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REVIEW

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Virtual reality-enhanced rehabilitation for improving musculoskeletal function and recovery after trauma

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Abstract

Orthopedic trauma remains a critical challenge in modern healthcare, often resulting in severe mobility limitations, acute pain, and delayed recovery. Conventional rehabilitation techniques, though effective, fail to address the individualized, high-precision interventions needed for musculoskeletal injuries like fractures, joint instability, ligament tears, and muscular atrophy. Virtual reality (VR) technologies, such as Apple Vision Pro and HTC Vive Pro, offer a transformative approach by enhancing diagnostic precision, rehabilitation effectiveness, and patient engagement through interactive, immersive environments that improve clinical outcomes. These VR technologies provide real-time biomechanical data, such as joint mechanics, muscle coordination, and movement patterns, allowing clinicians to design personalized rehabilitation programs. These technologies can thus facilitate neuromuscular re-education, improve muscle proprioception, and enhance muscle coordination. Studies have shown that VR-based rehabilitation advances functional recovery, improves pain management, and reduces psychological barriers associated with immobility. VR also facilitates telemedicine, increasing accessibility for patients with geographic or mobility issues. However, while VR may provide biomechanical data, it is important to note that they fall short in accurate motion tracking, particularly in fine motor control tasks. This scoping review follows PRISMA guidelines to explore the potential of VR in orthopedic rehabilitation, analyzing its diagnostic capabilities, personalized interventions, and real-time feedback systems. Despite this, barriers remain, including regulatory challenges, limitations in haptic feedback, high cost, and patient compliance. By presenting a balanced perspective on the landscape of VR in orthopedic care, this paper emphasizes the need for rigorous clinical validation, regulatory advancements, and interdisciplinary collaboration. Ultimately, VR offers the potential to significantly improve recovery outcomes, enhance patient engagement, and streamline rehabilitation protocols, but its successful integration into clinical practice must be approached with both optimism and caution.

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Introduction

Orthopedic trauma is a significant challenge in modern healthcare [1], often leading to severe mobility restrictions, acute pain, and delayed motor recovery [2]. These conditions pose substantial obstacles in both intensive care and post-discharge rehabilitation settings, frequently leading to decreased functional independence and prolonged rehabilitation periods [3]. The complex nature of orthopedic injuries, which include bone fractures, joint instability, and muscular atrophy, necessitates an integrated approach to rehabilitation beyond conventional physical therapy methods [4, 5]. The need for advanced technologies to accelerate recovery is particularly critical for patients experiencing complications such as bone pain, reduced range of motion, and impaired motor coordination. While traditional rehabilitation methods have proven effective for general cases [6], they can not provide the tailored, high-fidelity feedback required to optimize recovery in patients with severe trauma. In recent years, virtual reality (VR) technology has emerged as a promising solution to address these challenges in orthopedic rehabilitation [7–9]. In response, advanced VR systems, such as the Apple Vision Pro [10, 11, 105] and HTC Vive Pro [12], have gained attention as promising tools that offer immersive, interactive environments that precisely control of therapeutic activities [13]. These devices enable clinicians to develop tailored VR rehabilitation programs for specific orthopedic impairments, addressing fine and gross motor skills crucial for recovery from complex fractures or spinal injuries.

Studies show that VR can accelerate motor recovery by engaging patients in virtual environments that mimic daily activities, challenging their mobility, coordination, and pain thresholds [14]. This approach improves physical recovery and fosters greater patient participation, reducing psychological barriers associated with prolonged immobility [7, 15, 16]. The portability and accessibility of these systems further support rehabilitation beyond the hospital setting, facilitating smoother transitions to outpatient care [17]. VR systems can also provide precise feedback on posture, limb alignment, and load distribution [31] to enhance motor refinement and promote faster recovery, particularly for patients with restricted mobility.

By offering a controlled, immersive environment, VR technology has the potential to transform orthopedic rehabilitation practices and significantly improve patient outcomes. To ensure this paper encompasses a comprehensive and unbiased assessment of VR-based rehabilitation, it will use a structured methodology following PRISMA guidelines and employ randomized controlled trials (RCTs), high-quality meta-analyses, and systematic reviews published in peer-reviewed journals. Studies were selected based on predefined criteria, with a focus on the application of cutting-edge VR technologies in orthopedic trauma, neuromuscular re-education, and post-surgical recovery, particularly on the potential of devices like the Apple Vision Pro and HTC Vive Pro to enhance recovery outcomes for trauma patients. Exclusion criteria included studies with small sample sizes, lack of control groups, or insufficient outcome measures. By adhering to these selection criteria, we will constructively examine the latest advancements in VR-enabled therapeutic interventions and their implications for improving mobility, pain management, and functional independence across various clinical settings. Additionally, we will discuss VR's current limitations and future directions in orthopedic rehabilitation, providing a comprehensive overview of this rapidly evolving field.

Diagnostic capabilities of VR

VR technologies are emerging as valuable diagnostic tools in orthopedic settings (Fig. 1) based on their ability to provide real-time biomechanical for bedside evaluations of musculoskeletal function [18]. These devices offer a non-invasive, objective method to assess joint integrity and muscle coordination, common complications following traumatic orthopedic injuries [104]. However, while these technologies offer considerable potential, their integration into clinical workflows presents advantages and limitations that need to be carefully considered.

Recent RCTs, systematic, and meta-analysis reviews have demonstrated the effectiveness of VR-based rehabilitation across various clinical contexts [14, 18–21, 104]. These interventions have been shown to accelerate functional motor recovery in post-stroke patients [67], enhance proprioceptive training in individuals post-ACL surgery [47, 53, 55, 61, 62, 71], and improve gait rehabilitation in lower limb trauma [35, 50, 51]. We also looked at studies comparing robotic-assisted gait therapy and traditional physiotherapy to lament the advantage of VR-based rehabilitation over conventional methods in terms of patient compliance, physical therapy exercises, and therapeutic outcomes [101]. However, as it goes with all virtual environments, the benefits achieved by VR can be influenced by cognitive load, user interface design, haptic feedback issues [47], and the potential for VR-induced motion sickness [93]. Thus, its success is contingent on improving upon these issues that can significantly affect patient compliance.

Apple vision pro

The Apple Vision Pro (Fig. 2) leverages advanced optical tracking and high-resolution motion-capture technologies [22, 98, 105] to precisely track joint

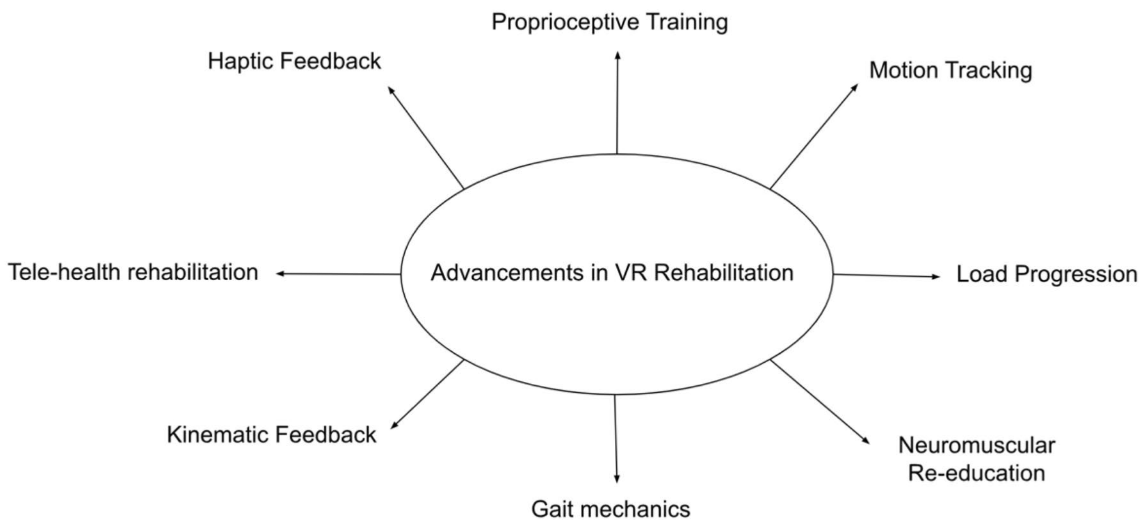

Fig. 1 Technological advancements in VR rehabilitation

Fig. 2 The Apple vision pro headset [98]

kinematics and musculoskeletal dynamics during recovery and rehabilitation. The device excels in tracking fine motor control and detailed joint movements, which is particularly useful for upper limb rehabilitation. For instance, in cases of distal radius fractures or rotator cuff injuries, this device provides detailed wrist or shoulder rotation tracking during rehabilitation exercises, like

Fig. 3 The HTC Vive pro headset [99]

Table 1 Comparison of VR technologies to traditional methods for orthopedic use

Feature	Apple vision pro [23–26, 28, 98, 105]	HTC vive pro [13, 30–35, 58, 99]	Traditional rehab methods
Tracking precision	High-resolution joint and fine motor tracking, upper limb rehabilitation	Room-scale and gross motor tracking, less precise, lower limb rehabilitation	Manual observation, goniometry
Clinical utility	Early detection of compensatory movements	Simulated ADLs, functional movement assessments	Standardized, but lacks real-time task adaptation
Applications	Joint motion analysis, proprioception training	Gait mechanics, balance training for gait, and ADL assessment	Physical therapy
Limitations	Require external sensors, expensive, sensor occlusion, patient compliance issues	Lacks fine motor tracking, limited haptic feedback, lacks precision for upper limb rehabilitation	Limited data tracking

Table 2 Overview of some key studies on VR in rehabilitation

Author (Year)	Population	Study design	VR technology used	Key outcomes
Adamovich et al. (2009) [67]	Stroke patients with hemiparesis	Proof-of-concept study	VR-based hand rehabilitation	Improved finger motion, task completion time, and keypress accuracy
Hemphill et al. (2020) [12]	VR in physical therapy	Calibration study	HTC Vive Pro	VR mobilization techniques optimized for rehabilitation
Kouijzer et al. (2023) [17]	Vrarious healthcare settings	Scoping review	Mixed VR applications	Examined VR implementation across clinical environments
Jeyaraman et al. (2024) [7]	Orthopedic patients	Narrative review	VR for orthopedic rehabilitation	Highlighted VR's role in neuromuscular re-education
Massiceti et al. (2018) [70]	Gait training in immersive VR	Experimental study	Visual-auditory substitution VR	Showed potential for gait and balance rehabilitation
Gazendam et al. (2022) [58]	Total knee arthroplasty	Systematic review and meta-analysis	Various VR devices	VR improved post-TKA rehabilitation outcomes
Kourtessis et al. (2023) [69]	Adults with Autism Spectrum Disorder	Cognitive-motor training study	HTC Vive Pro	VR enhanced both social skills and motor engagement

Table 3 VR applications in upper and lower limb rehabilitation

Injury type	VR rehabilitation approach	Expected benefits
Distal radius fracture	Simulated grasping tasks, wrist deviation tracking	Prevents malunion, improves grip strength
Rotator cuff repair	Glenohumeral rotation training with proprioceptive feedback	Reduces compensatory scapulothoracic motion
ACL reconstruction	Gait analysis, tibiofemoral alignment monitoring	Prevents valgus/varus malalignment, improves stability
Tibial plateau fracture	Virtual stair climbing, gait asymmetry detection	Corrects compensatory weight shifting

Table 4 Comparison of VR to traditional methods in orthopedic rehabilitation

Factor	VR rehabilitation	Traditional rehabilitation
Initial setup cost	Expensive, advanced VR hardware purchase and setup, software licenses, sensor attachments, and clinician training	Low-cost basic equipment (therapy tools)
Ongoing maintenance costs	Regularly system updates, hardware maintenance	Low-cost maintenance associated with equipment wear and tear and training
Training costs	Clinicians require specialized training to effectively use VR systems	Low-cost training for traditional physiotherapy
Treatment precision	Highly immersive, interactive experiences lead to better therapeutic adherence	Lack of precision and dynamic feedback
Customization	Highly customizable with dynamic adjustments	Manual adjustments less responsive to VR systems
Clinical efficiency	Allows for simultaneous treatment of multiple patients	Requires extensive physician involvement, limiting the number of patients that can be treated
Return on investment (ROI)	High ROI if implemented correctly for specific conditions (post-ACL surgery, etc.)	ROI takes much longer to achieve and requires more resources

an actively tracking wearable rehabilitation wristband that clinicians can use to gain quantifiable data on joint mechanics [25]. The device also provides real-time, high-fidelity movement data, allowing clinicians to precisely monitor upper limb critical recovery parameters such as joint range of motion (ROM), limb alignment, and functional movement patterns in patients recovering from fractures, ligament tears, or joint replacements [23, 24, 105]. By comparing real-time joint movements to normative data, clinicians can detect minor deviations from typical healing patterns [26]. For example, suppose a patient recovering from a femoral shaft fracture demonstrates abnormal tibial rotation during gait analysis. In that case, Apple Vision Pro can identify

Table 5 Advantages and limitations of VR in orthopedic rehabilitation

Aspect	Advantages	Limitations
Biomechanical feedback	Provides real-time data on joint angles and load distribution	May lack precision in detecting micro-movements
Patient engagement	Gamification elements improve motivation	VR fatigue and motion sickness may reduce adherence
Accessibility	Enhances telehealth rehabilitation, reaching remote patients	High cost, limited insurance coverage
Integration with therapy	Complements traditional physical therapy, enhances neuromuscular re-education	Cannot fully replace hands-on therapist intervention

Table 6 Barriers and solutions to VR implementation in clinical practices

Barrier	Challenge	Proposed solution
Regulatory hurdles	VR systems require FDA/CE approval for clinical use	Conduct RCTs, integrate real-world data
Technological gaps	Lack of haptic feedback prevents proprioception training	Develop AI-driven force-feedback mechanisms
Cost constraints	Expensive hardware and service maintenance	Offer monthly subscription models, insurance advocacy
Patient compliance	VR motion sickness, rehab fatigue	Adaptive difficulty, biofeedback monitoring

improper joint loading or compensatory movements that may compromise long-term recovery [27]. By offering high-resolution tracking of these movements, the Apple Vision Pro supports early detection of biomechanical errors [28] that might otherwise go undetected until later rehabilitation stages (Tables 1, 2, 3, 4, 5 and 6).

However, this device relies on external motion sensors and patient engagement with the VR system [22], which can be affected by pain, cognitive challenges, or technical limitations (e.g., sensor occlusion or environmental interference) [29]. Moreover, The Apple Vision Pro is less suited for full-body dynamic assessments, emphasizing the importance of complementary use with traditional clinical methods like manual goniometry or electromyography for comprehensive diagnostic accuracy.

HTC vive pro

On the other hand, the HTC Vive Pro (Fig. 3) is particularly effective for room-scale tracking, evaluating gross motor functions, and dynamic weight-bearing activities, which make it more useful in lower-limb and full-body rehabilitation [30, 31, 99]. While the Apple Vision Pro specializes in detailed joint tracking, the HTC Vive Pro allows clinicians to perform in-depth assessments of functional movement patterns, gait mechanics, and load distribution across affected joints [31]. For instance, the HTC Vive Pro was to track dynamic weight-bearing activities in patients recovering from tibial plateau fractures and hip arthroplasty, where it was used to simulate walking on various virtual terrains to assess for compensatory movements in patients that may compensate for pain or instability not evident from traditional clinical environments and make dynamic postural adjustments [32, 58].

Another strength of the HTC Vive Pro is its ability to simulate activities of daily living (ADLs) in a controlled virtual setting [14, 33]. It has been used in patients recovering from lower limb fractures who often struggle with complex motor tasks, such as climbing stairs or performing sit-to-stand transfers [34]. The HTC Vive Pro enables clinicians to record joint loading patterns, step cadence, and limb trajectory [35], helping clinicians to precisely identify functional deficits, postural imbalances, and improper weight distribution, which are essential in guiding rehabilitation sessions.

However, the HTC Vive Pro has some limitations in detecting fine motor control deficits [36]. While it excels in full-body movement assessments, its tracking sensors lack the precision required for upper limb and hand rehabilitation, such as hand or finger fractures [37], where subtle deviations in joint mechanics are crucial. Furthermore, without additional sensor integration, the device is less effective for evaluating subtle joint mechanics in cases of nerve damage or post-surgical stiffness [38], where detailed sensor feedback is crucial.

Therapeutic applications of VR: neuromuscular re-education and proprioceptive enhancement

Post-surgical patients often experience neuromuscular inhibition [55], where pain or inflammation causes a reduction in motor unit recruitment, particularly after total knee arthroplasty (TKA) or ACL reconstruction, where quadriceps activation is frequently impaired [56]. VR tracks neuromuscular re-education by providing real-time biofeedback, enhancing the patient's awareness of muscle activation patterns [57].

VR aids TKA rehabilitation by simulating functional tasks requiring fine motor control [58], such as sit-to-stand or stair climbing. The system tracks force distribution across the knee joint and provides haptic feedback to correct improperly engaged quadriceps muscles. VR thus allows for targeted muscle re-education through real-time adjustment of the therapeutic load, ensuring that weak muscle groups (e.g., vastus medialis obliquus) [59] are targeted while preventing early prosthesis wear or patellar instability [60].

VR also aids ankle rehabilitation (e.g., ankle fractures or ligament tears) by improving proprioceptive re-education [61]. Specifically, VR can simulate dynamic tasks, such as balancing on unstable surfaces or performing lateral shuffles, thereby stimulating the joint mechanoreceptors, enhancing feedback [62], and preventing chronic ankle instability, arising from inadequate proprioceptive rehabilitation post-injury [62].

Integrating VR into clinical practice: a balanced perspective

Virtual reality (VR) has emerged as a powerful tool for orthopedic diagnostics and rehabilitation, offering precise tracking of joint mechanics and motor function. Its ability to provide real-time biomechanical data, such as joint angles and movement patterns, makes it particularly useful for developing personalized rehabilitation plans for trauma patients [38]. By simulating functional activities such as gait cycles, VR enables clinicians to identify movement abnormalities earlier to prevent further joint injury. For better progression, targeted interventions should be designed to correct biomechanical alignment [39], and fine adjustments should be made to therapy regimens based on quantifiable metrics such as ROM. However, it is essential to note that real-time biomechanical data differs from motion tracking accuracy in that the latter can be affected by technical limitations in the system, particularly when monitoring subtle or compensatory movements.

A systematic review comparing robotic-assisted gait training (RAGT) with conventional physiotherapy to traditional overground walking training (OGT) alone in the setting of incomplete spinal cord injuries (SCIs) analyzed four randomized controlled trials (RCTs) encompassing 258 participants [101]. Results showed that combining RAGT with traditional physiotherapy improved locomotor function and gait quality more than OGT alone, highlighting its effectiveness in the subacute phase of rehabilitation [101]. Taken together, this suggests that while robotic therapy enhances movement precision, VR-based rehabilitation provides a more engaging environment that improves patient adherence and motivation. Integrating VR into rehabilitation programs could thus bridge the gap between the structured precision of robotic therapy and the accessibility of conventional physiotherapy.

However, VR should not be seen as a replacement for traditional diagnostic methods. While they provide an immersive simulation of functional tasks, their precision does not yet match direct biomechanical assessments, such as force plate analysis or dynamic MRI, which can provide deeper insights into the internal joint and muscle dynamics [40]. Additionally, patient-specific factors, such as body mass index (BMI), pre-existing musculoskeletal conditions, or cognitive impairments, can influence the accuracy and applicability of VR-based diagnostics [41]. For instance, a patient with severe arthritis may exhibit compensatory movements that are misinterpreted or not picked up by VR technologies.

Moreover, VR-based diagnostics rely on patient engagement with the virtual environment. In acute trauma cases, where pain and limited mobility are primary concerns, patients can struggle to fully interact with VR systems, reducing the diagnostic utility of the technology. To address this challenge, VR should be used with traditional assessment tools, ensuring that the diagnostic process remains holistic and adaptive to the patient's needs.

Personalized rehabilitation interventions

VR is revolutionizing orthopedic rehabilitation by offering individualized, precisely controlled environments where biomechanical, neuromuscular, and proprioceptive deficits can be addressed in real-time. Specifically, integrating VR into rehabilitation settings allows for detailed monitoring of joint kinematics, neuromuscular activation, and load distribution, which are pivotal to recovery in orthopedic trauma patients.

Additionally, integrating smartphone applications into rehabilitation through VR-based tools offers even more opportunities for improving patient outcomes. With the advent of mobile technology, VR-based rehabilitation can help patients enhance gait quality and access therapy more conveniently. Another comprehensive review analyzed 41 studies on iOS-based podiatry applications. It highlighted the benefits of these tools, emphasizing their usefulness in enhancing patient engagement and compliance, increasing accessibility to rehabilitation programs, and providing educational resources. These applications thus offer cost-effective solutions, reducing reliance on expensive medical interventions [102].

Integrating mobile-based VR into orthopedic rehabilitation also provides a new approach to enhancing patient outcomes by immersing patients in engaging virtual environments. This becomes particularly helpful for patients with limited access to in-person therapy sessions or those seeking more flexible therapeutic options. By examining the role of mobile applications in podiatry, this paper provides more evidence that mobile-based VR applications can serve as accessible and cost-effective alternatives to traditional high-cost VR headsets [102], showing that mobile applications can be integrated into orthopedic rehabilitation programs, offering new methods of patient engagement and flexible options to complement existing therapies.

Upper limb rehabilitation: post-surgical application and VR-assisted motor retraining

In upper limb trauma, such as distal radius fractures or rotator cuff repairs, early rehabilitation focuses on passive range of motion (PROM) exercises to prevent joint stiffness and atrophy [42]. However, the transition from passive to active-assisted range of motion (AAROM) and eventually active range of motion (AROM) can be challenging [43], particularly in patients with limited proprioception or pain-mediated guarding. VR systems can enable the visualization of joint kinematics during these exercises, ensuring that the movements are performed correctly and within safe biomechanical limits.

For example, post-operative patients following an open reduction and internal fixation (ORIF) of the distal radius can use VR to simulate load-bearing activities, such as grasping virtual objects, re-engaging their flexor and extensor muscles [46] while preventing radiocarpal deviations [44, 45]. Real-time feedback allows clinicians to detect malalignments that could predispose patients to complications like malunion or decreased wrist extension [46].

VR is also helpful in post-rotator cuff repair rehabilitation [47], where deficits in proprioception lead to compensatory scapulothoracic motion, delaying recovery [48]. VR-guided exercises that isolate glenohumeral rotation can prevent these compensatory actions, ensuring proper neuromuscular control and optimizing functional recovery [49].

Lower limb rehabilitation: load progression and kinematic feedback

Early weight-bearing and load progression are crucial in lower limb rehabilitation, particularly after tibial plateau fracture fixation or ACL reconstruction [50, 51, 58]. VR technologies like HTC Vive Pro offer real-time kinematic analysis of gait patterns, stride symmetry, and joint loading [35], which is essential for monitoring post-operative weight-bearing progression.

One of the primary goals post-ACL reconstruction is to restore the dynamic stability of the knee joint [52]. VR facilitates progressive limb loading while monitoring tibiofemoral alignment, tracking valgus/varus deviations, and ensuring proper quadriceps muscle activation [53]. By analyzing force distribution data across the knee joint during simulated walking and running [28, 31], VR reduces the risk of graft failure and prevents secondary injuries, such as patellofemoral pain syndrome, caused by improper quadriceps activation or lateral tracking of the patella [54].

VR also assists in tibial plateau fracture recovery by helping patients practice weight-bearing activities on uneven terrains while monitoring dynamic movements, such as ascending and descending stairs, gait asymmetry, and joint mechanics [32, 58]. It also monitors joint angle deviations, such as hyperextension or varus/valgus misalignment, allowing for targeted interventions. By detecting compensatory strategies, such as over-reliance on the unaffected limb or improper dorsiflexion, VR helps prevent gait and chronic musculoskeletal imbalances and optimize long-term functional recovery [32].

Real-time data-driven modulation of rehabilitation protocols

The most significant advantage of VR in orthopedic rehabilitation is providing real-time, data-driven rehabilitation protocol adjustments based on capturing joint angles, muscle activation, and force distribution. VR systems dynamically modify exercise difficulty to optimize motor learning and tissue healing. For example, in hip arthroplasty recovery, patients initially struggle with abduction due to gluteus medius weakness [63]. VR can gradually increase resistance in abduction by integrating force-feedback mechanisms or wearable resistance devices that adjust based on patient performance. Simultaneously, motion-tracking sensors and machine learning algorithms analyze compensatory movements, such as excessive trunk lean or hip hiking, providing real-time feedback to correct improper mechanics [63].

In complex fractures (e.g., pilon fractures of the distal tibia), VR tracks load distribution during weight-bearing activities to ensure patient adherence to appropriate weight-bearing restrictions while progressing through functional tasks [64]. Tracking load distribution prevents common complications such as malalignment or delayed union due to early loading. VR systems surpass traditional rehabilitation methods by providing a customizable and adaptive approach to the rehabilitation process. This precision ensures individualized patient rehabilitation programs, optimizing both short-term recovery and long-term functional independence.

Efficacy and limitations of VR in orthopedic and related rehabilitation applications

VR has been increasingly integrated into orthopedic and neurological rehabilitation protocols [65, 66], improving sensorimotor training, proprioceptive re-education, and cognitive-motor rehabilitation. However, the patient response variability, age, technical limitations of VR systems, and the challenges in simulating orthopedic tasks remain essential concerns.

These factors, combined with VR-induced dizziness, fatigue, and motion sickness [93], are crucial in considering the overall effectiveness of VR-based rehabilitation. Additionally, the economic feasibility of widespread incorporation of VR-based rehabilitation remains underexplored, particularly regarding the high costs of implementing these devices in hospitals and rehabilitation centers, new insurance reimbursement policies, and the level of advanced training needed for healthcare professionals to integrate VR effectively into standard protocols.

Sensorimotor rehabilitation: upper extremity interventions

Adamovich et al. published a proof-of-concept study on four patients with chronic hemiparesis secondary to stroke who performed VR hand rehabilitation. The system improved finger motion through a simulated piano task providing visual, auditory, and haptic feedback. Through training, patients demonstrated significant improvements in finger fractionation (the ability to move each finger individually), task completion time, and keypress accuracy, suggesting VR's potential in retraining fine motor skills in stroke survivors [67]. These findings also suggest that VR can augment conventional therapies by allowing precise upper limb kinematics tracking and providing real-time feedback on movement deficiencies. In hand or wrist fractures, VR systems can help patients regain dexterity and reduce compensatory movements through progressively increased task complexity (e.g., manipulating virtual objects of varying weight) [68]. Despite this, delays in haptic feedback and lack of fine motor force replication limit VR's full implementation in some rehabilitation applications.

Cognitive-motor rehabilitation and task-specific orthopedic recovery

For patients with cognitive impairments (e.g., older patients, traumatic brain injury (TBI), post-traumatic stress disorder (PTSD)), and complex orthopedic trauma, integration of cognitive and motor rehabilitation is crucial. Kourtesis et al. (2023) also explored the use of the HTC Vive Pro in VR-based social scenario training for adults with autism spectrum disorder (ASD) [69]. Although the study primarily focused on cognitive performance, the structured sessions, consisting of social and physical tasks, highlighted VR's adaptability. The system adjusted task difficulty, enabling clinicians to track both cognitive load and motor engagement, offering valuable insights VR's applications in rehabilitation scenarios involving simultaneous cognitive and motor tasks. For orthopedic specialists, VR may be used for patients with cognitive impairments and limited motor engagement that can limit recovery. Older patients also face reduced effectiveness of VR-based rehabilitation, as evidenced by a systematic review that found reduced engagement in VR environments and issues with study replicability [103].

Since the HTC Vive Pro can provide real-time feedback on task completion and cognitive performance and adjust task difficulty based on the patient's abilities [12, 31, 47], VR can promote patient engagement and adherence and ameliorate cognitive challenges in rehabilitation protocols. While the study showed promising results, further research is needed to explore and refine VR's role in trauma patients, geriatric populations, and cognitive-motor integration to improve compliance and clinical outcomes. It is also important to note that VR-induced motion sickness and fatigue still represent significant barriers to effective long-term patient engagement [93], especially for patients experiencing chronic pain and/or post-surgical limitations. Addressing these issues requires

Fig. 4 VR for exposure therapy for treating PTSD [100]

advancements in sensory feedback technologies and integration of adaptive scaling in task difficulty to accommodate various patient injury states.

The image titled "Virtual reality PTSD therapy" (Fig. 4) is licensed under the Creative Commons Attribution 2.0 Generic license (CC BY 2.0).

VR applications in gait and balance training

VR also shows promise in lower limb rehabilitation, specifically in retraining gait and balance post-surgery or trauma. Massiceti et al. studied the application of visual-to-auditory sensory substitution in VR for patients navigating immersive virtual environments [70]. Although the study focused on sighted individuals for obstacle avoidance, their approach to increasing the navigation complexity offers insights applicable to orthopedic gait training.

For patients recovering from tibial plateau fractures or ankle reconstructions, VR could simulate of progressively challenging environments for orthopedic recovery, helping them regain gait mechanics and balance under increasingly demanding conditions [58, 70]. Real-time sensory feedback, such as virtual cues for foot placement or body alignment, could aid in correcting compensatory strategies seen in patients recovering from lower limb injuries. Although Massiceti et al. focused on navigation [70], their findings emphasize VR's potential for motor skill development, providing a foundation for use in post-surgical rehabilitation and community ambulation after a joint replacement or knee reconstructions.

Limitations and challenges in orthopedic rehabilitation

While VR shows promise in orthopedic rehabilitation, several limitations must be acknowledged, particularly regarding haptic feedback deficiencies and motion tracking inaccuracies. The studies demonstrate VR's effectiveness but also show that it lacks advanced sensory and proprioceptive feedback needed for orthopedic recovery. VR systems lack usefulness due to poor haptic feedback that provides tactile stimulations, such as vibrations, and helps refine proprioceptive training and support long-term muscle recovery, such as after ligament reconstructions or tendon repairs. Haptic feedback provides users with tactile cues for accurate movement, force control, and spatial awareness. As a result, most VR systems rely primarily on visual and auditory cues that do not adequately replicate immediate and realistic tactile sensations necessary for nuanced neuromuscular re-education. This limitation is especially significant for patients recovering from fractures, ACL reconstructions, or tendon repairs, where resistance-based interactions are crucial for effective rehabilitation.

Motion tracking inaccuracies, arising from hardware limitations such as sensor lag and occlusion, calibration errors, and software inefficiencies, also continue to reduce the effectiveness gained from VR-based rehabilitation since it limits clinicians' ability to assess joint mechanics and movement patterns accurately. Patient variability in pain tolerance, cognitive engagement, and motor control also affects VR's effectiveness [72], highlighting the need to integrate it with traditional rehabilitation techniques. Furthermore, the impact of VR-induced fatigue and motion sickness can impair patient adherence, especially those with chronic pain [93]. These inaccuracies undermine the reliability of VR in long-term fine motor control recovery, reducing its clinical precision.

Beyond these technical limitations, regulatory, economic, and logistical barriers hinder widespread VR adoption. While high-end systems like the Apple Vision Pro and HTC Vive Pro offer sophisticated tracking, they may be cost-prohibitive for many rehabilitation centers, limiting their adoption. Further research is thus needed to determine VR's cost-effectiveness and explore low-cost alternatives, such as mobile VR applications [102], particularly in long-term outcomes and its impact on pre-injury rates and functional recovery. Low-cost alternatives can be more accessible options for patients with limited access to healthcare centers and facilities with limited budgets [102]. Additionally, new reimbursement policies need to accommodate VR-based therapy in different healthcare systems, as the lack of current procedural terminology (CPT) code makes it difficult for healthcare providers to secure insurance coverage. Without adequate reimbursement and financial incentives, clinics can struggle to reasonably front the costs of building and implementing VR systems at their facilities.

Regulatory approval further hinders VR integration, requiring compliance with FDA 510(k) clearance in the U.S. and CE marking under the EU Medical Device Regulation (MDR). In the U.S., most VR rehabilitation systems are Class II devices, needing 510(k) clearance to prove equivalence to an approved device, with stricter evidence required for complex applications like gait retraining. The EU's MDR imposes even tougher clinical and post-market requirements. While global organizations aim to harmonize regulations, country-specific rules add more complexity. Overcoming these barriers requires clinical trials proving cost-effectiveness, advocacy for new billing codes, and alignment with value-based care models. Governmental regulatory barriers will be further explored later in the text. For a detailed summary of the clinical studies on VR in rehabilitation, refer to Table 4.

Overcoming barriers and future directions in orthopedic rehabilitation using VR

Several barriers hinder VR's integration in clinical settings, including regulatory hurdles, technological limitations, VR-induced motion sickness, cost considerations, clinical integration, and patient adherence. Solutions need to align with the existing regulations to effectively address these barriers, and more studies need to elucidate VR's limitations relative to traditional rehabilitation methods. Below is an in-depth examination of these barriers and corresponding solutions, focusing ons U.S. and international healthcare regulations, clinical standards, and the pairing of VR technologies with conventional therapeutic modalities.

1. Regulatory and compliance barriers in VR-based orthopedic rehabilitation

1.1 Regulatory overview: FDA, EMA, and global standards

VR systems for orthopedic rehabilitation are regulated differently across global markets. In the U.S., the FDA categorizes most VR systems for orthopedic rehabilitation as class II medical devices, requiring 510(k) premarket clearance as they present moderate risk. This process ensures that the device is substantially equivalent to an already approved device [73] and includes compliance with performance standards, labeling requirements, and post-market surveillance to ensure device safety and effectiveness. Clinical evidence may be required, especially for more complex rehabilitation applications like gait retraining or balance improvement post-surgery [74].

In the European Union, the Medical Devices Regulation (MDR), which replaced the older Medical Device Directive in 2021 [75], regulate VR systems and places stricter clinical data and post-market surveillance requirements, increasing the burden on VR manufacturers. To be sold in the European Economic Area, devices must carry the CE mark, demonstrating compliance with safety and performance requirements [76–78]. Carrying the CE mark demands a high level of scrutiny for integrating VR technologies in rehabilitation, as real-world data on long-term patient outcomes remains limited.

Global organizations such as the World Health Organization (WHO) and the International Medical Device Regulators Forum (IMDRF) are working towards harmonization of regulations across borders [79]. However, countries like China and Japan have specific regulatory pathways for medical devices [80, 81], adding to the complexity of global VR implementation in healthcare.

1.2 Proposed solutions for regulatory challenges

To overcome these regulatory barriers, the following steps must be taken:

1 Collaboration between VR developers and healthcare institutions: VR developers should work closely with healthcare providers and regulatory agencies to conduct randomized controlled trials (RCTs) that compare VR rehabilitation with traditional methods. These trials must assess both short-term motor function improvements and long-term outcomes such as reduced re-injury rates, patient satisfaction, and return to work or daily activities. Such data will be critical in gaining 510(k) clearance from the FDA or CE marking under the MDR for VR systems used in orthopedic rehabilitation.

2 Integration of real-world evidence (RWE) into regulatory submissions: Real-world data collection from early VR technology adopters in rehabilitation settings can provide valuable evidence for regulatory bodies, including post-market surveillance data that tracks patient outcomes across diverse populations and injury types. The FDA's Breakthrough Devices Program, which accelerates innovative device approval [82], could also be a path for VR systems that show promise in improving recovery times and reducing healthcare costs in orthopedic rehabilitation.

3 Ensuring compliance with data protection regulations: VR developers must incorporate end-to-end encryption and multi-layered security protocols into their platforms to comply with HIPAA and GDPR. For instance, employing decentralized data storage and edge computing technologies could ensure that sensitive patient data remains secure while allowing real-time analysis during VR rehabilitation sessions. This would also enable more robust telerehabilitation models where patient progress can be monitored remotely without compromising data integrity.

2. Technological limitations and integration with traditional rehabilitation techniques

2.1 Precision and feedback deficiencies in current VR systems

A significant limitation of current VR systems in orthopedic rehabilitation is their inability to provide precise haptic feedback and proprioceptive simulation [83]. While devices such as the HTC Vive Pro and Apple Vision Pro excel at providing immersive environments [84], they lack the tactile precision needed for fine motor control, particularly in hand or finger rehabilitation. Even though these devices can simulate gross motor tasks like walking or weight-shifting, they fail to replicate the force-feedback mechanisms needed for nuanced tasks such as grip strengthening or joint mobilization.

Additionally, there continue to be significant issues with motion tracking accuracy in VR systems, especially when monitoring complex joint movements such as scapulohumeral rhythm during shoulder rehabilitation or pelvic tilt during gait retraining [85]. Traditional physical rehabilitation methods rely on real-time proprioceptive feedback and manual therapist adjustments, which make them difficult to replicate in a fully virtual setting.

2.2 Technological advancements in wearable sensors and AI

Advancements in wearable biomechanical sensors and AI-driven motion analysis are essential to address these limitations. Integrating electromyographic (EMG) sensors into wearable sleeves can provide real-time data on muscle activation patterns [86, 87, 106], allowing for better exercise adjustments. Combined with inertial measurement units (IMUs), these sensors can track joint angles and force vectors, providing more detailed feedback on movement accuracy and muscle coordination. In knee rehabilitation post-ACL surgery, EMG sensors can monitor quadriceps activation, while IMUs track knee movement [88, 106]. The VR system can trigger real-time corrective feedback or modify task difficulty when detecting abnormal muscle recruitment patterns (e.g., quadriceps avoidance or hamstring dominance), preventing compensatory movements that could lead to re-injury. AI algorithms could also analyze patient progress and predict recovery issues, thus predicting the likelihood of developing joint contractures and adjusting protocols to focus on enhancing recovery.

2.3 Integration with traditional rehabilitation techniques

While VR shows promise, it should complement, not replace, traditional rehabilitation methods used by physical therapists, such as manual therapy, soft tissue mobilization, and proprioceptive neuromuscular facilitation (PNF). These methods are essential for restoring normal joint mechanics and muscle function [89, 90]. VR should augment these therapies and focus on motor learning and skill acquisition. VR could help retrain scapulohumeral coordination during overhead tasks like lifting or reaching after manual therapy for shoulder impingement [91]. In gait rehabilitation, VR paired with robotic trainers or body weight-supported treadmills can simulate real-world scenarios and provide visual and proprioceptive feedback on joint positioning and muscle engagement to provide dynamic rehabilitation, improving posture and balance during recovery from orthopedic injuries.

Additionally, there is a significant risk of over-reliance on VR, especially in acute trauma settings where traditional physiotherapies might be more time effective [107]. Acute injuries often require immediate, time-sensitive medical treatment to prevent the patient's condition from worsening. In these cases, VR environments would not offer much benefit over traditional methods due to time restraints. Additionally, VR immersive environments may be maladaptive in surgical simulations, where intercollegiate interactions and the similarity of realistic tissue models to organs are necessary to build teamwork skills for patient care. Current VR platforms that enable students to learn minimally invasive surgical techniques rely on systems that only provide visual cues for errors without tactile feedback on models that lack the proper viscoelastic properties of human tissue. As a result, this limits the skills students can acquire and apply in a real-life setting. A polyhedral mesh was developed to improve virtual tissue's tactile and visual properties, enabling more complex surgical simulations such as hepatectomy [108]. Thus, balancing VR integration with conventional methods is crucial to bringing the best care to various patient cases and maximizing therapeutic outcomes. Lloréns noted that VR is also a valuable tool in neurorehabilitation, but its integration needs to be carefully considered with the patient case, particularly in those needing immediate, direct care [107].

3. Cost and economic constraints in VR integration

3.1 High initial investment and maintenance costs

The highest cost of procuring, maintaining, and training faculty represents a significant barrier to VR adoption in orthopedic settings. Advanced VR hardware like the Apple Vision Pro, with the necessary software licenses, sensor attachments, and maintenance costs, can create significant financial burdens for hospitals and rehabilitation clinics [17]. In addition to the high initial investment, the long-term costs associated with system upkeep and clinician training may deter healthcare providers, particularly in resource-limited settings. Further exploration into low-cost alternatives, such as smartphone applications, is necessary to make this technology accessible to facilities with limited budgets [102].

3.2 Current reimbursement models and limitations

In the U.S., the Centers for Medicare and Medicaid Services (CMS) and most private insurers do not currently provide adequate reimbursement for VR-based therapies [92]. Existing current procedural terminology codes are designed for conventional rehabilitation methods, leaving VR therapies unaddressed.

This lack of reimbursement makes it challenging for clinics to justify the upfront costs of VR systems, particularly in resource-limited areas. Thus, addressing reimbursement policies and the feasibility of implementing VR technologies into healthcare systems is crucial.

3.3 Proposed solutions for economic barriers

To overcome financial barriers, VR-based therapies need to be integrated within bundled payment systems and value-based care models currently being promoted by CMS. Demonstrating cost savings through accelerated recovery and fewer hospital readmissions is key to gaining insurer support. Additionally, clinics could pursue monthly-based subscription models to access high-end hardware and software and reduce the upfront costs and scale their use of VR over time. Partnerships between VR developers and hospitals could also create shared revenue models, benefitting both parties financially and improving patient outcomes.

4. Patient engagement and long-term adherence challenges

4.1 Rehabilitation fatigue and VR-induced motion sickness

Maintaining long-term patient engagement is critical for successful rehabilitation, but fatigue and VR-induced motion sickness are significant obstacles [93]. While VR is effective in creating immersive environments that promote patient engagement, many patients experience declined motivation over time, especially if they encounter consistent pain or difficulty completing tasks. The potential for VR-induced fatigue and motion sickness, coupled with a lack of appropriate haptic sensory feedback mechanisms for fine motor control, must be acknowledged in the further implementation of VR-based technologies.

4.2 Personalized, adaptive VR systems for enhanced engagement

To improve patient engagement, VR systems should use adaptive task difficulty algorithms that adjust tasks based on patient performance and fatigue [94]. The VR systems could dynamically reduce the task's complexity if the patient struggles with a complex motor task, promoting task completion. Biofeedback systems should also be integrated into VR platforms to monitor patient fatigue, heart rate, and pain during sessions [95], allowing for automatic adjustments or rest breaks to prevent overexertion. Finally, gamification elements, such as leaderboards, rewards, and achievements, can further enhance long-term adherence [96, 97], motivating patients to continue their rehabilitation by earning virtual rewards or competing against themselves.

5. Establishing clinical guidelines for VR-based rehabilitation

To better standardize VR rehabilitation protocols, professional organizations such as the American Physical Therapy Association (APTA) and the American Academy of Orthopaedic Surgeons (AAOS) should collaborate to establish evidence-based clinical guidelines for using VR in orthopedic rehabilitation. These guidelines should outline:

- *Patient selection criteria*, determining which injuries or conditions are most amenable to VR-based interventions.
- *The session duration and frequency recommendations*, based on clinical trial data to optimize outcomes.
- *Rehabilitation objectives tailored to specific conditions*, such as fracture recovery, ligament repair, or joint replacement.
- *Performance metrics for monitoring progress*, including range of motion, muscle activation patterns, and functional task completion rates.

Conclusions

Integrating VR technologies like the Apple Vision Pro (Fig. 2) and HTC Vive Pro (Fig. 3) represents a significant advancement in orthopedic rehabilitation by enhancing diagnostic accuracy, facilitating personalized rehabilitation, and providing immersive, data-driven environments. Monitoring biomechanical feedback and adjusting therapy dynamically based on patient difficulty marks a transformative shift in managing complex orthopedic cases beyond traditional physical therapy approaches. Limitations of current VR systems, such as the lack of precise haptic feedback and regulatory challenges, warrant cautious optimism and highlight the need for technological advancements and clinical validation. Further implementation and success depend on evolving regulatory protocols in the U.S. and globally to accommodate VR, ensuring device safety and efficacy while providing real benefits in patient outcomes, as well as ongoing collaboration between healthcare providers, VR developers, regulators, and insurance companies. VR can accelerate recovery, reduce healthcare costs, and offer more engaging rehabilitation, but practical considerations of cost, patient engagement, and clinical integration must be addressed. Once solutions are implemented, VR technology can revolutionize orthopedic rehabilitation and offer more personalized, effective pathways to recovery for patients worldwide.

Author contribution

1. R.K. wrote the main manuscript text and was involved in the conceptualization of the project. 2. P.P. wrote and edited the main manuscript text and was involved in the investigation section of the project. 3. E.W. wrote and edited the main manuscript text and was involved in the methodology section of the project. 4. K.S. edited the original draft and was involved in the collection of tables 1–6 and Figs. 1–3. 5. J.O. edited the original draft and was involved in the investigation section of the project.

Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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