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Editorial

Applications and Integration of AR in Orthopedic Practice

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When I visited my nephew last week, I found him engrossed in a video game, completely in another world. Curious, I sat down beside him. The graphics were so lifelike—each character moved with precision; the landscapes almost felt tangible. It was as if the game's world was blending into ours.

Watching him play, an idea struck me. What if we could bring this level of immersive, real-time visualization into orthopedic surgery? Imagine AR guiding us, overlaying critical structures, enhancing precision in real-time. Inspired, I left that evening with a renewed vision: to explore AR's potential in transforming surgical accuracy and outcomes and decided to share my thoughts.

Technological advancements have transformed orthopedic surgery, particularly for complex interventions like musculoskeletal tumor treatment, fracture reduction, and corrective osteotomies, where precision in preoperative planning and intraoperative accuracy is essential. Computer-driven methods, including robotic surgery, 3D-printed patient-specific instruments (PSI), and surgical navigation systems, now support surgeons in enhancing planning and execution. Augmented reality (AR) has emerged as an innovative tool, integrating computer-generated sensory data with real-world views to improve surgical guidance. Unlike robotics, AR's human-computer interface offers cost-effective, real-time visualization, reducing radiation exposure and optimizing information transfer for better outcomes.

Basics of augmented reality

In orthopedics for surgical navigation, essential data is extracted from preoperative 2D or 3D imaging to create a detailed virtual model. High-resolution CT scans (1 mm or smaller) are processed in software like Mimics, where thresholding and region-growing techniques isolate the anatomical area of interest. A 3D surface model is created using the Marching Cube algorithm and imported into planning software for simulated, step-by-step surgical preparation. Although automation via machine learning has progressed, expert human planning remains standard.

Registration in AR aligns a computer-generated image, like a radiologic scan, accurately with the surgical site. Once registered, tracking maintains this alignment as the user or instruments move, adapting to changes in position and orientation in 3D space. This process, known as pose reconstruction for instruments, ensures precise interaction with visualized elements. Limitations in registration accuracy or motion tracking can impact effectiveness, making reliable alignment essential for AR applications in surgery.

Tracking is a key challenge in AR for surgery. Current methods include camera-augmented C-arm registration, marker-based registration, and surface registration. Camera-augmented C-arms, pioneered by Navab., *et al*. synchronize intraoperative X-rays with the AR display for real-time visuals. Marker-based registration relies on markers placed within a 3D coordinate system but requires precise positioning. Surface registration, introduced by Liebmann., *et al*. captures a bony surface's unique pattern, overlaying 3D models for navigation.

Visualization combines real and virtual images via head-mounted displays (HMDs), monitors, or projectors. HMDs, with inside-out or outside-in tracking, adapt visuals based on user position. Despite advances, consumer AR devices often lack the precision required in surgery. The Xvision and Microsoft HoloLens are recent FDA-cleared HMDs for spinal surgery, paving the way for higher accuracy in clinical AR applications.

Uses in orthopedics

The spinal cord, spinal nerves, and nearby vessels are at risk of iatrogenic injury during spine instrumentation due to their proximity to the spine's bony structures. Improper placement of pedicle screws in spinal fusion can lead to severe neurological or vascular complications. Consequently, most AR applications in spine surgery focus on guiding pedicle screw placement.

In a study by Yoon., *et al*. 40 pedicle screws were placed using Google Glass as a head-mounted display (HMD) in 10 patients. The surgical team inserted screws in the cervical, thoracic, and lumbar regions, navigating with the Medtronic Stealth S7 system, paired with O-ARM imaging and controlled via voice commands. The study demonstrated HMD-guided pedicle screw placement as safe, reporting no complications. Liebmann., *et al*. developed a novel registration technique to overlay a 3D model of a patient's vertebra, including detailed planning data for pedicle screw insertion points and trajectories. Their approach involved creating a point cloud of the exposed bone surface using a marker-tracked pointing tool, aligning it with the 3D surgical plan. Testing on spine sawbone models, they used the HoloLens to navigate screws from L1 to L5, achieving an average accuracy of 3.38° ± 1.73 for trajectory orientation and 2.77 ± 1.46 mm for entry point positioning. Surface digitization required an average of 125 ± 27 seconds.

Precise osteotomy execution is essential in corrective surgeries to restore physiological anatomy, especially in complex cases with multiple oblique or curved planes, where navigation support is often required. Fallavolita., *et al*. developed an AR-based technique to display the mechanical axis of the leg during surgery. Utilizing a camera-augmented C-arm, they captured a panoramic view of the hip, knee, and upper ankle joint from three X-ray images. Testing this method on 25 cadaver legs with various varus and valgus deformities, they found it accurately aligned with CT data, with no significant discrepancies, and reliably tracked the leg axis intraoperatively using only three X-rays.

In arthroplasty, precise placement of prosthetic components relative to the patient's anatomy is crucial for optimal outcomes, functional recovery, and implant longevity. Studies using sawbones have shown that AR-guided navigation for hip and knee arthroplasties achieves greater accuracy than traditional freehand techniques. Ogawa., *et al*. conducted 56 total hip arthroplasties in 54 patients, using a smartphone-based AR system to guide cup orientation in one group and a goniometer in the other. CT scans taken three months post-surgery revealed that AR navigation significantly improved radiographic anteversion accuracy, averaging 2.7° compared to 6.8° with the goniometer method. Successful trauma surgery relies on precise anatomical alignment of fractured bone fragments. Ortega., *et al*. conducted a multicenter study with 50 patients using a head-mounted display (HMD) to view real-time fluoroscopic images from a C-arm directly in the surgical field. This approach reduced the need for surgeons to look away from the operative area to only five instances, compared to 207 with traditional methods, and also significantly decreased radiation exposure.

Oncologic surgery often requires balancing the need for adequate tumor resection with the preservation of functional tissue. Achieving high surgical precision is essential for both patient survival and optimal recovery. In an experimental study, Cho., *et al*. investigated the effectiveness of augmented reality (AR) using a tablet for bone tumor resection, comparing it with a traditional navigation method in 82 porcine cadaveric femurs. The conventional approach involved an optical tracking system, a display, and a workstation, while bone cement was injected into the cadaver limbs to simulate tumors. The aim was to maintain a 10 mm resection margin. The AR group achieved a mean error of 1.71 mm with no violations of tumor margins, while the conventional group had a mean error of 2.64 mm, resulting in three violations. Ultimately, the AR-guided resections met the targeted 10 mm margin in 90.2% of cases, compared to 70.7% in the conventional group.

In summary, augmented reality (AR) is emerging as a transformative tool in orthopedic surgery, providing enhanced precision across complex procedures including spinal fusion, corrective osteotomies, arthroplasties, trauma repairs, and oncologic resections. AR improves surgical navigation, accuracy, and safety, reducing radiation exposure and error rates. By integrating real-time guidance with patient-specific anatomical data, AR shows promising potential to improve surgical outcomes, optimize planning, and enhance recovery across various orthopedic disciplines.