development of Oculus Rift and HTC Vive [24,25]. These devices, capable of tracking the pose of controllers within 3D space, made VR technology more accessible, both in terms of cost and availability, to researchers and general users [25,26].

Tracking systems for HMDs are typically categorized into two types: outside-in and inside-out technology (Figure 1). Outside-in systems, such as HTC Vive, rely on external cameras and sensors to track the position and the orientation of the HMD and controllers, offering high precision, reliability, and performance in low-light environments, but they are costly and less portable [16]. Specifically, HTC Vive and Oculus Rift are PC-tethered systems that offer high-fidelity VR experiences using external sensors for precise motion tracking [25,26]. In contrast, inside-out systems, such as Oculus Quest 2, use cameras integrated into the HMD, providing greater portability, wireless operation, and simpler setup. In particular, Oculus Quest 2 is a standalone VR headset that integrates all hardware components and supports full 6-DoF tracking without requiring a computer, making it more accessible and portable for clinical use [20].

Recent studies have explored the use of immersive VR devices by patients recovering from RC injuries. Use of Oculus Quest 2 as a VR system for shoulder rehabilitation after arthroscopic RC repair was explored, utilizing a custom immersive application developed in Unity3D [20]. The study showed that the VR device and the immersive application allowed users to carry out standard rehabilitation exercises correctly, achieving shoulder movements within the prescribed ROM and minimizing positioning errors [20], suggesting that the VR application can be a reliable tool for both performing and assessing rehabilitation exercises. However, the study also emphasized the need for further investigations to confirm the long-term clinical efficacy of VR and its potential integration into traditional rehabilitation protocols [20].

In another recent study, a VR game-based rehabilitation system incorporating robotic assistance was developed to im-

Figure 1 Outside-in and inside-out virtual reality (VR) tracking devices (left) and representation of a patient during a shoulder rehabilitation exercise in a virtual environment (VE) (right).



prove patient adherence to therapy [21]. Using Oculus Quest 2 combined with a Kuka LBR Med 7 R800 robot, the study investigated how integration of immersive VR games and robotic assistance might enhance patient engagement and exercise performance [21]. The results indicated that the system had a significant impact on patient motivation, with 85% of participants reporting a higher level of engagement compared with traditional rehabilitation methods [21]. Despite these promising results, the study also highlighted the need for further research to understand the long-term effects of such systems on clinical outcomes.

The previously mentioned studies highlight the growing role of immersive VR in shoulder rehabilitation, particularly in the context of RC injuries. While their findings indicate the potential of VR to improve patient engagement, exercise performance, and adherence to rehabilitation protocols, further research is necessary to validate its long-term clinical effectiveness.

Advantages and disadvantages

The use of VR in rehabilitation can offer several advantages over traditional therapy. VR can enhance patients' motivation, engagement, and commitment by providing a personalized and dynamic approach to rehabilitation, helping to prevent the risk of monotony and sustain their interest throughout the rehabilitation session [2,18]. Moreover, VR devices can enable real-time quantitative assessments of patients' movements and performance, improving the accuracy of rehabilitation by allowing clinicians to make immediate adjustments [27,28]. VR devices can also provide customizable rehabilitation plans that can increase in complexity according to the patient's functional recovery, and are tailored to meet the specific needs of the individual, thereby promoting more effective rehabilitation outcomes [27,29]. Furthermore, immersive VR solutions can facilitate the inclusion of complex postural exercises that enhance proprioceptive input and balance, particularly during the advanced stages of rehabilitation [27]. However, validation of immersive VR applications is essential before they can be used in real-world rehabilitation settings, as they are primarily designed for entertainment and gaming, not for medical purposes [18].

The need for advanced equipment and suitable environments could limit the accessibility of VR devices. Prolonged use of HMDs may lead to discomfort, potentially affecting session duration and patient tolerance [27,30]. Furthermore, latency—delays between the user's actions and the corresponding feedback in the virtual world—can lead to disorientation and symptoms such as nausea, commonly known as "cybersickness" [2]. These issues could undermine the immersive experience during the rehabilitation session [2]. Thus, factors such as the lack of human interaction, technical support requirements, and the unsuitability for certain individuals (e.g., those with technophobia) should be considered before adopting immersive VR devices [29].

In terms of usability and acceptability, several studies have emphasized the feasibility of home-based rehabilitation using VR [31]. Research on VR in shoulder rehabilitation for patients with neuromuscular disorders has indicated that these low-cost devices are generally user-friendly, suggesting that they may be accessible to a wide range of patients, including those with limited familiarity with digital technologies [16]. However, the successful implementation of VR in real-world clinical settings also relies heavily on adequate end user training [32].

Future perspectives

The application of immersive VR solutions in shoulder rehabilitation is steadily expanding. However, research specifically investigating the use of this advanced technology for the rehabilitation of patients after arthroscopic RC repair remains limited in the existing scientific literature. In fact, several systematic reviews show that most studies have focused on the application of VR in the context of neuromuscular diseases and post-stroke rehabilitation [31,33]. Other investigations have addressed musculoskeletal conditions affecting the knee, back, and neck [34,35]. Only a limited number of randomized controlled trials (RCTs) have examined the efficacy of VR in musculoskeletal shoulder rehabilitation, reporting improvements in joint mobility, muscle strength, pain reduction, and quality of life [21,36-38]. Despite these promising results, further RCTs are needed to strengthen the effectiveness and to clarify the role of VR as a complementary method to conventional therapy in musculoskeletal shoulder rehabilitation [20].

The clinical implications of integrating VR into rehabilitation are significant [39]. VR offers the potential for more personalized and adaptable rehabilitation programs, tailored to the individual needs of each patient. This customization could enhance the precision of exercises and the ability to track progress quantitatively, improving both the quality and the efficiency of the rehabilitation process [40]. Additionally, VR offers the potential for rehabilitation to take place in more flexible environments, such as at home under remote supervision. This could significantly enhance accessibility for patients who face challenges attending in-person sessions [39].

As for future directions, the role of VR in the rehabilitation of patients with RC tears could expand to include both supervised and unsupervised approaches. Supervised VR-based physiotherapy, where physiotherapists guide patients through the rehabilitation session, would continue to be crucial for ensuring that exercises are performed correctly and that progress is closely monitored [27]. However, unsupervised VR-based rehabilitation could provide a valuable alternative for patients seeking more flexible and accessible options, especially for home therapy [39]. The development of remote monitoring solutions, including wearable sensors and real-time data analysis, could enable clinicians to track patient progress and provide timely interventions, even in unsupervised settings [4]. Future advancements in VR technology, including improved tracking accuracy and more immersive feedback systems, will likely further enhance the effectiveness and appeal of these approaches in clinical settings [24].

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