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Extended reality technologies and their applications in shoulder replacement

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ABSTRACT

The use of extended reality technologies such as virtual reality and mixed reality or augmented reality has increased significantly in multiple areas in recent years, including in orthopedic surgery. In shoulder replacement, there are applications of these technologies for preoperative planning and intraoperative execution as well as for education and training, and possibly also for postoperative rehabilitation.

"Reality" is what each of us perceives as the physical or real-world environment around us. In the context of surgery one can think of the surgical field and the operating room as our "reality". Extended reality is an umbrella term that encompasses any technology that alters reality by adding digital elements to the physical environment.[22] The term *virtual reality* (VR) was coined by Jaron Lanier in 1986[25] to describe a collection of technological devices including a 3-dimensional (3D) rendering capable computer, a head-mounted display (HMD) and controllers with at least one position tracker. Mixed reality (MR) technologies merge the real and virtual worlds.

Milgram and Kishino proposed a "virtuality continuum" to describe the extended-reality technologies and to help understand the different terms, as seen in Figure 1. These terms are not always distinctly separate but rather on a spectrum from completely virtual to completely real.[18]

According to Milgram and Kishino, the distinction between the terms 'real' and 'virtual' has a number of different aspects. The various classes of hybrid or MR can be classified according to whether it is primarily video or computer graphic based, whether the real environment is viewed directly or via some electronic display medium, whether the viewer is intended to feel part of the world or on the outside looking in, and whether or not the scale of the display is intended to map orthoscopically (meaning as a normal, distortion-free view) onto the real environment. Augmented reality (AR) can be thought of as a subset of MR in which virtual (computer graphic) objects are overlaid onto the real environment.

Other authors draw a distinction between AR and MR by the fact that in the MR experience, the user can see and interact with both the digital elements and the physical ones, while AR merely has a digital layer over the physical elements. The Microsoft HoloLens is one example of true MR. As discussed below, MR can have applications intraoperatively for shoulder arthroplasty, particularly in the context of translating a preoperative plan into intraoperative execution. Figure 2 shows the surgeon's intraoperative view of the preoperative plan for a reverse shoulder arthroplasty.

VR is a fully immersive digital experience. The user interacts entirely in the digital environment – almost entirely,

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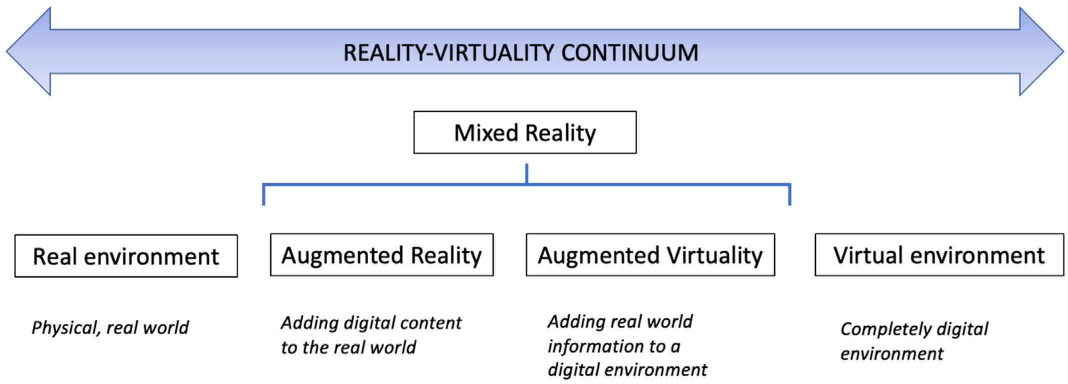

Figure 1 – A representation of the reality-virtuality continuum, as described by Milgram and Kishino.

in that the physical world around the user is still present so that for example if the user walks into a wall, he or she will still collide with the wall in the real world. In other words, the virtual end of the continuum is never really 100% virtual even when the user is fully immersed in the virtual environment. Haptic technology can be added to VR to recreate the sense of touch by applying motion, vibrations or forces to the user, and thus providing a more immersive experience. VR has been shown to have applications in surgical training, particularly in the area of arthroscopy but increasingly also in open surgery, including shoulder arthroplasty.[1,14-17]

Another area of shoulder arthroplasty where there are potential applications for extended-reality technology is in postoperative rehabilitation.[2,4]

Preoperative and intraoperative applications

Component positioning, particularly on the glenoid side, is a key factor in optimizing longevity and clinical outcomes in shoulder arthroplasty, both anatomic and reverse. Advanced, 3D preoperative planning for shoulder arthroplasty has, therefore, become an important part of practice for many shoulder surgeons in recent years.[9,10,20] The ability to better understand 3D anatomy of the arthritic shoulder or the shoulder with cuff tear arthropathy enhances preoperative decision making in terms of choice of procedure and implant selection. Iannotti et al have shown that in most cases, the use of 3D computed tomography (CT) preoperative planning has a positive effect on accuracy of glenoid component placement.[9,10] Single use, 3D-printed patient-specific instrumentation (PSI) guides or multiple use adjustable guides allow for reproduction of the glenoid guide pin positioning intraoperatively and help the surgeon translate the preoperative plan into intraoperative execution, Figure 3. While longer term data will be required to show that this in turn leads to better clinical outcomes, there is some evidence that 3D preoperative planning and use of patient-specific guides improves accuracy of implant placement.[6,9,24] Hendel et al[6] have demonstrated, in a randomized study comparing standard instrumentation to patient specific instruments, that use of a glenoid positioning system significantly reduced deviation from the ideal preoperative planned inclination and medial-lateral offset of the glenoid component, as well as increasing accuracy of reproduction of planned version. However, a meta-analysis published in 2019 did not show any statistically significant differences in version error, inclination error, or positional offset between PSI and standard instrumentation across 20 studies that included 518 shoulder arthroplasty procedures.[3]

MR offers another way to translate a preoperative plan into surgical execution. The surgeon wears a HMD, currently this is most commonly a Microsoft HoloLens 2, and can see the digital preoperative plan and CT scan overlaid onto the real environment, Figures 4 and 5. The surgeon can manipulate the digital images in real time to see different views of the CT scan, the 3D reconstructions and the plan itself. This can help guide steps of the shoulder arthroplasty procedure such as humeral cut and glenoid guide pin placement, by overlaying these parts of the plan onto the surgical field or by visually comparing them side by side. In situations where a physical PSI guide is unavailable for reasons of cost or logistics, MR offers an alternative method of guidance. The cost associated with MR use would comprise of the once-off cost of the HoloLens and any cost associated with a particular planning software, some of which are currently available to surgeons at no additional cost.

Aligning the digital content with the real operative field can sometimes be challenging, for example in cases of a difficult glenoid exposure. In the currently available intraoperative applications of MR, the user still has to replicate the digital plan by visual estimation. This introduces potential for error. A recent study investigated whether users can effectively differentiate between accurate and inaccurate spatial alignment of the virtual content, in this case a glenoid model, and the physical environment ie, the surgical field.[5] Twelve users (one surgeon and 11 computer engineers) were asked to classify the spatial alignment between virtual and real content based on the perceived accuracy delivered by three different visualization paradigms – wire frame, silhouette and heat map. The authors found that the ability of participants to reliably judge the accuracy of spatial alignment was moderate (58.33%). Heatmap-based visualization enabled the most accurate detection of misalignment by users but was the least favored paradigm by users. The conclusion was that conventional MR visualization paradigms are not sufficiently effective in enabling users to differentiate between accurate and inaccurate spatial alignment of virtual content to the environment.

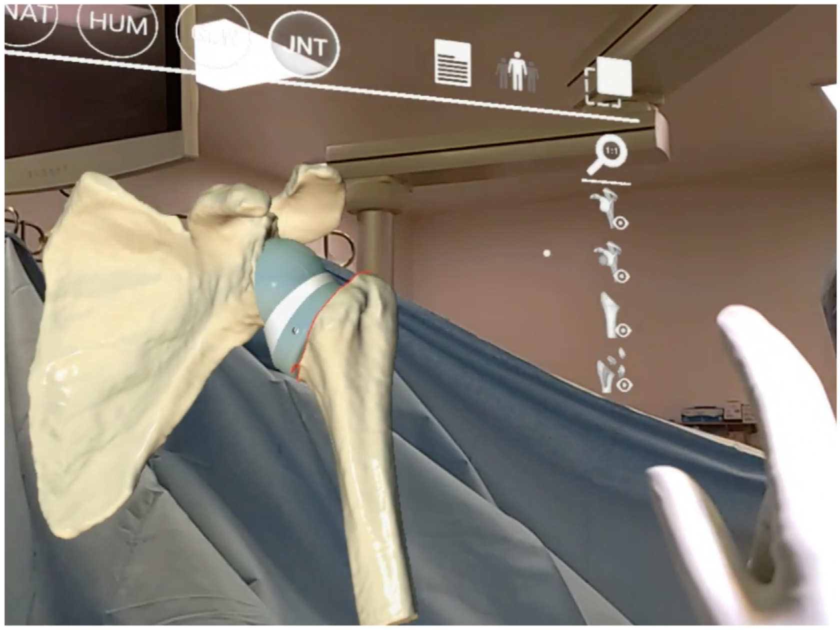

Figure 2 – A mixed reality view on a Microsoft HoloLens 2 of a planned reverse shoulder arthroplasty.

Figure 3 – Intraoperative use of a 3D-printed PSI guide for glenoid guidepin placement. This photo was taken intraoperatively by the surgeon using a HoloLens 2 using a voice command. *3D*, three-dimensional; *PSI*, patient-specific instrumentation.

Computer navigation is another technology available to shoulder arthroplasty surgeons to improve accuracy of execution of a preoperative plan. There is some data to show that use of optical navigation allows improved accuracy and precision for screw placement and precision for baseplate positioning in reverse shoulder arthroplasty.[7,8] Hones et al[8] have shown that navigation leads to fewer and longer baseplate screws being placed in reverse shoulder arthroplasty (in a system in which the baseplate has the option of using up to six screws). In a comparative study of 226 patients, Holzgrefe et al[7] demonstrated that while navigated and non-navigated RSAs yielded similar rates of improvement in range of motion and functional outcome scores, notching and reoperation was more common in non-navigated cases (but did not reach statistical significance).

An important future direction of MR use in surgery is to develop an image-based navigation system to improve accuracy while minimizing cost and disruption to workflow. Current MR navigation tools in development require application of a tracker to the coracoid and registration of points on the bony surfaces. The 3D-plan is projected over the real anatomy and in addition, the hologram shows the surgeon in real time how closely the planned parameters such as inclination and version are being replicated. In other words, the surgeon is receiving instantaneous feedback in MR on his or her accuracy as the guide pin position is adjusted and about to be inserted. Although challenges still exist before image-based MR navigation can be widely adopted by surgeons, a guided-navigation solution based on MR will be a desirable enhancement to both existing MR capabilities and existing navigation systems in improving accuracy of shoulder arthroplasty procedures.

Kriechling et al[12] reported a feasibility study of a navigation technique using MR via a HMD for surgical navigation to place the glenoid baseplate for reverse shoulder arthroplasty. This was an in vitro study using 3D-printed scapula models from CT data of cadaver scapulae. The preoperative digital plan was registered to the anatomy of the glenoid model by digitizing the glenoid surface and the base of the coracoid with optical tracking using a fiducial marker. After navigated placement of the central guide pin, the trajectory and entry point position were checked on repeat CT scan and compared to the digital plan. The mean deviation of the ten placed guidewires from the planned trajectory was 2.7° ± 1.3° (95% confidence interval (CI) 1.9°; 3.6°). The mean deviation to the planned entry point of the ten placed guidewires measured 2.3 mm ± 1.1 mm (95% CI 1.5 mm; 3.1 mm). The same group subsequently evaluated their system in 12 cadaveric specimens, reporting 3.5 mm ± 1.7 mm (95% CI 2.4 mm; 4.6 mm) and 3.8° ± 1.7° (95%

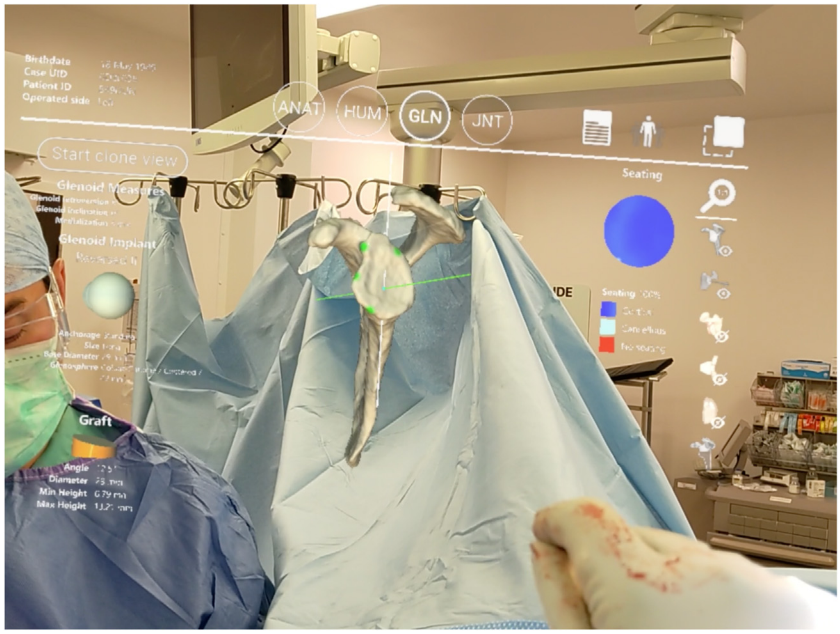

Figure 4 – Viewing the planned glenoid guide pin location and trajectory in mixed reality intraoperatively.

CI 2.6°; 4.9°) deviation.[11] These meaures of deviation are comparable to the findings of Venne et al[23] in relation to base plate placement using optical navigation and would suggest that MR-guided navigation is not inferior to currently available computer-guided navigation.

The clinical use of adding MR to a navigation system for reverse shoulder arthroplasty has been recently described.[21] Trackers are still required to be placed in the coracoid and the navigation system utilizes cameras and a control unit computer but the surgeon can view the navigation on the heads-up display provided by the HMD.

The learning curve for surgeons starting to use MR intraoperatively does not appear to be difficult. This author's anecdotal experience is that familiarity with the underlying planning software enabled smooth adoption of the MR extension of the software. The HoloLens can be worn for the entire case, or the visor raised and lowered by a nonsterile assistant, or the entire HoloLens can quite easily be put on and taken off by an assistant without the surgeon breaking scrub. The lens itself is tinted such that the view of the real environment is slightly darker when wearing the HoloLens. In cases where exposure is anticipated to be difficult, such as in severe glenoid deformity or revision cases, it may often be preferable to perform the exposure without the HoloLens and then wear it for the critical steps of glenoid guide pin placement, glenoid preparation and implant placement. The HMD unit is comfortable to wear and has not posed any significant ergonomic problems. In fact, a recent Korean study of thoracic, laparoscopic and thyroid surgeons found that, compared to using conventional viewing monitors, wearing AR glasses assisted with correction of bad posture in surgeons during video-assisted surgery and reduced muscular fatigue of the upper body.[13]

Teaching and training applications

Both MR and VR have important applications in the teaching of shoulder arthroplasty. The intraoperative use of MR allows projection of the surgeon's view through the HoloLens onto a viewing monitor for others to see. Due to the nature of glenoid exposure, usually only the operating surgeon can have a good view of the glenoid. When the surgeon is using a HMD with built in camera, trainees and students get the same view of the surgical field that the operating surgeon has. They can also see the superimposed digital content and how the surgeon manipulates it to enhance the accuracy with which the procedure is performed. Video can be recorded via the HMD which can also be used for teaching purposes. The capability to broadcast live from the HMD will further expand the teaching possibilities with MR. It is also possible for another surgeon to view the MR remotely and even annotate the MR view. This technology is still under development but offers the potential for experienced, expert surgeons to be able to assist an operating surgeon remotely.

The training application of VR in orthopedic surgery has been widely reported on. Lohre et al[16] have described the evolution of VR in shoulder surgery. Many of the VR programs available focus on arthroscopy.[19] The Precision OS Technology immersive VR is the only commercially available VR simulator for practicing open procedures such as shoulder arthroplasty with demonstrated transfer validity. This system has been used for training senior orthopedic residents on difficult glenoid exposure.[15] In a study examining effectiveness of this method of teaching, it was found that immersive VR demonstrated superior learning efficiency, knowledge, and skill transfer. Nineteen senior surgical

Figure 5 – Wearing the HoloLens 2 while operating.

residents were randomized to receive training on the immersive VR platform (9 residents) or with a mixed-media, multistep technique article as a control group (10 residents). After training, the group trained using VR completed cadaveric glenoid exposure significantly faster than the control group with improved instrument handling scores. Resident training was significantly faster using the VR system compared to reading the article.

Another aspect of education is mitigating skill decay amongst both trainees and established practicing surgeons. Concerns can exist around skill decay when there is an enforced break in operating due to circumstances such as the Covid-19 pandemic or personal or medical reasons that might necessitate time away from operating. Lohre et al[17] have written on the use of immersive VR in this situation. A novel curriculum for structured continuing medical education during and after periods of surgical disruption including e-learning, virtual meetings, and immersive VR simulators was produced from expert opinion and based on competency-based curriculum standards. The authors suggest that the virtual curriculum including immersive VR simulators may provide cost-effective solutions to training.

Postoperative rehabilitation applications

The role of remote virtual rehabilitation after orthopedic procedures has gained importance during the Covid-19 pandemic when there were significant limitations on face-to-face physiotherapy visits and on travel. In a systematic review, Berton et al[2] found that remote virtual rehabilitation was not inferior to face-to-face therapy in postoperative orthopedic patients. They report on 24 studies (9 randomized controlled trials and 15 nonrandomized studies) which included 2472 patients were included. 56% of the studies involved telerehabilitation (phone and video calls with the therapist). Smaller proportions involved using VR (28%) or AR to perform rehabilitation exercises, and gamification of rehabilitation was used in a small number of studies (16%) used gamification. The authors make the point that remote virtual technologies allow the delivery of high-quality care at reduced costs and opine that future studies need to develop specific and objective methods to evaluate the clinical quality of new technologies and definitively demonstrate advantages of VR, AR, gamification, and telerehabilitation compared to face-to face orthopedic rehabilitation. Carnevale et al[4] have examined VR as a joint kinematics monitoring system for shoulder rehabilitation. In a study evaluating the accuracy of the Oculus Quest 2 in measuring translational and rotational displacements of the upper extremity compared to a conventional optical capture system (Qualisys), they found that there was a mean absolute error for translation of 13.52 ± 6.57 mm and a maximum mean absolute error for rotational displacements of $1.11 \pm 0.37°$. These metrics were, in the authors' opinion, acceptable for monitoring shoulder joint angles, allowing for anthropometric measurements and correlating displacement of the Oculus Quest hand controller to angular displacement at the shoulder. This leads the authors to conclude that the Oculus Quest 2 is a promising VR tool for monitoring shoulder kinematics during rehabilitation and is a viable alternative to traditional motion analysis systems.

Conclusion

Extended reality technologies are beginning to play an increasing role in shoulder replacement surgery, including preoperative and intraoperative clinical use, education, and postoperative rehabilitation. The potential for harm from this technology is likely to be low, although factors such as extra operative time, sterility of headsets, registration errors of imaging, are not quantified in current studies. Intraoperative use does have a learning curve for the surgeon. There is the possibility of distraction of the surgeon's focus from the primary priority of caring for the patient and performing the best possible surgery and the surgeon must always guard against that distraction. The HMD can be easily removed during surgery if the surgeon feels that use of the technology is detracting from his or her ability to complete the procedure in an optimal fashion. The use of MR and VR in surgical training is already delivering benefits and will continue to grow. The use of extended reality technologies in postoperative shoulder rehabilitation may be more limited, taking into account patient characteristics and ability to engage with the technology as well as the need for face-to-face, human contact during the rehabilitation process.

These technologies are here to stay and will be part of life outside and inside the operating room. There are multiple conceivable areas for their use in shoulder arthroplasty. The potential low risk of AR/VR may be reasonable in light of the benefits. Many shoulder arthroplasty surgeons are open to embracing these technologies to possibly enhance patient care as shoulder surgery continues to evolve.

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