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The evolution of virtual reality in shoulder and elbow surgery

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Virtual Reality (VR) in orthopedic surgery has significantly increased in popularity in the areas of preoperative planning, intraoperative usage, and for education and training; however, its utilization lags behind other surgical disciplines and industries. The use of VR in orthopedics is largely focused on education and is currently endorsed by North American and European training committees. The use of VR in shoulder and elbow surgery has varying levels of evidence, from I to IV, and typically involves educational randomized controlled trials. To date, however, the terms and definitions surrounding VR technology used in the literature are often redundant, confusing, or outdated. The purpose of this review, therefore, was to characterize previous uses of VR in shoulder and elbow surgery in preoperative, intraoperative, and educational domains including trauma and elective surgery. Secondary objectives were to provide recommendations for updated terminology of immersive VR (iVR) as well as provide a framework for standardized reporting of research surrounding iVR in shoulder and elbow surgery.

Virtual Reality

Virtual reality (VR), first coined in 1986 by Jaron Lanier, has expanded from the entertainment industry to clinical medicine in the preceding decades.[55] This evolution is based on VR's unique ability to replicate scenarios and environments while teaching skills in a cost-effective manner. VR, as is currently available in the consumer entertainment market, uses a combination of equipment including a 3-dimensional (3D) rendering capable computer, head-mounted display (HMD), and controllers with position trackers. Increasingly common is the addition of haptic feedback to VR to re-create a sense of touch, vibration, and motion.[25,26] The transition of VR to clinical medicine and its application in available formats has lagged behind other venues, notably consumer electronics. The term *virtual reality* can be loosely applied to available products for orthopedic surgery in both low- and high-fidelity formats. Low-fidelity products include those that replicate single tasks, or multiple tasks with limitations of interactivity, visual presentation, or available content or commands. High-fidelity products are those that attempt to re-create greater immersion, replicating clinical and operative scenarios and tasks in a more interactive, visually appealing, and content-specific manner.[33] The limits of these designations remain ill defined in the literature. Increasing fidelity requires computer assistance, with the term *computer-assisted orthopedic surgery* (CAOS) increasingly cited in recent publications.[19] CAOS pertains typically to high-fidelity products used for enhancing pre- and intraoperative scenarios. Immersive VR (iVR) attempts to place the user in a realistic environment, using HMD with visual and auditory cues, controllers with haptic feedback, as well as adjunctive options for sense of movement. iVR, therefore, attempts realism through very high levels of multisensory fidelity, including visual, psychomotor, and cognitive capacity through user decision making. Currently, the field of orthopedic surgery lacks evidence-based iVR products on par with VR standards available in other industries, including automotive, aerospace, consumer entertainment, and tourism.

Other simulation modalities

As consumer-ready, cost-effective computing technology becomes available, so too do higher-fidelity VR constructs. VR, augmented reality (AR), and mixed reality (MR) devices have been used in numerous clinical and surgical fields aside from orthopedics, including neurosurgery, plastic surgery, and urologic

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This work did not involve clinical or behavioral research and did not require institutional review board approval.

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surgery.[25,30] In the field of orthopedics, VR has been used for areas of preoperative planning, intraoperative adjuncts, as well as surgical simulation for education purposes. VR in orthopedics has demonstrated great focus and potential in application for education secondary to its demonstrated face, construct, content, and transfer validity.[33] AR incorporates real-time use of graphic interfaces over real-world objects typically through a form of HMD, or as is seen in consumer electronics, a smartphone acting as a digital display. AR has seen use predominantly intraoperatively given the overlay of virtual images on real-life images. VR and AR exist on a spectrum of MR, with VR providing entirely virtual worlds, AR providing virtual image overlay onto real world interaction, and MR encompassing the breadth of application between.

Virtual reality in education

Surgical training has been progressively scrutinized over the validity of traditional teaching methods and Halsteadian "see one, do one, teach one" philosophies.[13] Working hours of surgical residents has been reduced in a number of countries including the United States and European Union through the Accreditation Council for Graduate Medical Education and European Working Time Directive, respectively.[43] Surgical expertise requires refined clinical decision making with a learned level of technical skill. VR provides the ability for learners to critically analyze technique and surgical decision making through error, absent of patient harm in a process of cognitive evaluation. These systems have the added bonus of continuous uninterrupted availability, with available mentorship provided through immediate metrics, the ability for repetition, and outcome measures for task completion. Learning effectively has been proposed by Kolb as progressing through a cycle of abstract conceptualization, active experimentation, concrete experience, and reflective observation.[12] VR provides a Kolb experiential learning cycle ad infinitum to the user. It is because of these reasons that orthopedic training committees and organizations around the world including the American Academy of Orthopaedic Surgeons, American College of Surgeons, and Haute Autorité de Santé in France endorse surgical simulation.[1]

VR evidence

VR publications in orthopedics have steadily increased since its introduction in the early 1990s.[48] The focus of the majority of these publications has been on surgical education, particularly that of arthroscopy given the complexity of skill and the difficult learning environment.[33,43,48] This was reflective in a number of other medical and surgical disciplines, including general and urologic surgery.[30] The infancy of VR provided insufficiently powered, low level of evidence publications without clear documentation on the fidelity of the system used; clear, consistent, and demonstrable outcomes measures; and inconsistency in reporting. As a means of improving this, in 2005 the Work Group for Evaluation and Implementation of Simulators and Skills Training Programmes subgroup of the European Association of Endoscopic Surgeons developed consensus guidelines for the design and reporting of simulation studies. Based on 5 commercially available general surgery simulators and 32 publications, a level of evidence and a level of recommendation system were developed based on the Oxford Centre for Evidence-Based Medicine classification system.[12] Subsequent to this, van Nortwick et al[47] in 2010 delineated lack of rigor in standardized reporting of surgical simulation. Their recommendations included a focus of studies on establishing validity and reliability and reporting instructions for validity assessments of construct, concurrent, and predictive validity. As VR improved, additional validity assessments were included in publications including face, content, construct, and transfer validity.

This review will present available VR systems pertaining to shoulder and elbow surgery in domains of preoperative planning, intraoperative utilization, and surgical training and simulation. Use of VR in trauma and elective shoulder and elbow practice will be discussed as well as for orthopedic surgical education. The validity of these simulators will also be discussed, including current standards for evaluation of VR systems. Furthermore, we hope to establish a benchmark, and updated definition of VR in orthopedic surgical application in keeping with current technologic advancement, abandoning low-fidelity and high-fidelity systems for that of iVR.

Current VR uses

Preoperative planning

Trauma

The AO group emphasizes preoperative planning of fracture care as essential in achieving successful reduction and fixation. Wade et al[50] elicited that nearly all consulting staff and orthopedic residents included in their study felt that surgical planning was important, but only approximately half of each respective group routinely planned fracture care. This was similar in regard to elective cases, though only encompassed knee and hip arthroplasty.[50] An appropriate preoperative plan has been characterized by Müller as a preoperative drawing of the desired end result, development of a step-by-step process to achieve this, and operative logistics of such.[17] Computed tomographic (CT) scans have improved spatial awareness of fragment displacement and reduction in periarticular fractures; however, classic reduction planning remains time-consuming, cumbersome, and difficult with increasing degrees of comminution and does not relate soft tissue effects and most efficient reduction pathways based on these soft tissues. Though the benefits are inherently expressed, there is no specific demonstrated reduction of operating room (OR) time or evaluation of wasted hardware for using preoperative planning in orthopedic surgery.

CAOS was developed for enhancement in preoperative planning and intraoperative assistance. CAOS functionally has elements of passive systems, semiactive systems, and active systems, denoting increasing degree of machine involvement in direct patient interaction.[23] Preoperative planning relates to passive CAOS systems. 3D reconstructive software has been produced to aid in reduction, with publications pertaining to shoulder and elbow surgery focusing on proximal humerus fractures.[7,14,18,35] A thorough review of computer-assisted preoperative planning demonstrates the complexity of computational ability and expert surgical involvement required to produce a usable model. Jiménez-Delgado et al[24] note preoperative planning consisting of generation of bone fragments, virtual reduction planning, and analysis of a virtual reduction plan. Although a number of software solutions have been proposed to delineate fracture morphology from CT images, including reconstruction into 3D formats, there does not exist a definitive model of stabilization methods once fracture reduction has been obtained, including postplanning analysis and evaluation of the proposed construct.[24] Proximal humerus fractures treated with open reduction internal fixation remain elusive regarding preoperative classification system, ideal surgical candidate, and confirmed benefit in postoperative functional outcomes.[16] The complexity of fracture, interplay of soft tissues, and reduction pathways of proximal humerus fractures lends to CAOS integration and more advanced 3D analysis. Attempts at improving intra- and interobserver reliability of classification systems has demonstrated

Table I
Recommended development and research avenues for VR in shoulder and elbow trauma

Development	Research
Development of VR systems in keeping with current industry standards of immersion and using HMD, position trackers, and haptic feedback	Validate VR systems in regard to current standards of face, content, construct, concurrent, and transfer validity
Immersive VR systems that are broad in utility including fracture characterization, reduction via user or computer assistance	Validate VR systems immersion based on industry standard validated immersion metrics (ie, SUS, Virtual reality usability diagnostic tool [VRUSE], and SFQ)
Identification of soft tissue components and optimization of reduction	Design high level of evidence studies to demonstrate immersive VR systems to optimization of operating room parameters
Tracking of user progress and tracking of other users' progress in a cloud-source environment for determining ideal reduction pathways	Subsequent to this, develop high level of evidence studies to demonstrate translation to patient-derived outcome measures
Security and privacy to accumulate user cases to facilitate greater breadth of fracture management	Demonstrate cost-effectiveness of VR

VR, virtual reality; HMD, head-mounted display; *SUS*, System Usability Scale; *SFQ*, Short Feedback Questionnaire.

that 3D reconstruction may benefit trainees or junior surgeons in understanding fracture morphology.[16] Harders et al developed a virtual environment consisting of simulated interactive assembly of multifragment proximal humerus fractures including haptic sensors and demonstrated usability in pilot study in 4 clinical scenarios.[18] Subsequent to this work, Fürnstahl et al[14] developed a semiautomated fracture reduction virtual environment for proximal humerus fractures based on 4 cadaver specimens and tested on 4 clinical cases with contralateral uninjured humerus for comparison. Automatic fracture reduction was seen to reduce time to task completion and produce small translational errors of 1.3 ± 0.4 mm and rotational errors of 3.4° ± 2.2° compared to the computational model built using the contralateral humerus in clinical scenarios, even when using lower-resolution CT scans.[14] Bicknell et al[7] produced a pre- and intraoperative system for preoperative planning and CAOS intraoperative guidance in a passive manner for 4-part proximal humerus fractures managed with hemiarthroplasty. Randomization was performed on 7 fresh-frozen cadaveric specimens to traditional reduction methods vs. CAOS for hemiarthroplasty. Three spheres were applied to the humerus to act as fiducial markers, allowing for conversion of CT scan data to 3D reconstruction and allow navigation and orientation in 3D space. Numerous software programs allowed for this conversion, as well as for intraoperative navigation via an electromagnetic tracking system. Anatomic characteristics of humeral head version angle, inclination angle, offset, humeral length, medial articulation point, and greater and lesser tuberosity position were used as primary outcomes. The system allowed for treatment of simulated 4-part proximal humerus fractures, restoring patient-specific anatomy with preoperative CT scans and intraoperative navigation. Of the 7 parameters measured, only humeral offset was seen to be significantly improved by the 3D reconstructive method, though the trial was significantly underpowered.[7] A recent study by Poltaretskyi et al[35] demonstrated a novel, automated method of determining premorbid proximal humeral anatomy using 3D technology in statistical shape modeling. A database of normal humeri was used to construct a model, which was then tested for validity in settings of osteoarthritis, proximal humeral fractures (neck), and proximal diaphyseal bone loss in parameters of retroversion, inclination, height, radius of curvature, and medial and posterior humeral head offset. In settings of humeral neck fractures, the model was accurate at predicting premorbid anatomy.

These initial systems, though promising in concept, lack experimental rigor and level of evidence, power, feasibility and availability, and clinical correlation to real operative scenarios.[7,14,18] There are many commercially available software platforms that integrate into imaging systems allowing for preoperative planning in elective joint replacement and fracture management. These systems use plain films and CT scans in 2D and 3D reconstructions and allow for templating with commercially available fixation systems. There is no published evidence regarding improved patient outcomes in translation of these products to clinical scenarios. Furthermore, they do not attempt immersion and can be classically defined as low-fidelity. There exists a large opportunity for development, validation, and application of VR systems for trauma pertaining to the shoulder and elbow. As incorporation of VR simulators increases in orthopedic surgery, development of these products and validation is important. In general, the virtual reality education community is moving toward immersive (iVR) simulators, broad in capability and able to be modified and updated in a secure manner. These simulators should be carefully validated for educational and real operative use with translational studies and, ultimately, cost-effectiveness. Table I summarizes the recommendations for iVR simulators in shoulder and elbow surgery.

Elective shoulder arthroplasty

Considering anatomic total shoulder arthroplasty (TSA), preoperative planning is crucial in implant stability and longevity. Clinical studies have demonstrated implant malposition correlating with implant failure in TSA and reduced functional range of motion. Implantation errors of version or inclination greater than 10° or offset errors greater than 4 mm can significantly contribute to the incidence of TSA failure.[9] The ideal position to prevent failure is less clear in rTSA, though malposition of the glenosphere may result in scapular notching. Standard radiographs and axillary views may underestimate glenoid wear and retroversion, with 2D CT scans better delineating glenoid anatomy. Friedman line and the validity of determining glenoid retroversion by Rouleau et al[39] has been presented for 2D CT scans.[53] Additionally, humeral head subluxation has been characterized by 2D CT scans in relation to the widest axial cut at the level of the Friedman line, with >55% posterior to this axis constituting posterior humeral head subluxation.[32] Humeral head size during humeral preparation is also important, as increasing thickness may reduce range of motion and decreasing thickness may result in point loading and inappropriate balancing.[32] The aforementioned parameters are conceptually given descriptors and corrective options in 2D referencing, but are actually multidirectional. 3D CT may be better in characterizing these deformities preoperatively. Walch et al[51] note glenoid retroversion, inclination, and humeral head subluxation as inferiorly characterized by 2D CT imaging and axillary radiographs compared with 3D CT reconstruction, while acknowledging the potential difficulty in obtaining these because of the manual segmentation required. 3D templating allows for creation of single-use or multiuse patient-specific implantation (PSI) guides. These guides are based on individual patient anatomy and theoretically allow for improved accuracy of glenoid component placement.[38] In the Walch et al[51] in vitro study using preoperative 3D templating and PSIs, their final constructs of 18 scapula demonstrated the reliability and precision of this technique. Similarly, a recent randomized controlled trial by Throckmorton et al[45] demonstrated improved mean deviation of version and inclination in TSA using PSI compared with standard instrumentation. Cabarcas et al performed a systematic review and meta-analysis of reported PSI studies that included 518 TSA procedures, with a mean postoperative error of 5° or less using PSI. There were no significant differences in positioning error in domains of version, inclination, or offset between PSI and standard instrumentation. The authors further commented that clinical outcomes were not commented on in included studies, and that this may be difficult to delineate given the overall 10-year survivorship of currently available implants.[10] Iannotti et al[21] in examining 173 patients receiving TSA demonstrated improved glenoid positioning over traditional instrumentation, and 2D glenoid imaging using PSI. Current commercially available software packages for preoperative planning in TSA include DePuy TRUMATCH Personalized Solutions System (Warsaw, IN, USA), DJO Match Point System (Lewisville, TX, USA), the Zimmer Biomet PSI Shoulder for Trabecular Metal Reverse Glenoid System (Warsaw, IN, USA), the Stryker TrueSight Personalized Planning System (Kalamazoo, MI, USA), the Wright Tornier BLUEPRINT planning software and PSI (Memphis, TN, USA), and the Arthrex Virtual Implant Positioning System (Naples, FL, USA). Although variations exist in level of automation, these commercially available systems allow for creation of PSI guides for glenoid positioning through examining version, inclination, and humeral subluxation and can even comment on the degree of reaming, backside glenoid polyethylene seating, and trialing. These available systems for preoperative planning of TSA and rTSA are interactive though largely single-function and nonimmersive in the contemporary, VR sense. Werner et al[53] demonstrated the improvement of 3D CT reconstruction in improving preoperative planning accuracy of glenoid version and inclination, with 7/50 preoperative plans changed in either implant position, or type of implant used based on 3D reformat results. In their study, 8% of patients had their proposed implant changed from an anatomic TSA to an rTSA based on 3D reformats compared with 2D CT and the amount of bone resection required based on inclination and version measurement differences.

Elbow arthroplasty

Lenoir et al[29] analyzed the morphologic features of 22 elbows as well as positioning parameters of components following total elbow arthroplasty to ascertain ideal component positioning to restore the flexion-extension axis of the elbow. They demonstrated high clinical correlation with prosthetic stem abutment within the bone canal and potential malpositioning given deformity magnitude and proximity to the joint.[29] Characterizing deformity could aid in reducing placement errors and illustrates the need for appropriate preoperative imaging in regard to preoperative planning. Iwamoto et al[22] have recently demonstrated the use of 3D CT in planning unlinked total elbow arthroplasty and demonstrated significant improvement of accuracy of both humerus and ulna placement with 3D planning compared with 2D. Given the higher failure rates in registry data of unlinked total elbow arthroplasty, this may improve the longevity of these implants. As in shoulder arthroplasty, the preoperative planning software that is available remains interactive, although it pertains to limited functionality and is nonimmersive.

Intraoperative

Advances in computing technology and available HMD have led to the development of AR systems to aid in fracture management and percutaneous fixation. Classic orthopedic fixation strategies require intraoperative fluoroscopy using a C-arm. Conversion of snapshots in 2D referencing to 3D scenarios suffer from projective simplification and are error prone, even in the hands of expert surgeons.[2] Proposed and studied examples include intraoperative cone-beam CT with use of an RGB-D (RGB plus Depth) camera, registration of preoperative CT to intraoperative fluoroscopic image, or external navigation tracking systems. Further advances include co-calibrated C-arm systems to see-through HMDs. Goals of future work include reduction of setup time, ease of use, and accurate localization of real-time surgical site information to preoperative imaging data.[2,46] These systems have been used in sacroiliac screw placement, intramedullary nail placement, and pedicle screw insertion in spinal surgery, though there is no evidence pertaining to shoulder or elbow surgery.[2,46]

Surgical navigation and PSIs have been proposed for shoulder arthroplasty, particularly to aid in glenoid positioning for implant longevity and functional outcomes in both total and reverse total shoulder arthroplasty.[51] Surgical navigation in total shoulder arthroplasty and PSI have been shown to improve glenoid positioning in 3 prospective randomized controlled trials and 1 prospective nonrandomized study.[27,45,49,51] Furthermore, a recent pooled meta-analysis of surgical navigation and PSI in total shoulder arthroplasty has demonstrated the superiority of these modalities for glenoid positioning in TSA, though long-term studies and clinical correlates are currently lacking.[9] Navigation has shown improvements in weighted mean glenoid version of 4.4° in navigated shoulders, vs. 10.6° ($P < .01$) in standard techniques through a recent meta-analysis of 5 navigation-only studies by Sadoghi et al.[40] In this study, glenoid weighted mean inclination of navigated shoulders was significantly different ($P < .01$) compared with standard shoulders, at 5.4° and 1.3°, respectively.[40] Navigation does have some disadvantages as it is labor intensive and suffers from increased procedural time, estimated at 31 minutes per case, as well as up to 37.5% abandonment due to system registration errors.[9] Verbogt et al[49] estimated an approximately 20-minute increase in surgical time for setup once accustomed. Recent advances have demonstrated a reduction in setup time to approximately 6 minutes. Furthermore, there are no current comparative studies published of computer-assisted vs. traditional total shoulder arthroplasty, as outlined in a recent review.[5]Currently, the only commercially available shoulder system is the Exactech GPS system, which uses the Exactech Equinoxe system. PSI has additional considerations of templating, ordering, and manufacturing surgical devices and the cost and time associated. Given these limitations and potential benefits, cost-effectiveness has not yet been demonstrated. Currently, there is little evidence for the use of AR or MR in shoulder arthroplasty, though a promising technological case report exists. There has been 1 published case of a Walch A2–type glenoid receiving a reverse total shoulder arthroplasty using an HMD with overlay of patient-specific 3D CT scan. This was simultaneously broadcast to the United States and United Kingdom from the surgery site in France.[15] There have been no additional follow-up studies or long-term studies published using this AR technology.

Surgical training and simulation

Shoulder surgical simulators

Simulation is currently defined in the medical literature as “any technology or process that recreates a contextual background in a way that allows a learner to experience mistakes and receive feedback in a safe environment."[43] There have been a number of reviews outlining VR use in surgical simulation in orthopedics,[25,33,43,48] which have focused on the available systems, levels of evidence and recommendation, validity of available systems, effectiveness on training, and concurrent/transfer validity of available systems. There appears to be more than 60 available VR products quoted in the literature relating to assessments of validity.[33] Six of these products are related to shoulder arthroscopy, namely, ArthroMentor/Insight Arthro (Simbionix, Airport City, Israel), Alex Shoulder Professor (Sawbones Europe, Malmo, Sweden), Procedicus arthroscopy (Mentice Corp, Gothenburg, Sweden), ArthroS (VirtaMed, Zurich, Switzerland), ArthroS (VirtaMed), and insightMIST (3D Systems, Rock Hill, SC, USA). Two products were seen to involve general arthroscopy skill training, namely, Swemac/Augmented Reality Systems (Swemac, Linköping, Sweden) and Virtual Reality Tetris Game Using Arthroscopy (VirtaMed). Only the Alex Shoulder Professor (Sawbones Europe) is regarded as a low-fidelity benchtop model. The PrecisionOS Technology immersive VR (iVR) system is the only commercially available iVR simulator for practicing open procedures, such as shoulder arthroplasty with demonstrated transfer validity. Fig. 1 depicts a hierarchy of products for surgical education, delineating the proposed new standard of iVR. As most studies use combinations of surgical trainees and experts, most studies include small sample sizes, the largest of which was seen to have an n of 78 in a study by Pedowitz et al.[34] Levels of evidence range from IB to IV.[34] The highest LoE (IB) was achieved via analysis of 22 trainees using the ArthroMentor/Insight Arthro product, demonstrating improvement of overall diagnostic arthroscopy times and defined objective measure of probe distance compared to a control cohort. The highest LoE awarded included the ArthoMentor/Insight Arthro product, as well as Procedicus arthroscopy, as level 2. Only 3 studies specifically mention face validity, determined via questionnaire and a Likert-type scale. Seven available studies demonstrate significant construct validity of available shoulder arthroscopy simulators in expert use compared to novice. Eight studies demonstrate transfer, or concurrent validity of shoulder arthroscopy simulators.[33] Rebolledo et al[37] demonstrated improved performance of 8 postgraduate-year (PGY) 1-2 compared to a control group of 6 PGY 1-2 in arthroscopic time to task completion and number of iatrogenic injuries following 2.5 hours of arthroscopy simulation. Waterman et al[52] in their comparison of 12 orthopedic trainees receiving repeated scheduled simulation sessions over a 3-month period vs. a cohort of 10 similar trainees receiving only a single training session had significantly improved Arthroscopic Surgery Skill Evaluation Tool (ASSET) scores. Banaszek et al[4] performed a randomized controlled trial with outcomes of Global Rating Scale score, arthroscopic checklist, and procedural time on fresh-frozen cadavers. The VR group received 6-8 hours of simulator training over a 5-week period compared to the control group either receiving a 15-minute video or 6-8 hours of training on a low-fidelity benchtop simulator. VR-trained participants outperformed others in Global Rating Scale scores and were significantly faster than video controls, though not significantly different in regard to speed compared with the low-fidelity control group. The study by Banaszek et al[4] additionally attempted to demonstrate further transfer of skill by incorporating an "untrained surprise task" of medial meniscectomy. None from the control group was able to perform the task, compared with 31% of the VR group. Given the demonstrated improvement in arthroscopic skills shown by learners, Rahm et al[36] determined via ASSET score that for PGY 0-5, 3-5 hours of arthroscopic VR use significantly improves camera handling, anatomy, and triangulation. Recently, Yari et al[54] demonstrated improved arthroscopic skill measured via Imperial Global Arthroscopy Rating Scale (IGARS) following training modules as a function of residency training level. They demonstrated that all years showed improvement of IGARS scores following virtual reality training using the ArthroS simulator, with greatest improvement in shoulder arthroscopic skill in senior residents. Their study, however, suffered from small sample sizes, with only 2 PGY5 residents involved, as well as use of ArthroS-specific composite scores as a representation of validated IGARS scores.[54]

iVR simulators

The only iVR study currently published for shoulder surgery is that of Lohre et al[31] using the PrecisionOS Technology system. In this study, senior (PGY 4 and 5) residents from multiple institutions were randomized to receive training on difficult glenoid exposure using the PrecisionOS Technology glenoid exposure module (v1.4) vs. training with a mixed-media, multistep technique article. Both groups completed both written and verbal knowledge assessments and were rated on a glenoid exposure using fresh-frozen cadaveric specimens with validated outcome metrics by blinded, consultant shoulder surgeons. Both VR and control groups had similar previous training and exposure to simulation and VR before the study. The group trained in VR completed the cadaveric glenoid exposure significantly faster than the traditional trained group with improved instrument handling scores. Knowledge testing was equivalent between groups in both written and verbal domains. Furthermore, the authors noted that resident training was significantly faster (by 570%) using the VR system than reading the article. The authors additionally sought to confirm domains of face, content, construct, and transfer validity. By doing this, the VR system was perceived as realistic, able to teach glenoid exposure, able to delineate expert and novice users, and provide translational improvements in performance. This study was adequately powered and thus receives an LoE of IB by the modified Oxford Centre for Evidence-Based Medicine criteria for simulation studies.[31] Fig. 2 depicts a representative example of an iVR simulator system.

Elbow surgical simulators

There is no benchtop or VR system for elbow arthroscopy. Elbow arthroscopy has a lower frequency of use than arthroscopy of other large joints, and coupled with smaller working spaces, proximity to neurovascular structures, difficulty in instrument handling with over-hand and under-hand use, and patient positioning in the lateral decubitus position, there is a potential for significant complications.[20] Elbow arthroscopy has an estimated 10% complication rate with 2.5% rates of neurologic injury, which may be underreported. This is higher than the reported rates of knee or shoulder arthroscopy.[42] There is also no consensus on the amount of elbow arthroscopy performed before proficiency, or expert status, though it has been estimated at 100 cases.[41] Given this, industry should be encouraged to create VR modules for the development of elbow arthroscopy skills in a safe manner. Most recently, Hilgersom et al[20] have determined the force metrics used by expert elbow arthroscopy surgeons in multiple planes and portal placements. This is an excellent step in the beginnings of simulated elbow arthroscopy training.

Current limitations and future avenues of research

Given the number of publications and varying simulation systems used, there exists significant heterogeneity between studies to preclude pooled meta-analyses. Bartlett et al[5] in a recent systematic review were critical of the lack of transfer validity in current publications and recommended that although promising

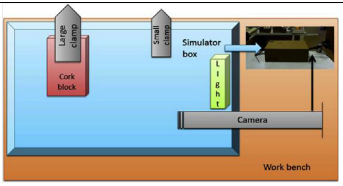
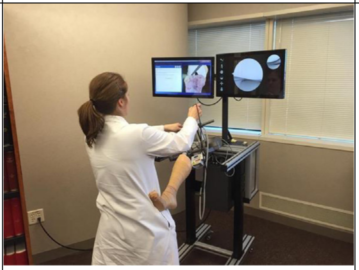
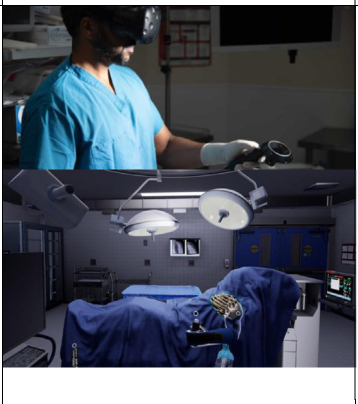
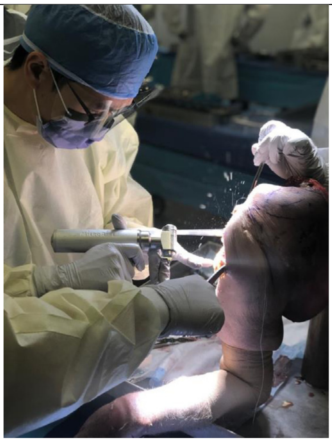
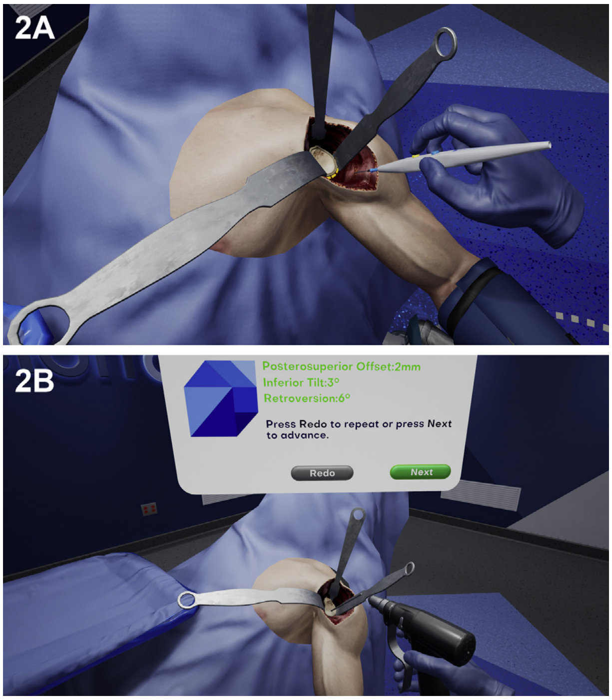
Format	Realism	Example Image	Advantages	Disadvantages	Available products with published evidence in shoulder and elbow surgery
Bench-top	Low fidelity		Inexpensive Development of basic instrument handling and triangulation Some systems widely available	Limited realism Lack of soft tissue factors Requires manual assessment	Alex Shoulder Professor (Sawbones Europe, Malmo, Sweden) Arealis et al. arthroscopic simulator[3]
VR	High fidelity		Instrument handling with haptic feedback and triangulation Record progress through tasks Monitor motion for efficiency Produce global ratings scale scores with automatic assessment	Limited realism Expensive Lack of concurrent and translation validity evidence	ArthroMentor/Insight Arthro (Simbionix, Airport City, Israel) Procedicus arthroscopy (Mentice Corp, Gothenburg, Sweden) ArthroS (Virtamed, Zurich, Switzerland) insightMIST (3D Systems, Rock Hill, South Carolina) Swemac/Augmented Reality Systems (Swemac, Linköping, Sweden) Virtual Reality Tetris Game Using Arthroscopy (VirtaMed, Zurich, Switzerland)
Immersive VR	Immersion and sense of realism		Realistic Inexpensive Motion analysis and haptic feedback of soft tissues Record progress through tasks Monitor motion efficiency Produce global ratings scale scores with automatic assessment Cognitive simulation capable	Lack of concurrent and translation validity evidence Early development	PrecisionOS (PrecisionOS Tech, Vancouver, Canada)
Cadaver	Adjunct to real OR scenario		Realistic anatomy	Expensive Accessibility and availability Specimen variability Risk of disease transmission Fresh tissue degrades quickly Prepared cadavers not realistic soft tissues Lack of concurrent and transfer validity	

Figure 1 Surgical simulation products available for orthopedic surgical education in shoulder and elbow surgery.



Posterosuperior Offset:2mm
Inferior Tilt:3°
Retroversion:6°

Press Redo to repeat or press Next to advance.

Figure 2 (A) Representative example of an immersive virtual reality simulator for learning shoulder arthroplasty. (B) Available metrics immediately available to user to learn guidewire insertion for baseplate orientation.

avenues in arthroscopy were presented, more evidence was needed before widespread use can be recommended.

Limitations of current literature are numerous despite attempts at conveying validity and transferability to real-life OR scenarios of VR systems. The literature and systems available focus on arthroscopic simulation systems. This may be due to the large learning curve associated with arthroscopic skill and therefore theoretically easier demonstrability of construct validity.

Real surgical practice combines technical skill with decision making. The available VR systems lack decision-making scenarios to learn from errors and other real-life components including consent processes, effective communication, leadership, and consideration of surgical or nonoperative alternatives. These transferrable skills are reflected in the Canadian orthopedic training requirements put forth by the Royal College of Physicians and Surgeons of Canada and the Accreditation Council for Graduate Medical Education, both of which are responsible for licensing and accreditation. In regard to validation, surgical simulators and VR systems should clearly define all aforementioned parameters and attempt to meet them, including face, construct, content, concurrent, and transfer validity. Emphasis should be placed on transferability either through real OR scenarios or close alternatives such as mock OR settings and fresh-frozen cadaveric specimens. As VR continues to develop, emphasis should be placed on creating and validating iVR systems, capable of realism and multiple scenarios that include cognitive simulation and decision making. These systems should additionally aim to be portable, easy to use, and cost-effective. Table II outlines recommendations for the development and validation of iVR surgical simulators for training purposes.

Once concepts of validity are established, iVR systems should convey cost of use in an effort to determine cost-effectiveness. Most publications pertaining to surgical simulation in orthopedics fail to mention the cost of simulators used. Yari et al[54] noted a total cost of the ArthroS system used at US$137,000 including purchase, installation, and warranty fees. Conversely, Arealis et al produced a guide for surgical trainees to produce their own arthroscopic simulator out of easily available, low-cost items such as cardboard box, piping, cork sanding block, and a piece of leather, with a webcam.[3] Additionally, there are even free orthopedic surgical simulators available, including TouchSurgery, a smartphone-based decision-making application. TouchSurgery, however, lacks transfer validity and does not employ tactile psychomotor simulation. Though developed with knee simulation, Camp et al[11] performed a randomized study comparing improvement of ASSET scores of residents with training via cadaveric models or high-fidelity simulator (ArthroSim). It was seen that residents increased arthroscopic competency via ASSET scores at a rate of 1.1 ASSET points per hour for the cadaveric group, vs. 0.5 ASSET points per hour for the simulator group. Although significantly less improvement was seen with the ArthroSim cohort than cadaveric, their estimates via value analysis was that 300 hours of use of the arthroscopic simulator per year would yield cost-effectiveness over cadaveric training.[11] Estimates of training a single resident orthopedic surgeon is $48,000 in the United States, coupled with estimates of 11,184 minutes of lost OR time during 4 years of subspecialty training and teaching.[8,44] A system of repeated and consistent training would improve on the current ad hoc clinical scenarios and decrease the ethical concerns of patient interaction. Recommendations have been presented previously to use the Transfer Effectiveness Ratio, which is currently the only validated measure of cost-effectiveness in VR systems in relation to real-life scenarios.[6] Currently, there are no publications pertaining to orthopedic virtual reality training that use this cost metric.

Cognitive simulation encourages trainees to rehearse procedures and movements in their minds without physical action. Similar neural pathways are employed in real and imagined scenarios if specific experiences are focused on. Kohls-Gatzoulis et al[28] performed a prospective trial of surgical residents at varying levels of training to perform a total knee arthroplasty, showing the

Table II
Recommendations for development and research pertaining to VR in surgical simulation and training

Development	Research
Focus on increased surgical simulator realism and immersion in VR	Validation of surgical simulators and VR constructs in face, content, construct, concurrent, and transfer validity
Development of low-cost and accessible VR solutions	Focus on well-designed, randomized controlled trials representing level of evidence 1a to move toward level of recommendation 1 by the EAES recommendations for surgical simulation
Development of VR platforms that focus on multiple aspects of learning, including 1. task-specific modules, 2. tracking of user skills and improvement, and 3. cognitive simulation scenarios in determining errors and focus on surgical decision making with ability for user-generated updated and produced scenarios.	Validation of cognitive simulation in immersive VR platforms Reliability and retention of surgical skill and training level using VR training Cost-effectiveness of VR using the Transfer Effectiveness Ratio

VR, virtual reality; *EAES*, European Association of Endoscopic Surgeons.

cognitive skills group performing better on error detection testing relative to controls. Similar to this, cognitive simulation is thought to be iVR.[30,43] Though currently not demonstrated in the literature, iVR has the potential to stimulate these cognitive pathways with task-specific modules and has the added ability of physical rendering of operative scenarios. There exists in this a great potential for learning that is equivalent to real OR scenarios and potential demonstrable transfer validity.

Conclusion

The availability of VR products has significantly increased in recent decades. Orthopedic surgery, and specifically shoulder and elbow surgery, have demonstrated promising early trials with virtual preoperative planning, and intraoperative adjuncts, particularly with fracture management. The largest focus of VR has been on surgical education and simulation, particularly that of arthroscopic trainers for shoulder surgery. Unfortunately, simulation training and validation of equipment rely largely on convenience sampling of trainees, product availability, and time constraints. Although promising, currently there is a lack of evidence of transfer validity to real OR scenarios with available VR products. Furthermore, confusion in the literature persists regarding definitions of fidelity and its use in relation to VR. Although many simulators demonstrate tactile realism, they lag behind other industries that provide iVR simulators that encapsulate multisensory realism. These iVR products have the potential to demonstrate validity, cost-effectiveness, and implement cognitive simulation. Through this review, we have highlighted the current limitations of VR in shoulder and elbow surgery and recommend focus on development, validation, and implementation of high-quality immersive VR products through rigorous research methodology.

Disclaimer

Jon J.P. Warner reports equity related to PrecisionOS Technology, outside the submitted work.

George Athwal reports equity related to PrecisionOS Technology, outside the submitted work.

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