The Journal of Arthroplasty 38 (2023) 2096–2104

Contents lists available at ScienceDirect

The Journal of Arthroplasty

journal homepage: www.arthroplastyjournal.org

Artificial Intelligence and Machine Learning

Exposure to Extended Reality and Artificial Intelligence-Based Manifestations: A Primer on the Future of Hip and Knee Arthroplasty

Hashim J.F. Shaikh, BS [a], Sayyida S. Hasan, BS [b], Joshua J. Woo, BS [c], Ophelie Lavoie-Gagne, MD [d], William J. Long, MD [e], Prem N. Ramkumar, MD, MBA [e, f, *]

[a] University of Rochester Medical Center, Rochester, New York
[b] Donald and Barbara Zucker School of Medicine at Hofstra, Uniondale, New York
[c] Brown University, Providence, Rhode Island
[d] Harvard Medical School, Boston, Massachusetts
[e] Hospital for Special Surgery, New York, New York
[f] Long Beach Orthopaedic Institute, Long Beach, California

ARTICLE INFO

Article history:
Received 28 October 2022
Received in revised form
6 May 2023
Accepted 8 May 2023
Available online 15 May 2023

Keywords:
arthroplasty
augmented reality
virtual reality
mixed reality
extended reality

ABSTRACT

Background: Software-infused services, from robot-assisted and wearable technologies to artificial intelligence (AI)–laden analytics, continue to augment clinical orthopaedics — namely hip and knee arthroplasty. Extended reality (XR) tools, which encompass augmented reality, virtual reality, and mixed reality technology, represent a new frontier for expanding surgical horizons to maximize technical education, expertise, and execution. The purpose of this review is to critically detail and evaluate the recent developments surrounding XR in the field of hip and knee arthroplasty and to address potential future applications as they relate to AI.
Methods: In this narrative review surrounding XR, we discuss (1) definitions, (2) techniques, (3) studies, (4) current applications, and (5) future directions. We highlight XR subsets (augmented reality, virtual reality, and mixed reality) as they relate to AI in the increasingly digitized ecosystem within hip and knee arthroplasty.
Results: A narrative review of the XR orthopaedic ecosystem with respect to XR developments is summarized with specific emphasis on hip and knee arthroplasty. The XR as a tool for education, preoperative planning, and surgical execution is discussed with future applications dependent upon AI to potentially obviate the need for robotic assistance and preoperative advanced imaging without sacrificing accuracy.
Conclusion: In a field where exposure is critical to clinical success, XR represents a novel stand-alone software-infused service that optimizes technical education, execution, and expertise but necessitates integration with AI and previously validated software solutions to offer opportunities that improve surgical precision with or without the use of robotics and computed tomography–based imaging.

Extended reality (XR) refers to technology that provides users with the experience of immersing themselves in simulated interactive worlds that either replace or augment reality [1]. In particular, XR consists of virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR removes reality and places the user in a completely simulated world, encompassing all senses [2]. AR and MR, however, supplement the real physical world with simulated images and designs [2].

Over the past 50 years, XR has undergone rapid development from its initial conception in the 1950s [3]. Initial interest in XR, and specifically VR, began in the federal sector, when VR flight simulators were used to train army pilots during World War II [4]. These simulators required large supercomputers and dedicated rooms to

One or more of the authors of this paper have disclosed potential or pertinent conflicts of interest, which may include receipt of payment, either direct or indirect, institutional support, or association with an entity in the biomedical field which may be perceived to have potential conflict of interest with this work. For full disclosure statements refer to https://doi.org/10.1016/j.arth.2023.05.015.

* Address correspondence to: Prem N. Ramkumar, MD, MBA, Hospital for Special Surgery, 535 E 70th Street, New York, NY 10021.

https://doi.org/10.1016/j.arth.2023.05.015
0883-5403/

allow for these projections [4]. As a result of the considerable cost and space limitations, VR remained unaffordable for the public and was limited to larger institutions. However, the advent of head-mounted displays (HMDs) has significantly streamlined XR technology, and within the last decade, XR has received increased attention in the public sphere [5]. Moreover, incorporation of artificial intelligence (AI) is central to maximizing the capabilities of XR by enabling automation that permits object recognition, seemless interaction, personalization, and real-time translation. Without AI, manually registering these processes would hamper efficiency and adoption. Thus, the success of XR depends upon AI incorporation.

Self-containing HMDs made VR available through video game entertainment sets, such as the Oculus Rift (Meta, Menlo Park, California) furthered innovation for AR and MR as well, through XR streaming in AR-based applications such as Pokémon Go (Niantic, San Francisco, California), Ikea Place (Ikea, Delft, South Holland, the Netherlands), and the MR-based Microsoft HoloLens (Microsoft, Redmond, Washington). Due to its unique ability to enhance medical information by visualizing vital information in real-time and replicating 3-dimensional (3D) images and experiences, as well as the fact that nearly all modern computers have the computing power to readily incorporate this type of technology, XR has already been adopted by the medical field. Initially, XR adoption was best used for medical training and education, namely the use of VR in building surgical and technical skills [6,7]. More recently, XR technology has advanced to surgical applications in tumor resection, neurosurgery, spine surgery, ophthalmology, vascular surgery, cardiothoracic surgery, maxillofacial surgery, and orthopaedic surgery [1,8–15].

Hip and knee arthroplasty are primed for XR incorporation given the nuance of implants, instrumentation, anatomic variation, balancing, and complexity of the revision setting. Robot-assisted surgery, fluoroscopy, and intraoperative navigation are increasingly leveraged to achieve heightened surgical accuracy. However, fluoroscopic intraoperative x-ray imaging can distort images, consume real estate in the operating room, and increase patient and surgeon exposure to radiation [16], while computer navigation and robot assistance may distract the surgeon from the surgical site with a computer screen. Additionally, fluoroscopic, computer-assisted, and robotics often involve large equipment in the operating room, sometimes necessitating extra personnel, which can become costly and problematic in the outpatient ambulatory surgical setting. In contrast, XR can seamlessly enhance hip and knee arthroplasty at lower costs by integrating data visualization into diagnostic and treatment procedures without the potential need for additional imaging, equipment, or machinery. Thus, XR's ability to incorporate data visualization into diagnostic and treatment procedures can greatly benefit hip and knee arthroplasty. Currently, there is limited understanding of XR application in hip and knee arthroplasty. The purpose of this primer is to overview and critically details the recent developments surrounding XR in the field of hip and knee arthroplasty while addressing potential future applications as they relate to AI.

Definitions

Extended Reality

XR is an umbrella term for technology that merges physical and digital reality [17]. It lies at the intersection of 3 technologies: VR, AR, and MR [12,18,19] (Fig. 1).

Virtual Reality

VR is a computer-simulated reality that portrays a fully artificial environment that does not physically exist. Within VR, users are isolated from the real world [20]. Its applications use interactive goggles or headset devices that send and receive information to immerse the user in a computer-generated environment that simulates reality [17]. The VR headsets, or head-mounted devices (HMDs), are unique as they are instrumental in deceiving the brain into believing it is immersed in the alternative reality. The HMDs are made to physically filter visual stimuli from the user's reality and to only allow visual input from a screen that displays virtual images [17,21]. Additionally, because VR headsets have gyroscopes and motion sensors, any head movements made by the user translate to the same degree in the virtual environment [22] (Fig. 2). Not unlike robotic-assisted surgery, a learning curve for the operative team will certainly be present with the introduction of new devices, such as a headset, console station, and sensor array. Given this, VR serves as an ideal platform for simulated training as demonstrated by Hooper et al in a randomized controlled trial involving 14 orthopaedic interns [7]. For instance, pilots often train in fully virtual simulators in preparation for flight. Similar to flight simulators, VR training can prepare surgeons for live operations, improve technical skills, and assist with case preparation [23].

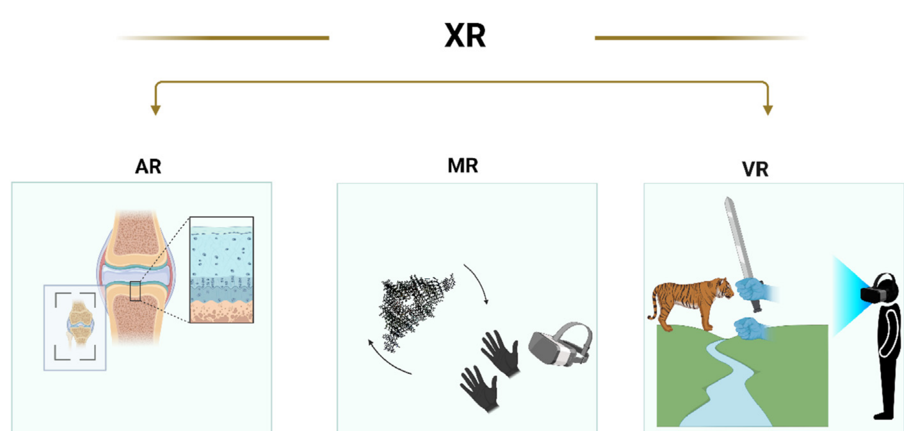

Fig. 1. Extended reality is an umbrella term that entails augmented reality, mixed reality, and virtual reality. All extended reality experiences involve an immersive experience for the user, whether that includes a wholly alternative reality (VR), a supplemented reality (AR), or a combination of either supplemental reality with interactive capability (MR).

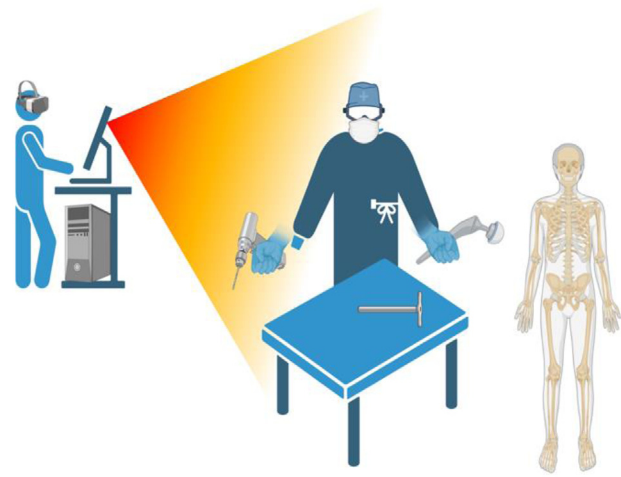

Fig. 2. Displays user with head-mounted displays and virtual reality software performing hip surgery in a simulated world for practice repetitions.

Augmented Reality

AR is a live view of physical reality that is enhanced by virtual-generated sensory input such as sound, video, graphics, or global positioning system data [24,25]. With the advancement of AR technology, the information about the surrounding real world of the user becomes interactive [26]. Artificial information about the environment and its objects can be overlaid on the real world, such as external rotation of the posterior condylar axis or the trans-epicondylar axis [27]. Amid the rise of the technological revolution for big data and analysis, one of AR's primary goals is to use AI to highlight specific features of the physical world, increase understanding of those features, and derive smart and accessible insights that can be applied to real-world applications. Not unlike flight training where pilots use AR to provide real-time data pertaining to terrain, weather, navigation, and traffic conditions, surgeons must similarly undergo a "flight checklist" and assess multiple intra-operative metrics to safely and accurately perform a hip or knee arthroplasty.

Mixed Reality

MR is the next wave of innovation for XR. An amalgamate of physical and VR, MR exists on the "virtuality continuum", with physical reality on one end and digital reality on the other (Fig. 3) [28]. Through the blending of realities, MR creates an intuitive 3D platform for interaction between computer, human, and environment [29]. It is largely based on innovations of AI-based systems such as computer vision (CV), software processing, display output, and cloud computing. Essentially using the same concept of computer graphics overlayed onto reality as AR, the main advantage of MR is that users can interact and manipulate digitally generated objects [30]. By doing this, MR technology enables surgeons to manipulate virtual surgical implants over patients before implanting actual ones, view coordinates over the anatomical site, and view their surgical plan all in real time, much like a fighter pilot would see a command eye view of the airspace while engaged in combat.

Extended Reality (Augmented Reality and Mixed Reality) in the Operating Room: Technical Considerations

Head-Mounted Display

XR overlays digital elements onto reality through the use of (1) an HMD placing the visual information close in front of the user's point of view; (2) handheld devices like a smartphone; or (3) a computer-generated overlay that is placed directly on real objects [31]. The HMD enables superposition of digitally generated content onto the user's reality while maintaining see-through vision to the real world. The HMD executes translation of virtual content on a 2-dimensional micro display outside the view of the HMD and transmits light rays to the user's eyes from a beam combiner. The HMD lenses between the beam combiner and display focus computer-generated images over the intended area, allowing the wearer to perceive 3D virtual augmentations [32]. The HMD also aids in positional tracking of the user and its relation to a tracker external to the HMD [33]. These peripherals can track the position of the user's head, body, and hands anywhere within the range of the device.

Registration

XR systems require 3 components to function in an operative theater: Registration, Tracking, and Spatial Modeling.

Registration embodies finding an optimal spatial transformation to ensure the feature points from 2 associated images have the same spatial and anatomical position [34]. Registration methods can be divided into 2 types: rigid and nonrigid. Rigid registration is the most common technique employed in orthopaedic procedures. Rigid registration focuses on ensuring that the target image corresponds to the feature points on the source image based on finding the free transformation of 6° of space [35]. A feasible registration workflow must provide high target registration accuracy, high robustness, and low computation time. Nonrigid registration serves to mold complex 3D shapes to align with an intended target and consists of 2 steps [36]. First, a set of corresponding points are computed using the closest point of interest, and then a nonrigid

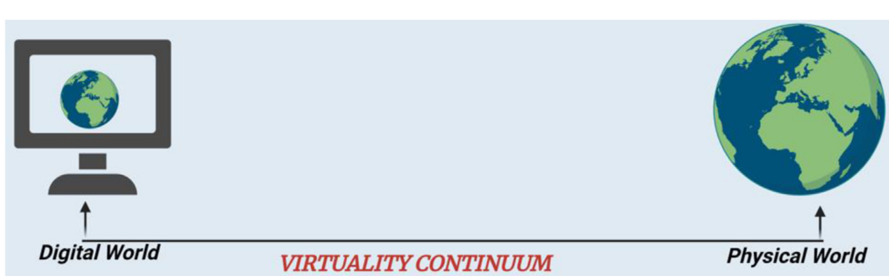

Fig. 3. Mixed reality (MR) exists along the virtuality continuum, bridging the physical to the digital world. Largely based in innovations of artificial intelligence–based systems such as computer vision, software processing, display output, and cloud computing, MR creates an intuitive three-dimensional platform for interaction between computer, human, and environment to incorporate dynamic intraoperative evaluation and allow for the virtual manipulation of implants before resection, cementation, and implantation.

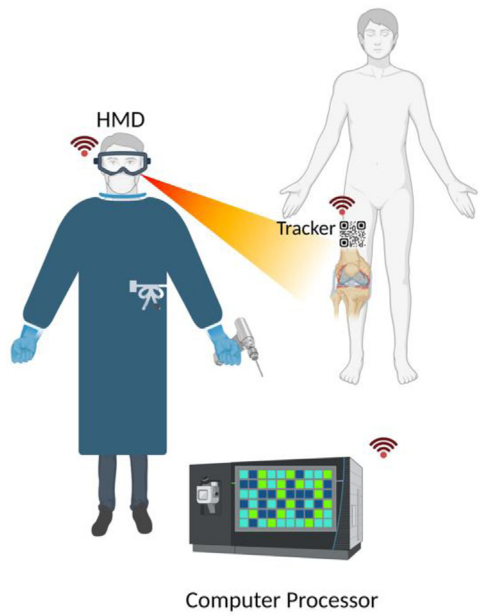

Fig. 4. Success of augmented reality in surgery requires the computer processor to communicate with head-mounted displays (HMD) and tracker. Intercommunication between the three systems creates the ability to overlap 2-dimensional (2D) digitally generated information into a 3D structure that is precise in measurement and overlays anatomic to the patient. As the surgeon moves throughout the operative theater, the wireless connection between the tracker, HMD, and computer process ensures the computer-generated image maintains the correct 3D orientation and overlap for display.

transformation is performed to minimize error metrics [37]. The system repeats itself with the goal of converging on a local minimum. As such, use of nonrigid registration may be better suited for tumor resections compared to stiff bony structures. In the arthroplasty setting, the proximal femur may require nonrigid registration given the mobility of the leg during total hip arthroplasty (THA) after the neck osteotomy.

Tracking allows the augmented object to stay in the intended orientation when the user moves while simultaneously adapting to the new user position in a 3D space [38]. Tracking involves the XR device referencing the augmented image from its original registration in a spatial room and adjusting for the change in coordinates. Optical-based tracking allows the superimposition of 3D images with precise spatial positions [39]. The target and the displayed 3D image can be correlated by target-image registration through marker or markerless-based means. The marker registration method uses external fiducial markers such as physical spheres, reflective lenses, or infrared light-emitting diodes attached to the target, whereas markerless registration mainly detects the intrinsic structural features of the target [40,41].

The spatial model serves to store information about the user's reality and the digital world. The user's reality serves as the template to reference, while the digital world provides content to augment the user's reality. XR creates a feedback loop between the user's reality and the computer-visualized object, such that the user is in control of the viewpoint of augmentation. At the same time, the system tracks the user's viewpoint, registers the pose in the real world with the virtual content, and presents a situated visualization (Fig. 4). With the use of AI, projections can be displayed that simulate relevant angles for interpolated axes, such as the transepicondylar axis for the knee of the acetabular version. Similarly, AI can approximate the anatomy of hip and knee anatomy when trained on a library of prior computed tomographies (CTs).

Artificial Intelligence–Based Computer Vision

XR (including AR and MR) and AI represent 2 emerging transformational technologies of recent interest in orthopaedics. While the value of AI is yet to be quantified or holistically studied, both AI and XR are advancing at a rapid pace to satisfy technological needs in their respective fields. Without AI, XR is hamstrung. Only when combined, can XR potential be unlocked. CV, a subset of AI, serves as the "eyes" for the computer, registering and processing visual data for the computer to interpret [42,43]. Thus, enabling XR software can process and analyze data just as human eyes send input to the brain. Then, it can overlay image or speech recognition data collected from prior user activity and overlay this information on the lens of a user HMD. Without AI-based CV, XR cannot interpret input signals into a meaningful display that the surgeon can appreciate, not unlike the brain analyzing the data to be output to the surgeon screen. This allows for real-time feedback while simultaneously cross-referencing digital libraries of surgical guides and imaging to anticipate the next surgical step [44]. For example, upon exposing the knee and registering anatomic surface landmarks, AI-based software is necessary to contextualize these points into a relevant 3D anatomic workspace that was previously trained on a library of human knee CTs to appreciate "normal" landmarks. Once registration is complete, resection depths and relevant parameters (ie, transepicondylar axis) can be extrapolated with demonstrable accuracy to replace the cost and radiation associated with individual preoperative CTs. Imagine a world wherein CV offers XR to assess a surgeon's technical preferences and workflows to digitally codify intraoperative attention and procedure. This would offer an indexed library of a surgeon's own steps for display to first assistants, scrub technicians, and circulating nurses to optimize team efficiencies and create the potential for 6 sigma efficiency. Similarly, for complex cases, indexed workflows from a surgeon's surgical mentors could be intraoperatively considered as a form of digital mentorship in perpetuity.

CV can be separated into 3 domains: classification, segmentation, and detection. Classification, for instance, can assign a real-time image to a predetermined class, such as instruments being present or absent in the surgical field. This may leverage a naïve Bayes machine-learning model. Segmentation serves to identify structural borders, such as the tibial plateau or femoral condyles, which may apply a support vector machine-learning model. Detection identifies specific areas of interest like the outline of a bony cut [45]. Thus, CV permits XR to analyze and interpret complex data with previously unseen computational performance. When combined with preoperative CT that has undergone autosegmentation and autoannotation for complex arthroplasty scenarios, visualization can be further optimized with augments for scenarios with massive bone loss to maintain the operational goals of a primary arthroplasty like offset and leg-length discrepancy.

Extended Reality in the Orthopaedic Literature

Education and Training

XR has been introduced and adopted into the healthcare field, initially as a tool for education supplementation. Multiple studies have found that increased practice and exposure to hands-on clinical training improves surgical outcomes, like the OSSO VR platform (San Francisco, California) which has demonstrated improved surgical performance, including step accuracy, superior postoperative patient global assessment, lower training time, and less surgical time in orthopaedic residents that used the VR platform compared to traditionally trained groups [7]. A recent blinded, randomized controlled trial analyzing the impact of VR in orthopaedic residents found VR-simulated training improves post graduate year 1 resident surgical and technical skills [7,46–48]. Using XR, residents and students can obtain full competency without affecting the ethical implications of clinical training on patient care [49]. Bartlett et al found that subjects using the validated Simbionix ArthroMentorVR Simulator (Simbionix, Cleveland, Ohio) developed markedly improved hip arthroscopy skills after 3 uses [49]. Using 9 senior orthopaedic residents (resident group) and 7 shoulder arthroscopy surgeons (expert group), Lohre et al compared a XR training tool to a traditional technical journal article control and found that residents using the XR tools demonstrated substantially improved translational technical and nontechnical skills acquisition versus traditional learning in senior orthopaedic residents [50]. Ponce et al developed a virtual interactive presence in an XR-based platform that layered a live video of a surgeon's hands into the local surgeon's operative field to provide concurrent and visual instructions [51]. This tool was used by surgeons on 15 patients undergoing shoulder arthroscopy. The study found that users found the real-time advice and visualization helpful without any compromise of patient care or increased operative time [51]. Similarly, an enhanced XR headset which tracked bony anatomy was used by 24 fourth-year medical students applying to surgical residency programs, who had prior arthroplasty experience, and conducted 4 simulated THAs using XR headsets. One group trained using XR with live holographic orientation feedback, while the other received one-on-one training from a senior hip arthroplasty surgeon. After the 4 once-weekly training sessions, the students who received XR guidance demonstrated significantly lower errors in orientation on pelvic sawbones than the students who were directly guided by the surgeon (1° versus 6°, $P < .001$) [15]. Although this study was underpowered and true impact remains to be determined, XR experiences offer trainees the potential to improve technical skills and decision-making in an environment that prioritizes education over efficiency—particularly in the context of a healthcare environment that values surgical volume. However, despite its success, one could argue that XR should never be used to replace direct patient contact. Additionally, there may be differences in terms of digital literacy, adaptability to new technologies, spatial awareness, perception of XR technologies, and attitude toward innovation between young surgeons who grew up with gaming and XR technologies compared to surgeons from earlier generations. However, it is important to note that individual variations and preferences can exist among surgeons of different age groups. Further research and training may help bridge the gap between generations and facilitate the successful integration of XR technologies into surgical practice. Understanding and addressing these differences can be a challenge but will be valuable in effectively implementing XR technologies in surgical training and practice.

Navigation Accuracy

XR goes beyond simulated training to offer the precision of robotic-assisted surgery potentially without the capital expenses of a robot or the radiation and necessity of a CT scan. One of the primary benefits of XR in orthopaedic surgery has been improved accuracy. Liu et al developed a navigation system using depth-sensing technology and the HoloLens (Microsoft, Redmond, Washington). Navigation guidance was generated according to preoperative imaging and superimposed into the surgical field via a robotic registration system which measured the pose of the patient's femur [52]. This system was assessed through measurements of guide hole drilling on sawbones in 3 different experimental groups, each consisting of 30 trials. The first group tested repeatability, the second group tested obstacle avoidance between the camera and the target femur, and the final group was conducted by students without medical backgrounds [52]. In total, there was an average 3D position error of 1.9 mm and an average direction error of 2.06° compared to the preoperative 3D scan [52]. Fotouhi et al used an XR-guidance system for placement of acetabular components during THA [53]. The XR-system used 2 C-arm x-ray images and combines them with XR visualization to provide real-time red-green-blue-depth data overlay onto the target femur, which could be adjusted as needed by the surgeons. Four orthopaedic residents conducted impactor and cup placement on sawbones, with reported differences of 2 mm in translation, 1° anteversion, and 0.5° abduction from preoperatively planned hip phantoms [53]. Thereby, XR was able to incorporate 2-dimensional images from a C-arm to reconstruct a 3D construct, without the need of dosing the patient with the equivalent amount radiation from a preoperative CT. Using the same XR technology, 8 orthopaedic surgery residents conducted placement of hip acetabular components on Sawbone (Pacific Research Laboratories, Inc, Vashon, Washington) foams through a direct anterior approach in a study by Alexander et al [54]. Compared to fluoroscopic measurements, the XR technique was associated with significantly increased accuracy for target inclination and anteversion and significantly increased precision for target anteversion [54]. The authors also reported that the XR technique was faster by 1.8 minutes ($P < .01$) and that the surgeons found the XR system easier to use and experienced markedly less radiation as a result [54]. Thus, XR not only enhanced accuracy but reduced operating time and radiation exposure.

In 2018, Ogawa et al developed an XR-based navigation system which allowed surgeons to superimpose a virtual acetabular cup onto the surgical field using a smartphone application, designed to improve the accuracy of acetabular placement angle measurement [55]. Using this system on 54 patients undergoing primary THA, the study found that the navigation system displayed significantly more accurate anteversion measurements than traditional goniometers (2.7° versus 6.8°, $P < .001$) [55]. However, a randomized control trial on 46 patients undergoing acetabular cup placement in THA found that this system did not demonstrate significantly improved accuracy in anteversion or inclination measurements [56]. Using the opposite concept, Hiranaka et al used XR to project the fluoroscope monitor onto the surgical field during a femoral head wire insertion and found this helped in improving accuracies as well as radiation exposure and insertion time. Use of XR in this setting may reduce the need of requiring constant x-rays throughout the procedure thereby reducing radiation to both the patient and surgical staff [57].

In 2019, Tsukada et al used the similar software to create for total knee arthroplasty (TKA) [58]. In the pilot study, knee resection was conducted on 10 femoral sawbones, with resection angles in the coronal and sagittal plane measured using XR with a CT-free software. By overlaying dimensions for bone resection with a smart phone and a bar code sensor, the AR measurements only differed from CT-based measurements scan 0.8° in the coronal plane and 0.6° in the sagittal plane—demonstrating reliability and accuracy [59]. A follow-up clinical study on 72 patients undergoing TKA demonstrated significantly lower error in resection angle for the XR group (1.1° versus 2.2°, $P < .001$) when comparing the absolute difference between the measured lateral distal femoral angle on a standing long-leg x-ray and the target (90°) [59].

Recently, in 2021, Iacono et al conducted a pilot study on 5 patients undergoing TKA using an AR system [60]. The surgeon was able to view the tibial and femoral axis superimposed on the surgical field through smart glasses. Axial alignment and orientation measurements were compared to standardized preoperative and postoperative full leg length weight-bearing, anteroposterior, and lateral knee radiographs. The study found coronal errors $\leq 1°$ for both tibial and femoral cuts and sagittal errors $\leq 2°$ for tibial cuts [60].

Current Applications in Hip and Knee Arthroplasty

In the past decade, the Center for Medicare Services has implemented competition-based hospital measures with remunerative consequences to incentivize reductions in readmissions, costs, and complications for hip and knee arthroplasty [61]. One such advancement can be seen with navigation robotic systems, which attempt to mitigate imprecision and increase reproducibility for successful outcomes after hip and knee arthroplasty. However, robotic-guided systems present additional costs, require initialization and personnel, and have bulky workstations, cameras, and screens [62]. XR technology in hip and knee arthroplasty may address these concerns. XR is designed with low-profile systems that eliminate the need for a surgeon to constantly switch their attention between the patient and the monitor [63]. It provides the surgeons with complete visualization and allows them to view their surgical plan directly on the patient [64]. This section is focused on providing up-to-date context.

Three-Dimensional Soft-Tissue Tracking

During knee arthroplasty, Medacta's NextAR (Medacta, Castel San Pietro, Switzerland) gives surgeons the ability to leverage XR and AI to monitor 3D soft-tissue activity in real time [65]. Common techniques within TKA require sacrifice of one if not both cruciate ligaments, putting extensive strain and restraint on the collateral ligaments. Elongation patterns of the collateral ligaments during functional movements following knee arthroplasty have important implications for postoperative knee stability, range of motion, and pain [66]. Optimal balancing of the collateral ligament allows the patient to obtain an arthroplasty, which feels natural and reduces risk of knee instability. The NextAR incorporates AI to add efficiency and precision by automating preoperative CTs for planning and analysis. As of 2020, this AR TKA has been approved by the Food and Drug Administration for consumer use and was the first XR system to be used for a TKA in the United States [65]. This information is uploaded virtually to smart glasses and displayed onto the patient. A tracker is positioned in the appropriate measurement area; it transmits its spatial position in 6° of freedom and limits the amount of error to less than 0.5°. As soon as the surgeon places the implant trial on the patient, data regarding tension of the ligaments are displayed on the smart glass. Currently, however, there is no end-to-end XR system available that offers a complete solution for the entire intraoperative workflow in hip and knee arthroplasty.

Precision in Femur and Tibia Resection

XR provides surgeons the opportunity to observe and trace over digital information overlaid on to the patient's anatomy to create precise and accurate femoral and tibia resection. The Augmented Reality Visualization and Information System (DJO, Dallas, Texas) provides real-time feedback and guides surgeons in making appropriate size and depth distal femoral and proximal tibia resections for implant placement [67]. This is a self-contained, wearable navigation system that can be worn on a headband or attached to surgical helmets surgeons normally wear in their routine procedure. The headset has 2 infrared cameras that track the instruments and anatomy accurately from the surgeon's perspective and minimizes line-of-sight issues [68]. A 3D XR display projects the real-time information of the patient's anatomy and biomechanical vectors as a hands-free interface; this system is advantageous to providers as it does not require additional external equipment, technicians, or CT/magnetic resonance imaging imaging prior to surgery.

Acetabular Component Placement

One of the leading causes of instability can be attributed to acetabular component positioning during THA [69,70]. Traditional navigation systems require large external workstations, cameras, or screens [71]. XR software enables surgeons to place the acetabular component in the proper orientation according to each individual's anatomy.

Hip Insight (Boston, Massachusetts) was the first Food and Drug Administration–cleared surgical guidance platform that contained entirely the Microsoft HoloLens (Microsoft, Redmond, Washington) [72]. The XR system incorporates the 3D nature of a CT to specifically model the patient's pelvis and femur. The computer model and plan are loaded into the XR headset; the surgeon will then briefly place a small tracking implant on the patient's pelvic bone. As the lens pairs with the tracker, the XR system displays real-time 3D models of the patient's anatomy, implants, and instruments inside the body, creating the sense of x-ray vision.

Future Directions

In 1998, Blackwell et al surmised that there was a potential for the successful incorporation of XR into multiple avenues of orthopaedic surgery [73]. Nearly 3 decades later, use of XR has begun to show promising clinical results in various subspecialties, including tumor resection and spine fixation [74–76]. Cost-effectiveness and space-effectiveness was one of the earlier challenges of XR implementation in clinical orthopaedics; however, since 2016, XR is accessible through wireless HMD and smartphone applications. Similarly, earlier concerns about image integrity granularity, crucial necessities in any surgical field, and especially in arthroplasty acted as barriers to use. However, with the exponential development of these new technologies and the renewed interest in their application, quality of images, feedback, and real-time application have equally improved. Thus, these advancements and the increasing demand for virtual spaces in medicine provide the ideal impetus for the XR boom.

Given that 2 million individuals are expected to undergo total joint arthroplasties annually by 2030 [77], lower limb arthroplasty continues to remain a strong candidate for XR application in orthopaedic surgery. Moreover, with the continued pressure to minimize procedural costs, total joint arthroplasty surgeries conducted under the precision and accuracy of XR may reduce an otherwise financially cumbersome revision [16]. One of the challenges in a successful arthritis procedure is maintaining appropriate 3D alignment and rotation of joint components. To do this, correct implantation of prosthetic components is critical. Traditionally, CT scans have been used to characterize these deformities preoperatively. However, the growing use of XR in orthopaedics may permit surface mapping upon joint exposure that lends to CT-free arthroplasty. The CT-free approach obviates the need for radiation exposure, cost, and insurer-based denials. Currently, some robotic-assisted arthroplasties necessitate the use of a preoperative CT scan, followed by registration, prior to performing the operation. XR may offer the ability to accurately detect surface landmarks through a registration process that can correlate with known anatomy (ie, without a CT) or patient-specific anatomy (ie, with a CT), to be used with or without the assistance of robotic arm assistance. One of the chief advantages of XR is greater accuracy with less hardware and fewer intraoperative distractions. While the ideal implant design and alignment remains to be determined, XR offers the ability to preoperatively simulate the normal condition and intraoperatively replicate an ideal postoperative state intraoperatively by marrying soft-tissue geometry with biomechanical properties. In trauma, Shen et al developed an XR implant design system for the preoperative creation of osteosynthesis plates in unilateral pelvic and acetabular fractions [78]. By using the preoperative CT data, the system virtually reduced the fracture and constructed an ideal curve to identify and create the necessary implant model, manipulating the implant according to its predicted planned trajectory. As a result, the surgeons could preoperatively bend osteosynthesis plates which reduced intraoperative surgical time and invasiveness. This same technology could be used in complex revision hip and knee arthroplasty as well, through the 3D rendering of massive bone defects from osteolysis or infection that could be supplemented with augments or double cup reconstructions. Similarly, XR could be leveraged for dynamic intraoperative stability testing, particularly in the setting of complex patient-specific spinopelvic biomechanics prior to intraoperative implant positioning. Similarly, XR models may facilitate a superior understanding of the case overall. In a survey conducted by Yu et al, participants found that XR models provided additional value over standard 3D imaging due to their ability to interact with the models, compared to the fixed horizontal and vertical rotation directions used in current clinical imaging [79]. Given the tight confines of hip and knee arthroplasty, this manipulation may enhance surgeon understanding. XR offers surgeons' reduced need for additive instrumentation or potentially problematic hardware during the actual surgery, as they can rely on the virtual planning to guide their surgical approach. This can help minimize the risk of infection, iatrogenic fracture, and the need for sterilization of such instruments. Additionally, this may ameliorate patient education preoperatively, as surgeons can directly show treatment plans and projected recovery.

Although it has been shown that XR can successfully be used to virtually consult surgeons while in the operating room, this may help bridge expert surgeons and unlock novel opportunities for surgical education, remote assistance, and academic collaboration [51]. Experienced surgeons can provide guidance and instruction remotely through VR or MR platforms, reducing the need for their physical presence in the operating room. This can help minimize the number of personnel in the operating room, thus potentially reducing the risk of infection and lowering the sterilization costs associated with traditional metal instrumentation. In smaller operating room environments with limited sterilization capacity like ambulatory surgical centers, XR is primed for adoption by both surgeons and ambulatory, cost-conscious environments alike. In addition to potentially avoiding the use of a CT or a robotic arm, an XR system that is implant agnostic and could be licensed and calibrated to accommodate the geometry of present-day implants would be the greatest cost-saving initiative rather than a siloed approach, whereby the XR platform is married to the use of the vendor's implant.

Continued development of these techniques and their associated consequences warrants further consideration. As with most emerging technologies, a fully mature solution must be available, safe, and efficacious to warrant consideration in the marketplace. In the case of XR, it must offer gainful improvement over the strong mid-term track record of robotic-assisted arthroplasty. As AI continues to gain utilization, XR will continue to improve with augmented and interactive images.

Limitations

This XR review has potential limitations. The largest consideration is that the marketplace and literature remain immature. The studies reviewed were often pilots consisting of small cohorts. As with any new technology, further investigation with long-term, comparative assessment is necessary to ascertain clinical relevance. Currently, it is unclear whether the improved precision and accuracy provided by XR during knee and hip arthroplasty procedures will result in improved long-term functional outcomes. Nevertheless, the increased accuracy provided by the combination of AI and XR technology may mitigate the limited shortcomings of hip and knee arthroplasty. The limitations of XR technology itself are important to discuss, as this lends to the limitations of the review.

Digital content viewed within XR settings are subject to temporal errors given the requirement for live updates arising from the dynamic motion between the user and object of interest. Image quality depends on the state of added systems, such as inertial sensors, input data, tracking sensor technology, and registration. For example, as the HMD user and the patient move, sensors are required for the registration and superimposition of medical images onto a patient's anatomy [80]. Although various motion prediction techniques are used for latency compensation, these temporal considerations have performance implications.

Tracking the user, the surgical tools, the HMD, and the patient pose further considerations. The accuracy of tracking is essential in task completion when reconciling the user's perspective with real-time tool visualization during surgery [81]. Users may experience visual dissonance as a result of differences between the projected visuals and reality, and in extreme cases, this can provide a "movie projector" effect in which the overlayed images are broadcast rather than incorporated into real-time input. Calibration is crucial to enabling this smooth transition; however, recalibration may be required as with robot-assisted surgery [66]. XR relies on visual spatial tracking. When a mismatch occurs between visual and vestibular processing, the user may experience motion sickness. Recently, the Mayo Clinic developed a galvanic vestibular stimulation to incorporate within XR headsets that serve to aid in synchronization between the users' vestibular system and visual processing, thereby reducing motion sickness [82]. As with all emerging technologies, continued iterations with further technical improvement and demonstrated evidence-based impact will be critical in proving the value of XR in hip and knee arthroplasty.

XR in combination with AI represents a new frontier in hip and knee arthroplasty that will give surgeons on-demand and immediate data in the operating room while maximizing exposure and minimizing inattention. However, XR represents a stand-alone software-infused service that optimizes surgical education and expertise but necessitates integration with AI to unlock the future of hip and knee arthroplasty.

Conclusion

In a field where exposure is critical to clinical success, XR represents a novel stand-alone software-infused service that optimizes technical education, execution, and expertise but necessitates integration with AI and previously validated software solutions to offer opportunities that improve surgical precision with or without the use of robotics and CT-based imaging.

References

[1] Furman AA, Hsu WK. Augmented reality (AR) in orthopedics: current applications and future directions. Curr Rev Musculoskelet Med 2021;14:397–405.
[2] Verhey JT, Haglin JM, Verhey EM, Hartigan DE. Virtual, augmented, and mixed reality applications in orthopedic surgery. Int J Med Robot 2020;16:e2067.

[3] Carmigniani J, Furht B, Anisetti M, Ceravolo P, Damiani E, Ivkovic M. Augmented reality technologies, systems, and applications. Multimed Tools Appl 2011;51:341–77.
[4] Jeon C. The virtual flier: The link trainer, flight simulation, and pilot identity. Technol Cult; 2015. p. 28–53.
[5] Shahab MH, Ghazali E, Mohtar M. The role of elaboration likelihood model in consumer behaviour research and its extension to new technologies: a review and future research agenda. Int J Consum Stud 2021;45:664–89.
[6] Logeswaran A, Munsch C, Chong YJ, Ralph N, McCrossnan J. The role of extended reality technology in healthcare education: towards a learner-centred approach. Future Healthc J 2021;8:e79–84.
[7] Hooper J, Tsiridis E, Feng JE, Schwarzkopf R, Waren D, Long WJ, et al. Virtual reality simulation facilitates resident training in total hip arthroplasty: a randomized controlled trial. J Arthroplasty 2019;34:2278–83.
[8] Yang Y, Porter D, Zhao L, Zhao X, Yang X, Chen S. How to judge pelvic malposition when assessing acetabular index in children? Three simple parameters can determine acceptability. J Orthop Surg Res 2020;15:12.
[9] Mikhail J, Grantham H, King L. Do user-applied safety labels on medication syringes reduce the incidence of medication errors during rapid medical response intervention for deteriorating patients in wards? A systematic search and review. J Patient Saf 2019;15:173–80.
[10] Zheng C, Li J, Zeng G, Ye W, Sun J, Hong J, et al. Development of a virtual reality preoperative planning system for postlateral endoscopic lumbar discectomy surgery and its clinical application. World Neurosurg 2019;123:e1–8.
[11] Edstrom E, Burström G, Omar A, Nachabe R, Söderman M, Persson O, et al. Augmented reality surgical navigation in spine surgery to minimize staff radiation exposure. Spine (Phila Pa 1976 2020;45:E45–53.
[12] Ong T, Wilczewski H, Paige SR, Soni H, Welch BM, Bunnell BE. Extended reality for enhanced telehealth during and beyond COVID-19: viewpoint. JMIR Serious Games 2021;9:e26520.
[13] Eves J, Sudarsanam A, Shalhoub J, Amiras D. Augmented reality in vascular and endovascular surgery: scoping review. JMIR Serious Games 2022;10:e34501.
[14] Sadeghi AH, Peek JJ, Max SA, Smit LL, Martina BG, Rosalia RA, et al. Virtual reality simulation training for cardiopulmonary resuscitation after cardiac surgery: face and content validity study. JMIR Serious Games 2022;10:e30456.
[15] Pepe A, Trotta GF, Mohr-Ziak P, Gsaxner C, Wallner J, Bevilacqua V, et al. A marker-less registration approach for mixed reality-aided maxillofacial surgery: a pilot evaluation. J Digit Imaging 2019;32:1008–18.
[16] Novikov D, Mercuri JJ, Schwarzkopf R, Long WJ, Bosco Iii JA, Vigdorchik JM. Can some early revision total hip arthroplasties be avoided? Bone Joint J 2019;101-B(6_Supple_B):97–103.
[17] Pottle J. Virtual reality and the transformation of medical education. Future Healthc J 2019;6:181–5.
[18] Morimoto T, Kobayashi T, Hirata H, Otani K, Sugimoto M, Tsukamoto M, et al. XR (extended reality: virtual reality, augmented reality, mixed reality) technology in spine medicine: status quo and quo vadis. J Clin Med 2022;11:1–23.
[19] Parsons TD, Gaggioli A, Riva G. Extended reality for the clinical, affective, and social neurosciences. Brain Sci 2020;10:1–21.
[20] Gupta A, Scott K, Dukewich M. Innovative technology using virtual reality in the treatment of pain: does it reduce pain via distraction, or is there more to it? Pain Med 2018;19:151–9.
[21] Cipresso P, Giglioli IAC, Raya MA, Riva G. The past, present, and future of virtual and augmented reality research: a network and cluster analysis of the literature. Front Psychol 2018;9:2086.
[22] Son H, Ross A, Mendoza-Tirado E, Lee LJ. Virtual reality in clinical practice and research: viewpoint on novel applications for nursing. JMIR Nurs 2022;5:e34036.
[23] Fussell SG, Truong D. Using virtual reality for dynamic learning: an extended technology acceptance model. Virtual Real 2022;26:249–67.
[24] Eckert M, Volmerg JS, Friedrich CM. Augmented reality in medicine: systematic and bibliographic review. JMIR Mhealth Uhealth 2019;7:e10967.
[25] Zhu E, Hadadgar A, Masiello I, Zary N. Augmented reality in healthcare education: an integrative review. PeerJ 2014;2:e469.
[26] Jud L, Fotouhi J, Andronic O, Aichmair A, Osgood G, Navab N, et al. Applicability of augmented reality in orthopedic surgery - a systematic review. BMC Musculoskelet Disord 2020;21:103.
[27] Laidacker A. The State of Augmented Reality. 2021. Jersey City, NY.
[28] Sutherland J, Belec J, Sheikh A, Chepelev L, Althobaity W, Chow BJW, et al. Applying modern virtual and augmented reality technologies to medical images and models. J Digit Imaging 2019;32:38–53.
[29] Park BJ, Hunt SJ, Martin C, Nadolski GJ, Wood BJ, Gade TP. Augmented and mixed reality: technologies for enhancing the future of IR. J Vasc Interv Radiol 2020;31:1074–82.
[30] Fonarov O. How mixed reality can be used in effective training solutions. https://www.forbes.com/sites/forbestechcouncil/2021/11/09/how-mixed-reality-can-be-used-in-effective-training-solutions/?sh=64531f7370b2. [Accessed 23 October 2022].
[31] Salehahmadi F, Hajialiasgari F. Grand adventure of augmented reality in landscape of surgery. World J Plast Surg 2019;8:135–45.
[32] Kashiwagi S, Asano Y, Goto W, Morisaki T, Shibutani M, Tanaka H, et al. Optical see-through head-mounted display (OST-HMD)-assisted needle biopsy for breast tumor: a technical innovation. Vivo 2022;36:848–52.
[33] Doughty M, Ghugre NR. Head-mounted display-based augmented reality for image-guided media delivery to the heart: a preliminary investigation of perceptual accuracy. J Imaging 2022;8:1–17.
[34] Andrews CM, Henry AB, Soriano IM, Southworth MK, Silva JR, et al. Registration techniques for clinical applications of three-dimensional augmented reality devices. IEEE J Transl Eng Health Med 2021;9:4900214.
[35] Andersen CR. Determination of rigid body registration marker error from edge error. J Biomech 2009;42:949–51.
[36] Haouchine N, Juvekar P, Wells WM, Cotin S, Golby A, Frisken S, et al. Deformation aware augmented reality for craniotomy using 3D/2D non-rigid registration of cortical vessels. Med Image Comput Comput Assist Interv 2020;12264:735–44.
[37] Zhu H. Robust non-rigid feature matching for image registration using geometry preserving. Sensors (Basel) 2019;19:1–18.
[38] Chan HHL, Haerle SK, Daly MJ, Zheng J, Philp L, Ferrari M, et al. An integrated augmented reality surgical navigation platform using multi-modality imaging for guidance. PLoS One 2021;16:e0250558.
[39] Marino E, Bruno F, Barbieri L, Lagudi A. Benchmarking built-in tracking systems for indoor AR applications on popular mobile devices. Sensors (Basel) 2022;22:1–17.
[40] Sadeghi-Niaraki A, Choi SM. A survey of marker-less tracking and registration techniques for health & environmental applications to augmented reality and ubiquitous geospatial information systems. Sensors (Basel) 2020;20:1–26.
[41] Sugiura A, Kitama T, Toyoura M, Mao X. The use of augmented reality technology in medical specimen museum tours. Anat Sci Educ 2019;12:561–71.
[42] Joshi N. How AR and computer vision lead to smart policing. https://www.forbes.com/sites/naveenjoshi/2022/01/03/how-ar-and-computer-vision-lead-to-smart-policing/?sh=98287e72078c. [Accessed 23 October 2022].
[43] Moawad GN. Augmented realities, artificial intelligence, and machine learning: clinical implications and how technology is shaping the future of medicine. J Clin Med 2020;9:1–7.
[44] Dennler C, Bauer DE, Scheibler AG, Spirig J, Götschi T, Fürnstahl P, et al. Augmented reality in the operating room: a clinical feasibility study. BMC Musculoskelet Disord 2021;22:451.
[45] Morris MX. Deep learning applications in surgery: current uses and future directions. Am Surg 2022;89:36–42.
[46] Student ASM. Core content of the medical school surgical curriculum: consensus report from the association of surgeons in training (ASIT). Int J Surg 2020;84:186–93.
[47] Margalit A, Suresh KV, Marrache M, Lentz J, Lee R, Tis J, et al. Evaluation of a slipped capital femoral epiphysis virtual reality surgical simulation for the orthopaedic trainee. J Am Acad Orthop Surg Glob Res Rev 2022;6:e22.00028.
[48] McKinney B, Dbeis A, Lamb A, Frousiakis P, Sweet S. Virtual reality training in unicompartmental knee arthroplasty: a randomized, blinded trial. J Surg Educ P 2022;79:1526–35.
[49] Bartlett JD, Lawrence JE, Yan M, Guevel B, Stewart ME, Audenaert E, et al. The learning curves of a validated virtual reality hip arthroscopy simulator. Arch Orthop Trauma Surg 2020;140:761–7.
[50] Lohre R, Bois AJ, Athwal GS, Goel DP. Improved complex skill acquisition by immersive virtual reality training: a randomized controlled trial. J Bone Joint Surg Am 2020;102:e26.
[51] Ponce BA, Jennings JK, Clay TB, et al. Telemonitoring: use of augmented reality in orthopaedic education. J Bone Joint Surg Am 2014;96:E84.
[52] Liu H, Auvinet E, Giles J, Rodriguez Y Baena F. Augmented reality based navigation for computer assisted hip resurfacing: a proof of concept study. Ann Biomed Eng 2018;46:1595–605.
[53] Fotouhi J, Alexander CP, Unberath M, Taylor G, Lee SC, Fuerst B, et al. Plan in 2-D, execute in 3-D: an augmented reality solution for cup placement in total hip arthroplasty. J Med Imaging (Bellingham) 2018;5:21205.
[54] Alexander C, Loeb AE, Fotouhi J, Navab N, Armand M, Khanuja HS. Augmented reality for acetabular component placement in direct anterior total hip arthroplasty. J Arthroplasty 2020;35:1636–1641.e3.
[55] Ogawa H, Hasegawa S, Tsukada S, Matsubara M. A pilot study of augmented reality technology applied to the acetabular cup placement during total hip arthroplasty. J Arthroplasty 2018;33:1833–7.
[56] Ogawa H, Kurosaka K, Sato A, Hirasawa N, Matsubara M, Tsukada S. Does an augmented reality-based portable navigation system improve the accuracy of acetabular component orientation during THA? A randomized controlled trial. Clin Orthop Relat Res 2020;478:935–43.
[57] Hiranaka T, Fujishiro T, Hida Y, Shibata Y, Tsubosaka M, Nakanishi Y, et al. Augmented reality: the use of the PicoLinker smart glasses improves wire insertion under fluoroscopy. World J Orthop 2017;8:891–4.
[58] Tsukada S, Ogawa H, Nishino M, Kurosaka K, Hirasawa N. Augmented reality-based navigation system applied to tibial bone resection in total knee arthroplasty. J Exp Orthop 2019;6:44.
[59] Tsukada S, Ogawa H, Nishino M, Kurosaka K, Hirasawa N. Augmented reality-assisted femoral bone resection in total knee arthroplasty. JB JS Open Access 2021;6:1–7.
[60] Iacono V, Farinelli L, Natali S, Piovan G, Screpis D, Gigante A, et al. The use of augmented reality for limb and component alignment in total knee arthroplasty: systematic review of the literature and clinical pilot study. J Exp Orthop 2021;8:52.

[61] Rana AJ, Yates AJ, Springer BD, Huddleston JI, Iorio R. Hip and knee arthroplasty alternative payment model successes and challenges. Arthroplast Today 2022;13:154–6.
[62] Sousa PL, Sculco PK, Mayman DJ, Jerabek SA, Ast MP, Chalmers BP. Robots in the operating room during hip and knee arthroplasty. Curr Rev Musculoskelet Med 2020;13:309–17.
[63] Esposito J. AR-enabled remote assist for surgical procedures. https://www.forbes.com/sites/forbestechcouncil/2022/06/02/ar-enabled-remote-assist-for-surgical-procedures/?sh=62c018017f6f. [Accessed 23 October 2022].
[64] Teich DA. Technology comes together: artificial intelligence, augmented reality, and 5g combine to aid surgeons. https://www.forbes.com/sites/davidteich/2020/08/20/technology-comes-together-artificial-intelligence-augmented-reality-and-5g-combine-to-aid-surgeons/?sh=3d71e24a67ae. [Accessed 23 October 2022].
[65] Sandberg J. Medacta to introduce NextAR(TM): first FDA-cleared augmented reality-based surgical platform for total knee replacement. https://orthospinenews.com/2020/07/14/medacta-to-introduce-nextartm-first-fda-cleared-augmented-reality-based-surgical-platform-for-total-knee-replacement/. [Accessed 23 October 2022].
[66] Hosseinian S, Arefi H, Navab N. Toward an end-to-end calibration for mobile C-arm in combination with a depth sensor for surgical augmented reality applications. Sensors (Basel) 2019;20:1–16.
[67] DJO invests in next-generation augmented reality technology primed for ASC market growth. https://orthofeed.com/2021/03/31/djo-invests-in-next-generation-augmented-reality-technology-primed-for-asc-market-growth/. [Accessed 23 October 2022].
[68] Wilmington D, Enovis Launches ARVIS. Only augmented reality surgical guidance system designed specifically to improve both total hip and knee replacement surge. https://www.djoglobal.com/arvis. [Accessed 23 October 2022].
[69] Zhang S, Liu YB, Ma MY, Cao Z, Kong XP, Chai W. Revision total hip arthroplasty with severe acetabular defect: a preliminary exploration and attempt of robotic-assisted technology. Orthop Surg 2022;14:1912–7.
[70] Malhotra R, Vaishya R. Revision arthroplasty in 2020. J Clin Orthop Trauma 2020;11:1.
[71] Migliorini F, Cuozzo F, Oliva F, Eschweiler J, Hildebrand F, Maffulli N. Imageless navigation for primary total hip arthroplasty: a meta-analysis study. J Orthop Traumatol 2022;23:21.
[72] HipInsight, Carl T. Talmo performs first augmented reality – guided anterior hip replacement at the new england baptist hospital. https://hipinsight.com/featured/dr-carl-t-talmo-performs-first-augmented-reality-guided-anterior-hip-replacement-at-the-new-england-baptist-hospital/. [Accessed 23 October 2022].
[73] Blackwell M, Morgan F, DiGioia 3rd AM. Augmented reality and its future in orthopaedics. Clin Orthop Relat Res 1998;354:111–22.
[74] Cho HS, Park YK, Gupta S, Yoon C, Han I, Kim HS, et al. Augmented reality in bone tumour resection: an experimental study. Bone Joint Res 2017;6:137–43.
[75] Liebmann F, Roner S, von Atzigen M, Scaramuzza D, Sutter R, Snedeker J, et al. Pedicle screw navigation using surface digitization on the Microsoft HoloLens. J Comput Assist Radiol Surg 2019;14:1157–65.
[76] Elmi Terander A, Burström G, Nachabe R, Skulason H, Pedersen K, Fagerlund M, et al. Pedicle screw placement using augmented reality surgical navigation with intraoperative 3D imaging. Spine 2019;44:517–25.
[77] Ramkumar P. Should millennials start saving money for their joint replacement now. https://www.forbes.com/sites/premramkumar/2022/03/19/should-millennials-start-saving-money-for-their-joint-replacement-now/?sh=464225122634. [Accessed 23 October 2022].
[78] Shen F, Chen B, Guo Q, Qi Y, Shen Y. Augmented reality patient-specific reconstruction plate design for pelvic and acetabular fracture surgery. Int J Comput Assist Radiol Surg 2013;8:169–79.
[79] Yu AW, Duncan JM, Daurka JS, Lewis A, Cobb J. A feasibility study into the use of three-dimensional printer modelling in acetabular fracture surgery. Adv Orthop 2015;2015:1–4.
[80] Khor WS, Baker B, Amin K, Chan A, Patel K, Wong J. Augmented and virtual reality in surgery-the digital surgical environment: applications, limitations and legal pitfalls. Ann Transl Med 2016;4:454.
[81] Parsons D, MacCallum K. Current perspectives on augmented reality in medical education: applications, affordances and limitations. Adv Med Educ Pract 2021;12:77–91.
[82] Mayo clinic may have just solved one of virtual reality's biggest problems. Forbes. www.forbes.com/sites/jasonevangelho/2016/03/30/mayo-clinic-may-have-just-solved-one-of-virtual-realitys-biggest-problems/?sh=1e2ab4cc6d9f. [Accessed 23 October 2022].