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ALTERNATIVE TREATMENTS FOR PAIN MEDICINE (C ROBINSON, SECTION EDITOR)

Effectiveness of Virtual Reality–Based Rehabilitation Interventions in Improving Postoperative Outcomes for Orthopedic Surgery Patients

Mark Ehioghae[1] · Alexis Montoya[2] · Ritwik Keshav[2] · Tarun K. Vippa[3] · Hayk Manuk-Hakobyan[4] · Jamal Hasoon[5] · Alan D. Kaye[6] · Ivan Urits[7]

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Abstract

Purpose of Review The surge in orthopedic surgeries strains the US healthcare system, necessitating innovative rehabilitation solutions. This review examines the potential of virtual reality (VR)-based interventions for orthopedic rehabilitation.

Recent Findings The effectiveness of VR-based interventions in orthopedic surgery patients is scrutinized. While some studies suggest better patient-reported outcomes and satisfaction, mixed results emerge from others, demonstrating comparable or varied results compared to traditional rehabilitation. The underlying mechanisms of VR-based rehabilitation are elucidated, showing its positive impact on proprioception, pain management, agency, and balance. Challenges of unfamiliarity, patient engagement, and drop-out rates are identified, emphasizing the need for tailored approaches.

Summary VR technology's immersive environments and multisensory experiences offer a novel approach to addressing functional deficits and pain post-surgery. The conclusion drawn is that VR-based rehabilitation complements rather than replaces conventional methods, potentially aiding in pain reduction and functional improvement. VR-based rehabilitation holds promise for enhancing orthopedic surgery outcomes, presenting a dynamic approach to recovery. Its potential to reshape healthcare delivery and reimbursement structures underscores its significance in modern healthcare. Overall, VR-based rehabilitation offers a promising avenue for optimizing postoperative recovery in orthopedic surgery patients.

Keywords Orthopedic surgery · Virtual reality rehabilitation · Postoperative outcomes · Patient engagement · Telerehabilitation · Rehabilitation

Introduction

The increasing prevalence of orthopedic surgery exerts considerable strain on the US healthcare system [1]. While hospitals and ambulatory centers allocate additional resources to address the surge in surgical volume, professionals involved at every stage of the perioperative period manage an increasingly demanding clinical workload. The interface between orthopedic surgery and rehabilitation is one area where this impact can be felt; as the number of surgical procedures increases, more patients require post-operative rehabilitation.

From the point of injury to surgery, patients undergo a healing progress while concurrently experiencing some degree of functional stasis. As a result, they may incur deficits in muscle strength, mobility, and proprioception as well as experience pain and inflammation [2]. Through a well-structured rehabilitation program, patients can make significant improvements in these functional measures and return

✉ Mark Ehioghae
o_ehioghae@hotmail.com

1 Medical College of Wisconsin, 8701 W Watertown Plank Rd, Milwaukee, WI 53226, USA

2 Eastern Virginia Medical School 825 Fairfax Ave, Norfolk, VA 23507, USA

3 University of Arizona College of Medicine-Phoenix, 475 N 5th St, Phoenix, AZ 85004, USA

4 Cedars Sinai Medical Center, 8700 Beverly Blvd #5725, Los Angeles, CA 90048, USA

5 McGovern Medical School, The University of Texas Health Science Center at Houston, 7000 Fannin Street, Houston, TX 77030, USA

6 Louisiana State University Health Shreveport, 1501 Kings Highway, Shreveport, LA 71103, USA

7 Southcoast Health Pain Management, 100 Rosebrook Way, Wareham 02571, USA

to full activity. However, the onus of this progress does not rest solely on the clinician supervising the rehabilitation; the active participation and commitment of patients themselves are critical to achieving rehabilitation goals. But how realistic are these expectations? With numerous factors like motivation or financial well-being affecting patient adherence to rehabilitation programs, clinicians and patients alike struggle to attain desired outcomes within expected timeframes [3]. As such, the demand for cost-effective and innovative solutions for this pervading issue continues to intensify.

Accelerated by the COVID-19 pandemic, telerehabilitation has emerged as a feasible model of care [4]. Within the same space, the use of virtual reality (VR) has shown promise with regard to patient satisfaction, compliance, functional outcomes, and cost savings [5, 6]. Given this, further exploration is warranted to evaluate the efficacy of this modality of rehabilitation in additional clinical contexts. The aim of this review is to summarize currently available VR-based interventions for orthopedic rehabilitation, assess their efficacy with regard to postoperative outcomes, identify potential limitations, and forecast its use in clinical practice.

Methods

Using PubMed, we analyzed studies published from 2010 to 2023. Emphasis was placed on studies published within the last 5 years for the article section. Keywords used were "Virtual Reality rehabilitation"; "Orthopedic surgery"; "Patient engagement"; and "Healthcare".

Overview of Virtual Reality-Based Rehabilitation Interventions

VR technology provides users with a computer-simulated environment that allows for an immersive, multisensory experience. Given these dynamic attributes, VR holds tremendous potential as a learning tool across a variety of fields including rehabilitation. Early use of VR technology capitalized on popular console-based systems like Nintendo Wii Fit™ to deliver rehabilitation care. These systems offer "exergaming" activities which have been shown to improve neuromuscular control and address balance deficits—proving effective as an adjunct to traditional total knee arthroplasty (TKA) rehabilitation, for example [7]. Now, with advancements in three-dimensional tracking to quantify pose and motion and digitally stimulated coaching for real-time feedback, VR-based rehabilitation has reached new levels of efficacy through careful monitoring of both patient activity and exercise quality [5]. As such, it has now proven effective in lieu of traditional orthopedic rehabilitation altogether; several factors have been attributed to this emerging paradigm shift [5, 6].

One notable advantage of VR as a supplementary or standalone modality of rehabilitation is cost savings [5, 8]. When comparing total health service use costs between individuals undergoing a VR-based rehabilitation program and those receiving usual rehabilitative care, Bettger et al. [5] found a nearly threefold increase in median cost savings for individuals using the VR-based program 12 weeks post-TKA. In addition to the VR system used in this study, VR-based devices are powerful in their ability to capture biometric data that can be quantified for real-time or asynchronous tracking; such data may aid either the users themselves to make appropriate adjustments in their movement or the supervising therapist to assess goodness of exercise [8–10]. With engaging, game-like virtual environments, VR-based rehabilitation can also motivate patients to perform necessary rehabilitation activities—subsequently improving long-term adherence to their program [11]. One interesting benefit of VR in the use of rehabilitation is virtual "embodiment". This notion applies well to neurorehabilitation contexts wherein the disuse of an affected limb results in progressive shrinkage of its cortical representation within the somatosensory cortex [12]. In an immersive VR environment, user integration of motor imagery and action observation empowers users with a greater sense of personal agency in controlling motor activity while also strengthening neural networks [12, 13].

Postoperative Outcomes in Orthopedic Surgery Patients

While VR-based rehabilitation offers numerous advantages, its potential impact in the postoperative period following orthopedic surgery, particularly concerning the functional complications and challenges patients may experience in this critical phase of recovery, demands attention. Potential complications vary in both severity and acuity. Among the more acute complications that may arise are blood loss leading to anemia, wound-healing issues, surgical site infection, and thromboembolic events [14–16]. While complications like deep vein thrombosis (DVT) remain one of the most feared postoperative events, their incidence after TKA or total hip arthroplasty (THA) has not changed significantly from 2004 to 2013, thanks to more comprehensive prophylaxis risk assessment measures [17]. Potential complications that can occur later include implant loosening, joint instability, chronic infection, fracture, osteolysis, and arthrofibrosis [15]. Arthrofibrosis, specifically, results from excessive fibrosis leading to joint stiffness. Like other late-stage complications, it can be attributed to patient-related factors like compliance to rehabilitation, among other causes [18].

As such, rehabilitation remains a critical component of the postoperative recovery process in not only mitigating these adverse events but also achieving total joint restoration to return to full activity. Indeed, in a follow-up study conducted by Della Villa et al. [19] on nearly 80 sport-active patients who underwent revision anterior cruciate ligament reconstruction (ACLR) 1–4 years prior, it was observed that the rate of return to sport at pre-injury activity level was almost twofold higher (86% versus 45%) among those who were fully compliant with post-operative rehabilitation, compared to the noncompliant group. Although psychological factors like fear of reinjury may have also contributed to this disparity, the investigators believed that because all study participants enrolled in a customized rehabilitation program, they may have been more motivated, on average, than less-active individuals. Nonetheless, findings like this underscore the crucial role of postoperative rehabilitation in achieving superior long-term outcomes.

In addition to return to activity/sport, however, what other measures exist to evaluate progress and rehabilitation success? Tangible measures like range of motion and associated muscle strength are both reliable indicators of postoperative function. In the setting of ACLR rehabilitation, tangible metrics extend beyond these two measures to include hop testing and limb symmetry index among others which aid rehabilitation personnel in identifying and targeting muscle imbalances [20]. By consolidating this data, the quantity of movement can be assessed [21]. However, evaluating both the quality and quantity of movement offers a more comprehensive understanding of functional performance. In the setting of ACL rehabilitation, quality of movement can be appraised by the occurrence of dynamic knee valgus or degree of knee flexion when landing from a jump, for example [22, 23]. Patient-reported measures provide important insights into the patient's subjective experience of their recovery and overall well-being as well. As such, patients often complete a battery of patient-reported outcomes measures (PROMs) during their recovery to assess their pain, instability, quality of life, etc. [24]. Ultimately, incorporating both objective and subjective measures into the standard of care enables more vigilant tracking of outcomes, which can help rehabilitation personnel better understand when to intervene if needed.

Effectiveness of Virtual Reality–Based Rehabilitation Interventions

Effectiveness of Virtual Reality–Based Rehabilitation Interventions in Orthopedic Surgery Patients

Virtual reality (VR) interventions have shown promise in improving pain reduction, functional improvement, and overall patient satisfaction in orthopedic surgery patients. These interventions provide a unique and engaging approach to rehabilitation, potentially resulting in improved patient outcomes. Several studies have investigated the impact of VR interventions on outcomes such as pain reduction, functional improvement, and overall satisfaction.

A systematic review and meta-analysis conducted by Gazendam et al. [31••] examined the efficacy of VR-based rehabilitation versus traditional rehabilitation following total knee arthroplasty (TKA). The results suggested VR therapy results in better patient-reported outcomes at 3 and 6 months after surgery, comparable levels of pain reduction, and significant cost savings as compared to traditional methods [25••]. Similarly, a study on patients who underwent TKA by Chughtai et al. [26] showed that VR rehabilitation improved adherence to prescribed rehabilitation regimens, earlier and more successful recoveries, and better overall patient satisfaction. However, some studies suggest mixed effectiveness of VR rehabilitation in orthopedic surgery patients, with similar patient-related outcomes compared to traditional rehabilitation [5, 27••].

Overall, VR rehabilitation shows potential in facilitating functional recovery and improving mobility for orthopedic surgery patients. The conclusion from the current literature suggests VR rehabilitation should not be considered a replacement for traditional rehabilitation methods. Rather, it can be seen as a complementary tool that adds value to the recovery process. Continued research and advancements in this field have the potential to optimize outcomes and provide patients with more effective rehabilitation solutions.

Virtual Reality Rehabilitation on Postoperative Pain Management

The reduction in pain achieved through VR rehabilitation is a promising finding that could potentially reduce reliance on pharmacological interventions and improve the quality of life for post-operative patients. VR rehabilitation may help in diverting attention from pain and creating an illusion of a healthy limb during the exercises, which allows for the performance of more challenging tasks. Previous studies have demonstrated the effectiveness of VR in reducing pain in various conditions such as phantom pain, neuropathic pain, and post-stroke patients, indicating the potential of VR in post-operative pain management [28, 29]. In 2018, Koo et al. [30] conducted a prospective randomized controlled trial (RTC) comparing enhanced reality interventions and standard pain management techniques in 60 patients who underwent TKA, and found the experimental group had significant and longer-lasting analgesia compared to the control group. However, subsequent

studies had differing conclusions regarding the effectiveness of VR rehabilitation in pain management for surgical orthopedic patients.

In the meta-analysis conducted by Gazendam et al. [31••] involving 835 patients, there were no significant differences in post-operative pain scores between the VR-based rehabilitation group and the traditional rehabilitation group at both the 2-week and 3-month marks following TKA. In another systematic review, two trials showed a statistically significant reduction in pain in the VR training group compared to the control group for patients after TKA but also found two other studies that did not find such differences between the VR and control groups for these patients [27••]. In an RCT that compared VR with traditional physical therapy care for 306 patients who underwent TKA, the differences in pain between the two groups at the 12-week mark were deemed non-inferior when compared to the pre-established margins for these outcomes [5]. Similarly, Fuchs et al. [32] conducted a study of 55 patients who underwent TKA, comparing outcomes between conventional physiotherapy including continuous passive motion device equipment and virtual therapy in addition to the conventional treatment, and it was determined there was no significant difference between the groups in terms of pain, anxiety, and long-term knee function.

Virtual Reality Rehabilitation on Functional Recovery and Mobility Improvement

Studies have demonstrated that VR rehabilitation can enhance functional recovery by providing a dynamic and engaging environment for patients. These virtual environments simulate real-life activities and challenges, allowing patients to practice and improve their motor skills in a safe and controlled setting. Additionally, VR systems can provide biofeedback, allowing patients to monitor and adjust their movements in real-time, which further contributes to functional gains. Chughtai et al. [26] investigated the advantages of virtual reality rehabilitation in enhancing functional recovery after TKA in a group of 157 patients and found that VR rehabilitation led to significant improvements in Knee Society Score (KSS) function and Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores.

In the systematic review conducted by Gazendem et al. [31••], disease-specific scores such as WOMAC and Knee injury and Osteoarthritis Outcome Score (KOOS) were utilized to assess patient outcomes. The findings indicated that at both 12 weeks and 6 months postoperatively, VR-based rehabilitation demonstrated significant improvements in disease-specific impairment compared to traditional rehabilitation [31••]. However, these findings did not align with the outcomes observed in subsequent studies that compared the efficacy of VR rehabilitation to traditional rehabilitation in patients undergoing TKA.

In the RCT conducted by Bettger et al. [5] VR physical therapy was deemed non-inferior to usual PT in terms of the KOOS at 6 and 12 weeks. While Fuchs et al. [32] demonstrated improvement in WOMAC scores 6 months postoperatively in patients who underwent VR rehabilitation following TKA, there were no differences in the total improvement when compared to traditional rehabilitation. Furthermore, an RTC conducted in 2020 with 56 participants demonstrated that while incorporating VR-based games and biofeedback into balance and proprioception exercises led to noteworthy enhancements in clinical, gait, and postural outcomes, the improvements were not significantly greater than those achieved through traditional therapy methods [33•].

Patient Engagement and Motivation in Virtual Reality Rehabilitation

Several studies have examined the effects of VR rehabilitation in orthopedic surgery patients, with a focus on patient engagement. Engaging with VR technology creates an immersive and interactive experience for patients, which can potentially increase their motivation to perform exercises and actively participate in their rehabilitation program. Further, VR therapy potentially overcomes several barriers such as therapist availability, distance to therapy centers, and transportation, hence possibly increasing protocol adherence. There are studies that suggest VR rehabilitation in patients undergoing TKA demonstrated higher levels of patient engagement and motivation in the VR rehabilitation group compared to the traditional rehabilitation group [31••, 34]. The interactive nature of VR allowed patients to visualize and interact with virtual scenes and objects, providing them with a sense of agency and autonomy in their recovery process [35]. However, it is important to note that not all studies have shown consistent results in terms of patient engagement and motivation in VR rehabilitation. Some trials have reported similar levels of engagement between VR and traditional rehabilitation modalities. Ayoade et al. [36] evaluated patient adherence and participation in the rehabilitation process by assessing the number of days the patients actively engaged in planned exercises and found similar levels of involvement in both VR rehabilitation and standard exercises. These discrepancies could be attributed to variations in the design of VR experiences, individual patient preferences, and the level of supervision provided during the rehabilitation sessions.

The current literature suggests that virtual reality rehabilitation has the potential to enhance patient engagement and motivation in the orthopedic surgery population. Further research is needed to optimize VR interventions, tailor them to individual patient needs, and elucidate the long-term effects of VR rehabilitation on patient outcomes.

Virtual Reality Underlying Mechanisms of Action

One underlying mechanism by which VR-based rehabilitation can potentially improve post-operative outcomes in total knee arthroplasty (TKA) patients is by producing somatosensory input that is helpful for standing and more complex movements. Gianola et al. [37] suggest that VR-based rehabilitation may prevent injury in patients who have undergone TKA given a statistically significant improvement in global proprioception in the experimental group compared to the traditional rehabilitation group. Additionally, it can provide contexts in which perceived visual threats are reduced. In those with phantom limb pain, VR can improve patient confidence, agency, and embodiment when converting the mental imagery of a movement to a physical movement within the context that virtual reality can provide [27••]. According to these findings, it is possible that improvements in proprioception, confidence, and agency are transferrable to those completing VR-based rehabilitation after TKA.

It is well known that the diversion of attention from painful stimuli to another stimuli decreases the sensation of pain [27••]. A meta-analysis found that distractions via virtual reality, itself, limited pain. Intentional distraction to reduce pain was found effective in studies of fibromyalgia, chronic neck pain, and during wound-dressing changes [38]. Therefore, virtual reality used as a modality of anesthesia can take advantage of the limited capacity of attention and therefore induce and promote movement [27••, 32]. Motivation, a significant aspect of a patient's adherence to therapy, can be increased by way of game-like virtual reality programs. VR is capable of making the patient feel as if they are in reality and interacting with the surrounding environment, improving agency and confidence [37].

In a study investigating a post-TKA patient population that received 3 weeks of inpatient rehabilitation, the Telehealth Usability Questionnaire (TUQ) completed at the 12-week follow-up point after additional virtual reality telerehabilitation assessed the ease of use, learnability, satisfaction, future use, and reliability of this therapy. This intervention, along with the initial traditional therapy, was ranked highly in all areas except reliability. The questionnaire included both mental and physical health components suggesting an improved holistic health-related quality of life among the intervention group despite equivalent increases in mobility and decreases in joint-related complaints for both groups. Although difficult to tease apart the exact origin of patient satisfaction in this combined study, and of course, being unable to blind patients to reduce bias, the results suggest a need for further investigation of the effect of VR-based therapy on quality of life alone [39].

Post-operative fall risk is often determined by the ability to balance upon standing. In a comparison of a fully immersive virtual reality rehabilitation (FIVR) base jumping program in post-operative TKA patients with standard continuous passive motion (CPM) and exercise therapy, both static and dynamic balance parameters were improved in the FIVR group. The investigators attributed this finding to the stand-up design and movement of the patient's center of mass that the program required. Although, a meta-analysis of randomized controlled trials found both significant and nonsignificant differences in studies that assessed balance with the Five Times Sit-to-Stand Test (FTSST) [6]. It is possible that the effect of VR rehabilitation on balance depends on the type of program and corresponding exercises. This was exemplified by the design and effects of the base-jumping VR program. Thus, FIVR therapy for post-operative TKA patients may be able to reduce post-operative falls, and therefore negative post-operative outcomes, by way of improving both static and dynamic balance.

Virtual Reality Potential Limitations and Challenges

Limitations to VR-based rehabilitation include unfamiliarity and lack of comfort with the rehabilitation device. This finding appears to have contributed to a larger drop-out rate among a VR-based rehabilitation group in one study [40]. A more recent study found that among the potential candidates for post-operative pain management with VR rehabilitation, fear was a key component in their refusal to participate [41]. The creation of a more user-friendly experience in conjunction with more time devoted to patient education could improve familiarity among the elderly-dominant population that is in most need of a TKA.

Other factors that led patients to choose in-person, conventional therapy over VR-based therapies included more facetime with a therapist and therefore more individualized care plans, the personal touch of a therapist, and poor adherence to technology [40]. Rutledge et al. [42] created a randomized controlled trial in which a virtual reality bicycle pedaler for rehabilitation of phantom limb pain was varied and customized to the patient's preference of pace as well as upper versus lower extremity amputation. The intention was to create a customized rehabilitation with as little difficulty as possible for the patient once at home and able to perform rehab mechanics independently. This proved that patients' concerns with a lack of individualized care have the potential to be addressed appropriately. Albeit a small trial testing improvement of a different pain modality, patients rated the VR rehabilitation experience itself very highly in helpfulness, immersion, realism, and satisfaction. In a VR-based

rehab for upper extremity fractures, a user-friendly interface with feedback systems was created for the therapist to make changes that adapt to difficulties experienced by the patient along their therapeutic journey [43]. Although standard in-person rehabilitation remains the preferred modality for post-operative TKA patients' recovery, VR-based rehabilitation could work as an alternative, given that major concerns of patients are adequately addressed.

Future Directions and Implications

Future Studies

Although virtual reality has emerged as an effective platform for rehabilitation interventions, there are many gaps in current research that can set the stage for future studies and investigations.

One of the most important considerations for the implementation of VR rehabilitation into clinical practice and healthcare delivery is proper standardization. There is significant heterogeneity among both VR and comparator protocols' exercise type and duration. No studies have compared different protocols, so the optimal type and duration have yet to be analyzed [31••]. Additionally, multiple systematic reviews have cited that the quality of evidence is low or moderate and have called for more high-quality and robust RCTs with standardized protocols [25••, 31••]. Regarding specific orthopedic pathologies and procedures, a systematic review and meta-analysis from 2019 showed that virtual reality-based rehabilitation could be an effective option for individuals with neck pain, shoulder impingement, osteoarthritis, and ACL reconstruction. However, the evidence for VR-based rehabilitation for total shoulder arthroplasty, total knee arthroplasty, and back pain – a large percent of orthopedic procedures – is largely inconclusive or absent from the literature [44].

There is also little research regarding the implementation of VR rehabilitation technology at different levels of the healthcare ecosystem, including the patient, health system, and payer. As CPT codes for VR-mediated therapy have been codified over the last few years, payers and health systems will need to adapt to integrate new modalities of VR therapies into existing continuums of care. Although Bettger et al. [5] reported that VR rehabilitation is less of a financial burden on payers compared to traditional rehabilitation, future trials should compare this to other telerehabilitation modalities in order to obtain a more relevant understanding of costs in a telemedicine climate. The reimbursement structure of telerehabilitation also varies by state and will involve local interpretation of laws and payment structures for fluid implementation and health system updates [5].

The effectiveness of physical therapeutic modalities hinges on patient compliance, which is another area that calls for investigation. An RCT from 2021 showed mixed results regarding compliance with VR-based rehabilitation —while VR-based cardiac rehabilitation increased program adherence among patients, it also decreased patient motivation and absorption, a measure of immersion into the program [45]. Further research is warranted regarding how compliance pertains to specifically orthopedic patients, and how to reconcile the apparent disparity between compliance and motivation/absorption. Additionally, cybersickness, a form of virtual reality–induced motion sickness, can serve as a barrier to compliance. Considering that previous studies of virtual reality have reported rates of cybersickness varying from 22–80%, further research is necessary to detail protocols to prevent or treat cybersickness, both on the program developer's side and on the clinician's side [46].

While many studies involving VR-based therapy encompass a broad range of age groups, more research is needed to determine how older age and different levels of technological literacy can affect adoption among users. Additionally, studies involving other key social determinants such as race, education level, and income are called for in order to ensure that marginalized communities are not facing barriers involving access or differential outcomes with respect to virtual reality rehabilitation [47].

Implications for Healthcare

The adoption of VR-based rehabilitation interventions has many implications for clinical practice and could propose potential value to all key players of the healthcare industry —including the patient, healthcare systems, and payers. The COVID-19 pandemic has driven the quick implementation of telemedical tools, including VR-based rehabilitation [48]. Virtual reality–based rehabilitation dovetails well into this movement, as it can be combined with traditional forms of telerehabilitation and at-home rehabilitation. For patients, VR-based rehabilitation techniques can help bridge locational or transportational gaps of access to centralized rehabilitation facilities. Wait times for PT/OT can be up to 30 days, and VR-based rehabilitation, especially if implemented at home, can help cut down the time of injury or surgery to therapy [49]. Additionally, as VR programs further integrate artificial intelligence and adaptive algorithms, rehabilitation can be personalized and adjusted to meet the patient's performance and ability [50]. The cost-saving possibility of virtual rehabilitation has been documented, and when paired with further savings by reduced therapist time and ensuing increased patient volume and turnover, VR-based rehabilitation can be a compelling financial motivator to drive uptake among health

systems [5, 51]. If lower costs are maintained, and more robust data can show reductions in hospital readmissions, fewer complications, better long-term outcomes, and otherwise less healthcare utilization, VR-rehabilitation would present a significant value proposition to payers and could be quickly adopted into reimbursement plans.

Conclusion

The rising prevalence of orthopedic surgery presents significant challenges in the healthcare system, necessitating innovative solutions for postoperative rehabilitation. The connection between orthopedic surgery and rehabilitation is crucial for ensuring optimal patient outcomes as surgical volumes increase. Although well-structured rehabilitation programs are effective in addressing post-surgery functional deficits, patient adherence remains a challenge influenced by various factors. Virtual reality (VR) and telerehabilitation have gained prominence, particularly due to the COVID-19 pandemic, as promising models of care in this context.

VR-based interventions offer an immersive, engaging, and potentially cost-effective approach to postoperative rehabilitation. Studies have shown their effectiveness in improving patient-reported outcomes, reducing pain, and enhancing functionality after procedures like total knee arthroplasty. However, the efficacy of VR compared to traditional rehabilitation methods varies across studies. VR's benefits extend to pain management, distraction, proprioception, and balance improvement. Overcoming challenges like patient familiarity with technology and personalized care is essential for successful implementation. Standardization, rigorous research, and adaptation to patient needs are crucial for integrating VR-based rehabilitation into clinical practice.

VR-based rehabilitation represents a paradigm shift in orthopedic postoperative care, enhancing patient engagement, motivation, and recovery potential. It complements traditional methods rather than replacing them. The future of VR-based rehabilitation in orthopedic surgery depends on further research, strategic implementation, and a commitment to improving patient outcomes. Opportunities lie in standardization, addressing patient barriers, and providing holistic value propositions for healthcare systems and payers.

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•• Of major importance

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