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Special Article

Virtual and augmented reality in contemporary orthopedics: From simulation to the operating room

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Abstract

Virtual reality (VR) and augmented reality (AR) technologies are redefining the landscape of orthopedic surgery by enhancing surgical education, preoperative planning, intraoperative navigation, and postoperative rehabilitation. These immersive tools provide surgeons with spatially rich environments to rehearse procedures, interact with patient-specific anatomical models, and perform operations with enhanced precision. Intraoperative AR applications, in particular, have demonstrated potential to improve accuracy while minimizing reliance on conventional imaging. In rehabilitation settings, VR-based platforms promote patient engagement and functional recovery through interactive and gamified experiences. While extended reality (XR) is increasingly integrated into clinical workflows, barriers such as hardware limitations, cost, and lack of high-quality clinical evidence remain. Nonetheless, the growing body of early clinical experience highlights its feasibility, safety, and impact. Extended reality is no longer a theoretical promise; it is a practical tool that is actively reshaping orthopedic care. Further studies are needed to guide the safe and effective expansion into routine surgical practice.

Level of evidence I; Therapeutic studies - investigating the results of treatment.

Keywords: Augmented reality; Virtual reality; Healthcare; Orthopedic procedures.

Introduction

Over the past three decades, immersive technologies have evolved from simple experimental tools into sophisticated platforms capable of reshaping orthopedic practice. Early medical applications were limited by rudimentary graphics, high costs, and restricted computational power. Advances in processing, motion tracking, display technologies, and artificial intelligence (AI) have since transformed virtual reality (VR), augmented reality (AR), and the broader field of extended reality (XR) into practical tools used across the entire surgical pathway—from preoperative training and procedural planning to intraoperative navigation and postoperative rehabilitation.

In modern surgical education, VR provides fully immersive environments that allow safe, repetitive practice of complex procedures such as arthroscopy, fracture fixation, and joint arthroplasty. High-fidelity simulators, often equipped with haptic feedback, have been shown to accelerate skill acquisition, enhance knowledge retention, and support the effective transfer of technical competence to the operating room[1-3].

Conversely, AR enhances intraoperative visualization by overlaying key digital information—such as anatomical landmarks, surgical trajectories, and navigation cues—directly onto the surgeons' field of view. Evidence shows that this real-time guidance improves implant positioning accuracy and reduces complication rates in spine, trauma, and arthroplasty procedures[4-6]. The integration of AR, VR, and related modalities within the XR framework is enabling more precise, patient-specific, and data-driven surgical workflows.

This review aims to clarify the core principles of VR, AR, and XR and to synthesize their current and emerging applications

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in orthopedic surgery, with particular emphasis on their expanding role in foot and ankle procedures.

Definition

Extended reality is an umbrella term for technologies that merge physical and virtual environments, including VR, AR, and mixed reality (MR) (Table 1)[7-9].

Virtual reality

Virtual reality represents the fully virtual end of the reality spectrum, immersing users in a computer-generated, three-dimensional (3D) environment with realistic spatial and interactive features[7,10]. Virtual reality simulators typically employ head-mounted displays (HMDs) and handheld controllers, often enhanced with haptic feedback and real-time simulation of anatomical structures or surgical tasks[2]. These systems provide a safe and controlled environment for repeated practice and objective performance assessment, making VR particularly valuable for education, patient engagement, and rehabilitation[6,7]. However, because users are visually disconnected from the real world, the direct use of VR in the operating room is limited.

Augmented reality

Augmented reality occupies the opposite end of the spectrum, overlaying digital information (graphics, text, medical images) directly onto the user's view of the real world[4,6-8,10]. These systems use HMDs with see through displays or with front-facing cameras to reproduce the outside world on internal displays, as well as handheld devices such as smartphones, allowing surgeons to visualize preoperative plans or anatomical data within the surgical field. Overlaying the information reduces distractions and optimizes operating room space[11]. This technology is increasingly recognized as a versatile intraoperative tool with the potential to enhance surgical precision and reduce radiation exposure.

Mixed reality

Mixed reality bridges the gap between VR and AR by integrating elements of both, enabling complex, simultaneous interaction with physical and virtual objects[7]. Examples of such technology include the HoloLens® (Microsoft Corporation, Redmond, WA, USA) and the Vision Pro® (Apple Inc., Cupertino, CA, USA). Advanced 3D manipulation of computed tomography (CT) reconstructions is available during preoperative planning and enables seamless integration of these plans with the patient's anatomy intraoperatively, facilitating navigation, guidance, and visualization[11]. Surgeons can interact with virtual data in real time using voice commands, gaze, or hand gestures. Mixed reality HMDs also offer a potentially more cost-effective and space-efficient alternative to traditional navigation surgical systems.

Extended reality applications

Training and education

Extended reality technologies, particularly VR and AR, are permeating orthopedic education by providing immersive, risk-free environments for acquiring and refining surgical skills (Table 2). This shift away from the traditional apprenticeship model ("see one, do one, teach one") underscores the growing need for complementary tools, such as surgical simulators[2,11,12].

Anatomy education is a particularly promising application of VR[4]. Three-dimensional anatomy is a persistent challenge for surgeons in training. At the same time, access to cadaveric specimens is declining, and while physical anatomical models remain valuable, they are costly and often fail to capture the full complexity of the spectrum of anatomical variants.

Virtual reality offers a powerful solution by delivering interactive, 3D visualizations of complex musculoskeletal structures[13]. These systems allow users to isolate muscles, tendons, ligaments, and bony landmarks, thereby promoting a deeper and more clinically relevant understanding of

Table 1. Key modalities of extended reality in medical practice. The table summarizes definitions, characteristic devices, and primary applications of virtual reality, augmented reality, and mixed reality

Extended reality modality	Definition	Devices / Features	Applications
Extended reality	Umbrella term for technologies merging physical and virtual environments, including VR, AR, and MR	–	General concept encompassing VR, AR, MR
Virtual reality	Fully virtual, immersive 3D environment	HMDs, controllers, haptic feedback, and real-time anatomical simulation	Education, surgical training, patient rehabilitation; limited intraoperative use
Augmented reality	Overlays digital information onto the real-world view	Optical HMDs, smartphones, tablets	Intraoperative guidance, visualization of anatomy/plans, improves workflow, and reduces radiation exposure
Mixed reality	Combines VR and AR and allows interaction with both physical and virtual objects	MR HMDs (HoloLens®, Vision Pro®), hand gestures, gaze, voice commands	Preoperative planning with 3D CT, intraoperative navigation, guidance; cost- and space-efficient alternative to robotics

VR: Virtual reality; AR: Augmented reality; MR: Mixed reality; XR: Extended reality; CT: Computed tomography; HMDs: Head-mounted displays; 3D: Three-dimensional.

Table 2. Summary of extended reality applications in orthopedics

Extended reality application	Description / Use	Key findings
Anatomy education	VR-based anatomical visualization of musculoskeletal structures (hip, knee, shoulder, spine, foot, and ankle)	- Allows isolation of muscles, tendons, ligaments, and bony landmarks - Facilitates understanding of functional anatomy - Improves comprehension of 3D relationships (e.g., acetabulum and femoral head)
Surgical education and planning	VR for rehearsing anatomical pathways and procedures (arthroscopy, fracture fixation, joint replacement)	- Visualization of portal trajectories and deep structure orientation - Anticipation of spatial constraints
Surgical skill acquisition	Simulator-based training with PBP	- Structured progression, stepwise skill reinforcement - Objective performance feedback - Accelerates learning curve and improves procedural competency
VR simulation performance	VR surgical simulators for orthopedic and minimally invasive procedures	- Faster task completion - Fewer errors - Effective discrimination between novice and experienced trainees - Transferable skills to the real operating room
Operative competence in orthopedics	VR-based orthopedic and robotic surgery training	- Enhanced surgical planning and reasoning - Increased trainee engagement and satisfaction - Higher validated skill scores in cadaveric procedures
Remote collaboration and expert guidance	MR with HMDs for real-time interaction between trainees and experts	- Facilitates global surgical collaboration - Real-time 3D holographic projections and audiovisual communication - High surgeon satisfaction; potential to support remote/underserved areas

VR: Virtual reality; HMDs: Head-mounted displays; 3D: Three-dimensional; PBP: Proficiency-based progression.

functional anatomy that is difficult to achieve with traditional two-dimensional (2D) resources.

For example, VR simulations of the hip joint can dynamically demonstrate the critical 3D relationships between the acetabulum, femoral head, and surrounding soft tissues—structures essential for diagnosing conditions such as femoroacetabular impingement or gluteal tendinopathy. A mixed-methods study comparing a VR skull model with traditional cadaveric skulls and anatomical atlases found that VR users achieved comparable post-test scores while reporting significantly higher learner satisfaction and a more positive perception of the educational experience[14].

Beyond basic learning, VR-based anatomical tools are increasingly incorporated into orthopedic surgical education, effectively bridging the gap between theoretical knowledge and hands-on operative practice[15]. These platforms allow surgeons and trainees to examine anatomical pathways and rehearse procedures such as arthroscopy, fracture fixation, or joint replacement (Figure 1). A recent systematic review and meta-analysis reported that VR-based instruction produces a moderate but significant improvement in anatomical knowledge compared with traditional teaching methods (standardized mean difference ≈ 0.58), with particularly notable benefits in visualizing complex musculoskeletal regions[16].

Figure 1. Virtual reality used for simulation-based training in total hip replacement (Johnson & Johnson, Warsaw, IN, USA). The immersive platform enables step-by-step rehearsal and enhances anatomical orientation for trainees.

Beyond anatomical knowledge, VR platforms can further enhance surgical education by accelerating the learning curve through repeated, high-volume practice[17]. Simulator-based training—especially when guided by proficiency-based progression—is effective in developing surgical skills. These systems objectively track and analyze user performance, providing measurable feedback that reinforces learning. Proficiency-based progression is a structured training model in which learners must achieve predefined proficiency benchmarks before advancing to more complex tasks[18]. A landmark meta-analysis of VR surgical simulators, encompassing multiple studies, found that surgeons trained with VR completed tasks more quickly and with fewer errors than control groups[12].

In a randomized, double-blind trial, Seymour et al.[19] studied 16 surgical residents, with eight receiving proficiency-based VR training and eight receiving standard instruction. VR-trained residents completed laparoscopic cholecystectomy tasks 29% faster and exhibited a significantly lower mean error rate (1.19 errors per case) compared to the non-VR group (7.38 errors per case), representing a sixfold reduction. Non-VR-trained residents were also substantially more likely to cause nontarget tissue injury or gallbladder perforation and to experience temporary procedural lapses.

Similarly, Logishetty et al.[20] conducted a randomized controlled trial involving 24 surgical trainees with no prior experience in the anterior approach for total hip arthroplasty (THA). Half of the participants completed a six-week VR training program in a simulation laboratory, while the other half received conventional preparatory materials. All trainees subsequently performed cadaveric THA. VR-trained surgeons outperformed controls, completing 33% more key procedural steps, achieving 12° greater accuracy in component orientation, and performing the procedure 18% faster. The study concluded that both procedural knowledge and psychomotor skills learned in VR successfully transferred to cadaveric performance.

A 2024 systematic review and meta-analysis including over a thousand participants found that VR-based orthopedic training significantly improved clinical operation scores (SMD = 1.44), enhanced surgical planning and execution, strengthened clinical reasoning, and increased trainee engagement and satisfaction compared with traditional training methods[21]. Similarly, procedural VR training in robotic surgery has been shown to improve objective surgical performance: participants who trained with VR achieved higher validated skill scores during subsequent cadaveric procedures than those without VR experience[22].

A particularly compelling application of XR is the enabling of real-time interaction between expert surgeons and trainees. Head-mounted displays provide accessible platforms for collaboration across distances. Gregory et al.[23] described the use of MR technology in 13 orthopedic procedures performed by surgical teams across 13 countries, most involving joint replacements. Expert collaborators maintained real-time audiovisual communication online while local teams leveraged computer-based tools and 3D holographic projections. Surgeon satisfaction was consistently high, with all participants recognizing the potential value of this technology for future practice. This approach holds considerable promise for expanding global surgical collaboration, extending expert guidance to remote or underserved areas, and advancing both surgical education and patient care.

Surgical planning

Extended reality technologies can play a crucial role in advanced preoperative planning, converting conventional 2D imaging—such as CT and magnetic resonance imaging—into interactive 3D virtual models that enhance the surgeons' understanding of patient-specific anatomy and pathology (Figure 2). Mixed reality, in particular, enables enriched 3D interaction with CT-based reconstructions, allowing surgeons to manipulate virtual bone models.

Surgeons can visualize fracture patterns and plan reductions and fixation options using a risk-free environment. For example, a 2024 study comparing traditional CT-based planning with VR-assisted planning for complex tibial plateau fractures found that VR not only significantly reduced operative planning time but also increased surgeons' confidence in their chosen surgical strategies[24].

Complementing these findings, a feasibility study demonstrated a low-cost, high-fidelity VR system that allowed surgeons to import patient-specific CT data and overlay virtual trauma implants within the same 3D environment. This approach facilitated detailed preoperative planning for complex fractures, including acetabular and proximal femoral fractures[25]. The results suggest that XR-based surgical planning may enhance operative preparation, reduce intraoperative uncertainty, and potentially shorten operative time while lowering complication rates.

Beyond trauma, XR-based planning is increasingly applied to arthroplasty and prosthetic implant positioning. In a prospective case–control study of primary THA, preoperative planning using VR-derived 3D models improved the accuracy of acetabular cup placement compared with conventional planning methods[26].

In orthopedic oncology, XR technologies are increasingly being applied[27]. In this context, XR converts patient-specific imaging data into interactive models, enabling precise delineation of tumor margins, improved understanding of the relationships to neurovascular and musculoskeletal structures, and detailed planning of resection planes. Proof-of-concept studies using MR with HMDs have shown that this approach enhances surgeons' spatial awareness of bone tumors, reduces cognitive workload during planning, and outperforms conventional 2D imaging for preoperative assessment[28].

In pelvic sarcoma cases, surgeons using a custom VR platform modified their surgical approach or planned margins in nearly half of cases after reviewing 3D models, suggesting

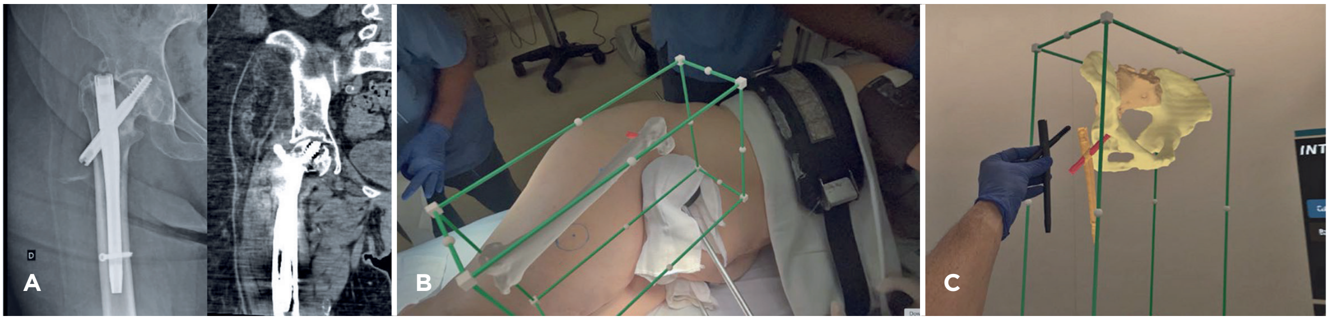

Figure 2. Augmented reality application in surgical planning. (A) Radiograph and computed tomography showing failed fixation of an intertrochanteric femoral fracture. (B) Using the Vision Pro® (Apple Inc., Cupertino, CA, USA) with the IntraVision XR® application (DICOM Director, New Haven, CT, USA), the surgeon superimposes a three-dimensional reconstruction onto the patient's thigh. (C) Following implant removal, the high fidelity between the virtual reconstruction and actual implant positioning is evident.

that VR can meaningfully influence decision-making and potentially reduce the risk of positive margins or incomplete resections[29]. Similarly, XR is proving valuable in planning complex spinal surgeries, including tumor resections, deformity corrections, and instrumentation procedures.

A recent user study comparing VR-based planning with conventional computer-based visualization for spinal tumor surgery found that VR allowed surgeons to identify more anatomical and functional structures, improving the selection of surgical approaches by anticipating anatomical constraints and optimizing access routes[30]. Furthermore, a systematic review of AR and VR applications in spine surgery reported benefits in preoperative planning, including reduced operative time, decreased blood loss, and improved procedural accuracy across interventions ranging from instrumented fixation to tumor resection[31]. Together, these findings demonstrate that XR can enhance surgical planning and patient safety in spinal oncology and complex spine cases by providing immersive, patient-specific anatomical insight before the first incision.

Extended reality intraoperative applications

Augmented reality technology is particularly valuable for intraoperative guidance, as it allows the superimposition of critical surgical information directly onto the physical operative field. In procedures involving fluoroscopy, XR can reduce the cognitive effort required to mentally reconstruct 2D images into 3D anatomical relationships, thereby enhancing surgical precision. These systems can project virtual anatomical models onto the surgical site or generate real-time virtual guides to assist with implant positioning and osteotomy planning, making intraoperative AR one of the most transformative innovations in orthopedics to date.

An emerging application of AR in sports medicine involves mirroring the arthroscopy display onto HMDs (Figure 3). This setup offers several advantages, including improved screen resolution, the ability to incorporate additional floating windows—such as 3D reconstructions—and greater flexibility in operating room logistics. By eliminating the need for fixed external monitors, this approach can enhance workflow efficiency, particularly in crowded surgical environments.

In orthopedic trauma surgery, intraoperative XR—particularly AR—is increasingly used for real-time guidance, improving fracture reduction and implant placement. For instance, a feasibility study demonstrated that intramedullary nail insertion in a tibial fracture model could be performed using only AR guidance, without intraoperative fluoroscopy, via an HMD[32]. In this system, surgeons visualized patient-specific 3D anatomy and overlaid the virtual nail trajectory directly onto the surgical field, enabling precise alignment and reducing reliance on 2D radiograph images. Such real-time guidance has the potential to shorten operative time, decrease radiation exposure, and reduce the risk of malreduction or implant misplacement, particularly in complex fractures or in situations where fluoroscopy is limited[33].

Similarly, in arthroplasty surgery, XR-assisted intraoperative navigation shows significant potential for improving precision and reproducibility[34]. A recent study evaluating a novel AR-based navigation system during total knee arthroplasty (TKA) reported that bone resections and implant placement were performed with high accuracy, with angular and thickness deviations from the preoperative plan remaining below 1° and 1 mm, respectively[35].

Furthermore, comprehensive reviews of AR applications in orthopedic surgery indicate that AR and MR can enhance implant placement accuracy (including screws and prostheses), reduce postoperative complications related to malalignment, shorten operative time, and lower radiation exposure for both surgeons and patients (Figure 4)[36]. These findings collectively suggest that intraoperative XR represents a highly transformative innovation in orthopedic surgery, providing a practical, precise, and safer alternative to conventional techniques.

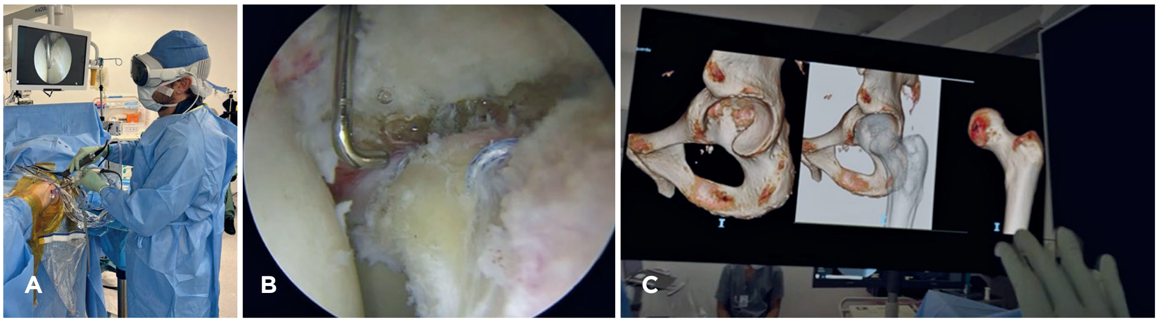

Figure 3. Augmented reality application in hip arthroscopy. (A) Surgeon using Vision Pro® (Apple Inc., Cupertino, CA, USA) during the procedure. (B) Arthroscopic view seen through the headset. (C) Floating screen with three-dimensional reconstructions for enhanced anatomical guidance.

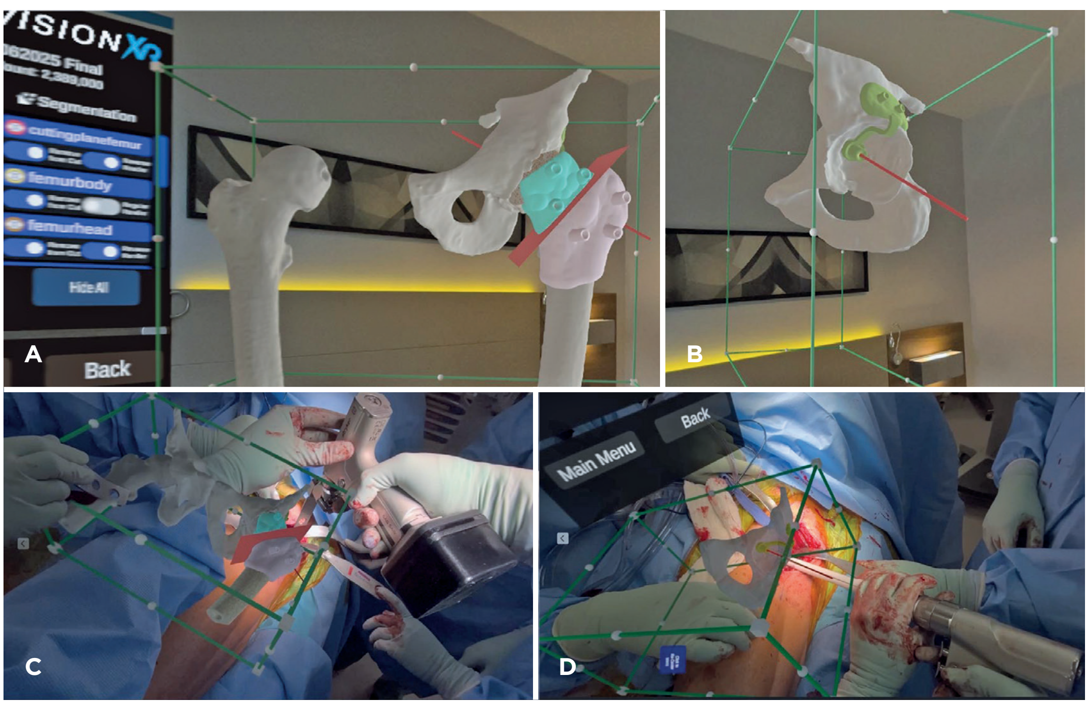

Figure 4. Proof-of-concept demonstration of virtual surgical guides for total hip arthroplasty using the Vision Pro® (Apple Inc., Cupertino, CA, USA) and the IntraVision XR® platform (DICOM Director, New Haven, CT, USA). All images are direct screen captures from the surgeons' headset. (A) Virtual guide designed for femoral osteotomy. (B) Virtual guide for acetabular preparation and cup placement. (C) Intraoperative view where the virtual guide could assist with positioning the surgical saw along the planned osteotomy plane. (D) Intraoperative view where the virtual guide could support optimal acetabular reamer orientation.

In orthopedic oncology, particularly for bone or pelvic tumor resections, intraoperative AR can substantially improve surgical precision and safety. A recent preclinical feasibility study demonstrated that an AR-based guidance system using HMDs enabled accurate placement of patient-specific surgical guides and execution of osteotomies in 3D-printed pelvic models, achieving angular errors below 3° and linear deviations under 2 mm[(37)]. This ability to overlay virtual cutting planes and guide trajectories directly onto the surgical field provides surgeons with immediate visualization of both the anatomy and the planned resection, which is critical for achieving precise tumor margins and preserving vital structures. Accurate delineation and placement of patient-specific guides in complex bone or pelvic tumors can reduce the risk of tumor compromise or the need for reoperation.

Similarly, in spine surgery—including procedures involving intradural and extradural tumors—microscope-based AR heads-up displays have been successfully utilized to enhance intraoperative anatomical orientation and improve visualization of both the target and at-risk structures[17]. In this approach, relevant information is projected directly onto the microscope's eyepiece or screen during the procedure, integrating digital guidance into the surgeons' field of view. In a series of ten patients with spinal cord tumors, AR allowed accurate visualization of tumor contours and their anatomical relationships, achieving a mean registration accuracy of approximately 0.7 mm and facilitating safe tumor resections[38].

Moreover, recent literature reviews indicate that AR and VR in spine surgery can assist with instrumentation placement, vertebroplasty, tumor resection, and osteotomies. Potentially offering increased accuracy and spatial orientation, and reduced intraoperative radiation exposure[31].

Rehabilitation and recovery

Immersive VR offers non-pharmacological strategies for pain management and plays a growing role in enhancing engagement during post-surgical recovery and rehabilitation. The multissensory immersive environments provide cognitive distraction, reducing pain perception through attentional redirection[39]. This can be particularly valuable in early postoperative phases when patients are acutely focused on pain, limiting participation in rehabilitation. Virtual reality platforms simulate functional tasks and controlled exercises within gamified frameworks, promoting active participation and sustained motivation, and are on par with conventional rehabilitation[40]. These interactive systems aim to improve adherence by transforming repetitive exercises into engaging, personalized activities. Additionally, VR enables remote telerehabilitation, allowing patients to complete guided exercises at home under clinical supervision—thereby expanding access, reducing logistical barriers, and promoting continuity of care, especially in underserved areas. In populations that adapt well to these systems, it is non-inferior to in-person rehabilitation[18]. Overall, VR represents a promising complement to conventional therapy, offering scalable, individualized, and patient-centered rehabilitation solutions.

Applications in foot and ankle surgery

The use of XR in foot and ankle surgery has expanded beyond education and training, with promising clinical applications in surgical planning, intraoperative guidance, pain management, and rehabilitation. Recent studies have shown that VR and AR technologies can improve surgical precision and patient outcomes, particularly in complex foot and ankle cases.

Moreno-Marín et al.[41] conducted an in-depth analysis of the foot ossification process through a systematic review. Based on their findings, the authors generated accurate 3D digital reconstructions of the bones and subsequently imported these models into a virtual reality environment. They propose that innovative educational tools, such as virtual anatomical models, can enhance students' understanding of the sequential ossification of foot bones by offering an interactive and spatially accurate representation of skeletal development.

Augmented reality can also support surgical planning in foot and ankle procedures. Abdel et al.[10] reported a case of synovial sarcoma of the foot in a patient who had previously received inadequate treatment, complicating the surgical approach. The authors utilized an AR application running on a smartphone camera to overlay preoperative imaging onto the patient's foot, enhancing intraoperative orientation. This approach facilitated complete tumor excision with negative surgical margins. At the 12-month follow-up, the patient remained disease-free, highlighting the potential of AR to improve precision in complex oncologic foot surgeries.

Phantom limb pain presents a complex therapeutic challenge, and VR has emerged as a novel tool to support its management. This approach typically involves patients wearing a VR headset while engaging with a virtual representation of their missing limb, which can help restore sensory-motor integration. Hali et al.[42] conducted a systematic review of 15 studies investigating VR-based interventions for phantom limb pain. Fourteen of these studies reported reductions in objective pain scores, either after a single VR session or a series of sessions. Furthermore, the combination of VR with tactile stimulation demonstrated superior efficacy than VR alone, suggesting that multimodal strategies may yield enhanced analgesic outcomes.

Extended reality technologies have also shown potential in supporting rehabilitation following foot and ankle surgery. VR-based interventions, including video game–driven platforms, have been applied to the recovery from ankle sprains[43]. However, their effectiveness has not consistently surpassed that of conventional physical therapy or even no intervention, suggesting that VR may not offer significant benefits across all clinical scenarios. Elaraby et al.[44] conducted a systematic review and meta-analysis to evaluate the efficacy of virtual training in the rehabilitation of orthopedic ankle injuries. Their analysis of ten randomized controlled trials revealed improvements in balance and several gait parameters, although no significant differences were found in the Foot and Ankle Ability Measure (FAAM). The authors also highlighted the suboptimal methodological quality of the included studies and concluded that, while VR-based rehabilitation programs may be a viable adjunct, further high-quality trials are necessary to clarify their true clinical value.

Limitations and challenges

Despite the potential of XR technologies in orthopedics, several limitations restrict their widespread clinical adoption. Technical challenges, particularly those concerning accurate visualization and spatial registration, remain significant barriers. Markerless tracking systems can be affected by soft-tissue deformation, changes in lighting, and obscured anatomical landmarks, all of which may reduce intraoperative accuracy[45]. Studies in spine and trauma surgery indicate that such registration inaccuracies can negatively affect implant placement, despite ongoing advancements in tracking and calibration. Although ongoing improvements in computer-vision and sensor-fusion technologies are expected to reduce these problems, their consistent performance across different surgical environments still requires further validation.

User experience and ergonomics are also critical factors. Although modern XR HMDs are increasingly lightweight, concerns regarding cybersickness, visual fatigue, and reduced situational awareness during prolonged use persist. Controlled studies report that up to one-third of users may experience simulator-related discomfort; however, newer devices with improved display resolution, frame rates, and field-of-view design show a markedly lower incidence[46]. These physiological and cognitive limitations are anticipated to diminish with ongoing hardware and interface development.

Economic considerations further complicate adoption. High initial costs for hardware, software, maintenance, and training may limit accessibility, especially in resource-constrained settings. Early adoption models suggest that, as with prior surgical technologies such as navigation and robotics, costs are likely to decrease as XR systems mature and become more widely distributed[4].

A major limitation in the field is the lack of high-quality clinical evidence. Most existing studies are feasibility projects, cadaveric experiments, or small observational cohorts. Systematic reviews repeatedly emphasize the need for rigorous, standardized randomized controlled trials to assess how XR affects surgical accuracy, operative efficiency, complication rates, and patient-reported outcomes[31]. Developing uniform reporting standards will also be essential to ensure meaningful comparisons across future studies.

Finally, integrating XR safely into established surgical workflows remains a significant challenge, as poorly designed interfaces can increase cognitive load or divert the surgeons' attention during critical steps. On the other hand, when combined with structured training and evidence-based protocols, XR can enhance surgical judgment, improving precision and situational awareness. Ongoing collaboration among engineers, clinicians, and human-factors experts is essential to optimize usability and ensure that XR technologies support performance without compromising patient safety.

Future directions

As XR technologies mature, their integration with other emerging tools—such as AI, robotics, and intraoperative navigation—will likely accelerate their clinical utility. These synergies may enable real-time data analysis, intelligent surgical guidance, and adaptive planning, further personalizing and refining orthopedic care. In parallel, advances in hardware design must address current ergonomic limitations, including headset comfort, weight distribution, and visual strain, to support extended use in surgical environments. Cost reduction and platform interoperability will also be critical for broader clinical adoption.

Equally important is the generation of high-quality evidence. Future research should prioritize well-designed clinical trials, long-term outcomes, and cost-effectiveness analyses to validate the role of XR in surgical decision-making and patient care. With thoughtful implementation, XR, when combined with complementary digital technologies, has the potential to reshape the surgical landscape and elevate the standards of orthopedic practice.

Ultimately, the successful realization of the transformative potential of XR technologies in orthopedic practice over the coming decade will require sustained, interdisciplinary collaboration among clinicians, engineers, and industry stakeholders[9].

Conclusions

Extended reality is no longer a futuristic concept; it is an emerging reality within orthopedic surgery. From education to intraoperative guidance and rehabilitation, XR technologies are already reshaping how surgeons learn, plan, and operate. As clinical adoption grows, these tools are poised to elevate precision, safety, and patient outcomes. Continued research and high-quality clinical studies will be essential to ensure the safe and effective integration of XR into routine surgical practice.

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