■ INSTRUCTIONAL REVIEW

Does virtual reality simulation have a role in training trauma and orthopaedic surgeons?

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Aims
The aim of this study was to assess the current evidence relating to the benefits of virtual reality (VR) simulation in orthopaedic surgical training, and to identify areas of future research.

Materials and Methods
A literature search using the MEDLINE, Embase, and Google Scholar databases was performed. The results' titles, abstracts, and references were examined for relevance.

Results
A total of 31 articles published between 2004 and 2016 and relating to the objective validity and efficacy of specific virtual reality orthopaedic surgical simulators were identified. We found 18 studies demonstrating the construct validity of 16 different orthopaedic virtual reality simulators by comparing expert and novice performance. Eight studies have demonstrated skill acquisition on a simulator by showing improvements in performance with repeated use. A further five studies have demonstrated measurable improvements in operating theatre performance following a period of virtual reality simulator training.

Conclusion
The demonstration of 'real-world' benefits from the use of VR simulation in knee and shoulder arthroscopy is promising. However, evidence supporting its utility in other forms of orthopaedic surgery is lacking. Further studies of validity and utility should be combined with robust analyses of the cost efficiency of validated simulators to justify the financial investment required for their use in orthopaedic training.

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While the model of apprenticeship training in surgery remains relevant, the emergence of technically demanding disciplines such as arthroscopy, combined with a reduction in operating opportunities for trainees, has resulted in steep learning curves in orthopaedic surgery.[1-8] The increases in time constraints and difficulty have led to a search for alternative means of surgical education.[9-11] Multiple studies have investigated the length of time taken to achieve competency in orthopaedic procedures and have highlighted that outcomes are significantly worse when an inexperienced surgeon is operating.[12-15] Although it is not possible for every case to be performed by an expert, these poor outcomes mandate the formation of a strategy for overcoming this initial learning curve.

Over the last decade, there has been increasing investigation of the potential role of virtual reality (VR) simulation in solving this problem. This technology involves the computer-generated simulation of three-dimensional images or environments with which the learner can interact in a seemingly real or physical way. Advances in this field have prompted a rapid expansion in the number of commercially marketed surgical simulators, with more than 400 models currently available.[16] As surgical procedures can be deconstructed into a series of steps in which a learner can be trained and assessed, many simulators focus on the particular surgical skills involved in one of these steps, enabling deliberate practice of important and common aspects of procedures. These skills can be practiced efficiently until competency is acquired without exposing patients to undue risk.

The technology lends itself to those procedures that can be replicated on a two-dimensional display and so there is a particular interest in its use for training in arthroscopic surgery. As

Table I. Types of validity and their means of demonstration

Type of validity	Objective or subjective?	Explanation	Means of demonstration
Face	Subjective	Describes the verisimilitude and appropriateness of the simulator's psychomotor fidelity*	Responses to surveys and questionnaires by expert surgeons with extensive understanding of the real-world procedures
Content	Subjective	Describes the appropriateness of the variables measured by the simulator (e.g. time taken, efficiency of hand movements, and number of collisions)	Responses to surveys and questionnaires by expert surgeons with extensive understanding of the real-world procedures
Construct	Objective	Describes how effective the variables measured are at differentiating between levels of procedural skill	Ability to distinguish between novice and expert or show correlation between experience level and simulator performance
Concurrent	Objective	Describes the extent to which the measured variables agree with existing performance measures	Correlation between simulator performance and real-world performance

*Psychomotor fidelity describes the degree to which a simulation produces the sensory and cognitive processes within the trainee as they might occur in the operating theatre; it is not restricted to the physical fidelity of the simulation (ie how visually realistic it is)

arthroscopic procedures represent an expensive proportion of the workload of the modern orthopaedic surgeon, additional increases in efficiency and patient safety are very attractive.[17]

However, before introducing VR simulators in orthopaedic surgical training, it is important to demonstrate measurable and cost-effective benefits. These may be considered in terms of validity of the simulator, whether objective or subjective (Table I), and by an individual's progression along a learning curve. It must further be demonstrated that these improved skills in the simulated environment can be transferred to operative practice, termed concurrent validity. This review aims to evaluate whether sufficient evidence exists to support the use of VR simulation in training orthopaedic surgeons.

Materials and Methods

A literature search using the MEDLINE, Embase, and Google Scholar databases was performed in July 2017. No date restrictions were specified. The search was performed with the terms "virtual reality" and "surgery", yielding 1643 articles published between 1993 and 2017. These results were then refined to those with "orthopaedic", "orthopedic", "fracture", "spine", "hip", "knee", "shoulder" or "arthroscopy" in the title, yielding 149 papers published between 1994 and 2017. Each abstract was then examined for relevance, and the article's references examined. Articles discussing low-fidelity simulators were excluded from this study, unless used for comparison with VR simulators. Furthermore, studies solely assessing subjective measures such as face and content validity were excluded.

Results

A total of 31 articles addressing the objective validity and efficacy of specific virtual reality orthopaedic surgical simulators, published between 2004 and 2017 were identified. Of these, 18 assessed the construct validity of simulators designed for training surgeons in various procedures or their component parts, including knee arthroscopy, shoulder arthroscopy, hip arthroscopy, fracture fixation, orthopaedic drilling, and generic arthroscopic skills. Eight studies investigated skill progression on a simulator: four in knee arthroscopy, one in hip arthroscopy, one shoulder arthroscopy, and two assessing fracture fixation. Five studies (four of knee arthroscopy, one of shoulder arthroscopy) were found that reported the concurrent validity of VR simulators.

Studies assessing construct validity. Multiple studies have demonstrated the construct validity of simulators by showing a correlation between a surgeon's experience and their performance on a simulator.[18-35] The procedures where this has been reported include diagnostic and therapeutic knee, hip and shoulder arthroscopy, hip fracture fixation, the fixation of complex intra-articular fractures and basic orthopaedic skills, including drilling (Table II).

Studies assessing learning curves. A number of studies have investigated the improvement in trainee performance on a VR simulator over the course of a training session, or sessions, demonstrating progression along a learning curve (Table III).[26,36–42] Pollard et al[38] demonstrated this learning curve for simulated hip arthroscopy with the patient in both lateral and supine positions, measuring time taken, the total path-length of the hands and the number of hand movements, for 20 orthopaedic trainees with minimal hip arthroscopy experience. A similar learning curve was demonstrated using the Sheffield Knee Arthroscopy Training System (University of Sheffield, Sheffield, UK) in both experienced and inexperienced individuals, and a passive haptic knee arthroscopy simulator in medical students.[26] A particularly steep learning curve was noted in a similar study by Rahm et al[41] when using a passive haptic knee arthroscopy simulator.

The insightMIST (3D Systems, Rock Hill, South Carolina) shoulder VR simulator has also been shown to provide learner progression, supporting VR simulation in shoulder surgical training.[37] Two studies conducted by Sugand et al[40,42] have explored the training effect of both the TouchSurgery application (TouchSurgery Labs, London, United Kingdom) and the TraumaVision Dynamic Hip Screw VR (Swemac, Linköping, Sweden) simulator (3D Systems, Rock Hill, South Carolina), showing progression by medical students and surgical trainees respectively.

The retention of the skills acquired during simulation have also been investigated. One study evaluating manipulation of

Table II. Studies assessing construct validity of virtual reality (VR) simulators

Study	Simulation	Task	Participants	Outcomes measured	Results and conclusions
Tillander et al (2004)[33]	Melerit TraumaVision and Phantom Arm (3D Systems, Rock Hill, South Carolina)	Distal locking of a femoral nail	Ten experienced orthopaedic surgeons and 15 medical students	Total surgery time; total fluoroscopy time; number of drill holes	Total surgery time and total fluoroscopy time were significantly shorter for surgeons; number of drill holes did not differ between the two groups
Srivastava et al (2004)[30]	Mentice Corp Procedicus (Mentice, Gothenburg, Sweden)	Shoulder arthroscopy – hook manipulation, scope navigation exercise, and anatomical identification	35 test subjects stratified into novices (no arthroscopy experience), intermediate (performed or assisted in 1 to 50 shoulder arthroscopies) and expert groups (performed or assisted in > 50 shoulder arthroscopies)	Time and accuracy of both hook manipulation and navigation exercises; anatomical landmark identification; hook collisions; path length; injuries	Significant differences were found between the three groups for time and accuracy measures of scope navigation and hook manipulation; anatomical identification scores were found not to be significant between the groups; number of hook collisions was not significantly different between the groups; intermediate group had a significantly lower number of hook collisions compared with the other groups
McCarthy et al (2006)[26]	Sheffield Knee Arthroscopy Training System (SKATS) (University of Sheffield, Sheffield, United Kingdom)	Knee arthroscopy - scope navigation in order to locate five loose bodies	11 experienced surgeons and 12 novice surgeons	Time to complete task; number of loose bodies found; number of collisions; total scope path length	Experienced surgeons performed significantly faster, located significantly more loose bodies, and showed significantly shorter arthroscope path lengths than less experienced surgeons
Gomoll et al (2007)[22]	Mentice Corp Procedicus (Mentice, Gothenburg, Sweden)	Shoulder arthroscopy – scope navigation and triangulation	Eight novices (no surgical experiences), 11 PGY-2/3 surgeons, 14 PGY-4/5 surgeons, and ten fellows/attendings (experienced)	Time to complete task; distance travelled; average velocity of the probe; number of collisions	Close and statistically significant correlation between simulator results and surgical experience; significant differences between groups for time to complete task, path length, and probe collisions; no significant difference was found between groups for average velocity of the probe
Blyth et al (2008)[19]	BoneDoc DHS (Otago Innovation, Otago, New Zealand)	Screw and plate fixation of hip fractures	Six medical students, Six basic trainees (< 3 yrs operating experience) and six advanced trainees (> 4 yrs operating experience)	Time to complete; reduction position; incision length; number of misplaced drill holes; final screw placement accuracy; number of radiographs taken	Accuracy, number of x-ray exposures, and speed were significantly different between medical students and trainee surgeons; significant differences between all groups for misplaced drill holes; no other variables were significantly different between the groups
Vankipuram et al (2010)[34]	Sensable Phantom Desktop device (3D Systems, Rock Hill, South Carolina) modified with a Synthes surgical drill (DePuy Synthes, Raynham, Massachusetts U.S.)	Orthopaedic drilling	Six expert orthopaedic surgeons, 11 orthopaedic residents, and six novices	Time taken to complete task; number of tissue contact errors	Resident and expert surgeons made significantly fewer errors per trial; no significant difference was found in the time taken to complete the task
Froelich et al (2011)[20]	Melerit TraumaVision (Swemac, Linköping, Sweden)	Placement of a centre guide wire during fixation of an intertrochanteric proximal femur fracture	Six PGY-1/2 orthopaedic surgeons and nine PGY-3/4/5 orthopaedic surgeons	Time to complete task; 3D accuracy of placement (measured in sagittal and coronal planes); final tip-apex distance; fluoroscopy time; number of attempts	Statistically significant difference in placement accuracy on the lateral view, fluoroscopy time, and number of attempts per trial between groups; no statistically significant difference in time to completion, final placement accuracy on anterior/posterior view and tip-apex distance
Martin et al (2012)[25]	insightARTHRO VR Shoulder Simulator (3D Systems, Rock Hill, South Carolina)	Shoulder arthroscopy – object localization task	27 orthopaedic residents over the course of three years – 11 subjects were tested in only one training year, eight were tested over two training years, and eight over three training years (resulting in a total of 51 simulation testing sessions over the three-year study period)	Time to completion; simulator camera distance; simulator probe distance	Negative correlation between time to complete and number of previous shoulder arthroscopies ($r = 0.55$), and time to complete and stage of training ($r = 0.60$); negative correlation between mean simulation camera distance and number of previous shoulder arthroscopies ($r = 0.44$), and time to complete and seniority in training ($r = 0.52$); negative correlation between time to complete and number of previous shoulder arthroscopies ($r = 0.31$), and time to complete and seniority in training ($r = 0.31$); for every additional seniority in training, there was a 16-second improvement in time to completion; for every additional 50 shoulder arthroscopies performed, there was a 12-second reduction in time taken to complete
Le Blanc et al (2013)[24]	Haptic Ulnar Surgical Fixation Simulator and Phantom Haptic Devices (3D Systems, Rock Hill, South Carolina)	Surgical ulnar fixation	12 PGY-1/2 orthopaedic surgeons and ten PGY-3/4/5 orthopaedic surgeons	Procedural checklist; self-defined global rating scale; time to completion	Significant differences were demonstrated between groups' global rating scale scores, but not for checklist completion or procedure time
Akhtar et al (2015)[18]	TraumaVision simulator and Geomagic Touch haptic device (Swemac, Linköping, Sweden)	Dynamic hip screw fixation of a trochanteric femoral fracture	30 postgraduate orthopaedic trainees divided into three groups of ten participants (novices, intermediates and experts) according to clinical experience	Number of attempts at guide-wire insertion; total time taken; total fluoroscopy time; tip-apex distance; probability of cut-out	Statistically significant differences in performance between groups in all measures; intermediate group performed the procedure most quickly, with the lowest fluoroscopy time, the lowest tip-apex distance, and the lowest risk of cut-out; this correlated with their frequency of exposure to running the trauma list for hip fracture surgery
Rose and Pedowitz (2015)[29]	Swemac/Augmented Reality Systems, (Swemac, Linköping, Sweden)	Arthroscopy – centring and image stability, basic triangulation, and coordinated motions of arthroscope and probe	Ten expert faculty surgeons, ten orthopaedic residents, ten medical students	Mean velocity; accuracy; efficiency of motion	Significant differences between intermediate and experts *vs* novices for basic triangulation and coordinated motions of arthroscope and probe; no significant difference was found for centring and image stability
Fucentese et al (2015)[21]	Computer-based knee arthroscopy simulator using passive haptics (Computer Vision Laboratory, Zurich, Switzerland)	Diagnostic knee arthroscopy, removal of 5 foreign bodies and resection meniscal tear	33 novices (< 20 knee arthroscopies performed), 19 intermediates (21 to 99 knee arthroscopies performed) and 16 experts (≥ 100 knee arthroscopies)	Time taken for each task; number of foreign bodies removed in ten minutes; camera and grasper/punch distances	Significant differences were shown in all measures between novices and experts but not when comparing other groups
Jacobsen et al (2015)[23]	Simbionix ARTHRO Mentor (3D Systems, Rock Hill, South Carolina)	Diagnostic knee arthroscopy; probe examination of a bucket handle lesion, lateral partial discoid meniscus, and whole knee; and resection of a horizontal tear in medial meniscus	13 arthroscopy novices (< 200 knee arthroscopies) and 13 experienced arthroscopic surgeons (≥ 200 knee arthroscopies)	Camera distance and roughness (all procedures), time taken (all procedures), probe distance and roughness (all tasks except diagnostic hip arthroscopy), combined 'z-score' for each procedure based on above metrics	Tear resection was excluded due to lack of significant difference; z-scores for each group were statistically different for diagnostic arthroscopy and probe examinations with experts outperforming novices
Stunt et al (2015)[31]	VirtaMed ArthroS (VirtaMed, Zurich, Switzerland)	Knee arthroscopy – standardized navigation task	Nine beginners (no arthroscopy experience), nine intermediates (< 60 arthroscopies) and nine experts (≥ 60 arthroscopies)	Time to complete task	Beginners were found to be significantly slower than experts for all trials; no significant difference was found between the expert and intermediate groups and intermediate and novice group
Pedowitz et al (2016)[27]	Virtual Reality Tetris Game Using Arthroscopy (VirtaMed, Zurich, Switzerland)	Ambidextrous arthroscopy and grasper manipulation	15 expert arthroscopic surgeons and ten orthopaedic surgical residents	Exercise time; grasper length; camera length (recorded for each candidate twice – one for each hand)	Statistically significant difference in all parameters between orthopaedic resident's hands, with better performance using the grasping tool in the dominant hand; no significant difference between hands of experts (experts showed greater ambidextrous motor skills)
Rahm et al (2016)[28]	VirtaMed ArthroS (VirtaMed, Zurich, Switzerland)	Diagnostic shoulder arthroscopy; removal of five foreign bodies	25 novices (< 20 shoulder arthroscopies) and 26 experts (> 100 arthroscopies)	Time to complete each task; distances moved by camera and grasper	Experts were significantly faster in both exercises, had a shorter camera path in the diagnostic task, and shorter grasper path lengths; no significant difference in camera length for foreign body removal
Stunt et al (2016)[32]	PASSPORT simulator (Medishield, Delft, The Netherlands)	Knee arthroscopy – basic navigation	15 beginners (no arthroscopy experience), eight intermediates (< 60 arthroscopies) and eight experts (≥ 60 arthroscopies)	Time to complete task	Significant differences in median task time between novices and experts; no significant difference was found between experts and intermediates or intermediates and novices
Khanduja et al (2016)[35]	Simbionix ARTHRO Mentor (3D Systems, Rock Hill, South Carolina)	Hip arthroscopy – Basic navigation & probe examination	Ten novice surgeons (< 250 independent arthroscopies) and nine experienced surgeons (≥ 250 independent arthroscopies)	Time taken to complete task; number of soft-tissue collisions; number of bone collisions; camera-tissue contact time; distance travelled by arthroscope; length of femoral head scratches	Significant differences in mean time taken, number of soft-tissue collisions, number of bone collisions, and camera contact time for basic visualization task; no significant differences between group means in any measures for basic probe examination

PGY, postgraduate year

the arthroscope demonstrated limited degradation of skills at four weeks post-training, and another study of simulated arthroscopic meniscal repair showed improved simulator performance as long as six months after an initial training session.[36,39]

Studies assessing concurrent validity. A small number of studies have attempted to assess the concurrent validity of several VR simulators, with positive results (Table IV).[43–47] Cannon et al[43] showed orthopaedic residents who had undergone VR simulator training outperformed their control

Table III. Studies assessing the learning curves of virtual reality (VR) simulators

Study	Simulator	Task	Participants	Outcomes measured	Results and conclusions
Bliss et al (2005)[36]	Procedicus Virtual Reality Knee Trainer (Mentice, Gothenburg, Sweden)	Knee arthroscopy – landmark identification and arthroscope and probe manipulation	Ten psychology graduate students	Correct landmark identification; number of collisions	Improvements in both parameters across training sessions over five-day period; minimal degradation after four weeks
McCarthy et al (2006)[26]	Sheffield Knee Arthroscopy Training System (University of Sheffield, Sheffield, United Kingdom)	Knee arthroscopy – scope navigation in order to locate five loose bodies	Three arthroscopy novices	Completion time; path lengths of probe and arthroscope; number of collisions	Significant improvements in task completion time, arthroscope path lengths, probe path lengths, and arthroscope tip contacts after the first two practice sessions
Andersen et al (2011)[37]	InsightMIST (3D Systems, Rock Hill, South Carolina)	Shoulder arthroscopy – identification of spheres, centring of sphere with camera, and palpation with a probe	Group 1, seven arthroscopic surgeons; Group 2, seven orthopaedic interns with no independent arthroscopy experience	Completion time; number of collisions; maximum depth of collision; paths lengths of probe and arthroscope	After completing a five hour training programme, the arthroscopy-nave residents showed marked improvement in their skill; after five hours training, Group 2 reached proficiency of Group 1, or surpassed it
Pollard et al (2012)[38]	Sawbones Hip Simulator (Sawbones, Vashon, Washington)	Supine and lateral Hip arthroscopy – landmark identification	20 orthopaedic trainees with minimal hip arthroscopy experience (10 in supine group and 10 in lateral group)	Total path length of subject's hands; total number of hand movements; time taken to complete the task; iatrogenic cartilage damage	Both groups demonstrated learning with objective improvement in all parameters
Jackson et al (2012)[39]	Sawbones Knee Simulator (Sawbones, Vashon, Washington)	Knee arthroscopy – lateral menisca l repair	19 orthopaedic residents	Time to complete; distance travelled; number of hand movements	All subjects demonstrated a clear learning curve during the initial learning phase, with significant objective improvement in all motion analysis parameters over the initial 12 sessions
Sugand et al (2015)[40]	TraumaVision VR (Swemac, Linköping, Sweden)	Dynamic hip screw procedure – fixation of an intertrochanteric fracture	26 novice undergraduate surgical trainees	Total procedural time; fluoroscopy time; number of radiographs; tip-apex distance; number of attempts; probability of cut-out; a simulator defined global rating scale	Statistically significant improvements in all measures after ten sessions
Rahm et al (2016)[41]	VirtaMed ArthroS (VirtaMed, Zurich, Switzerland)	Knee arthroscopy – triangulation, partial meniscectomy, and removal of foreign bodies	20 medical students	Procedural time; distance travelled by tools and camera; number of foreign bodies removed	Novices improved significantly within 4 × 30-minute training sessions but not thereafter
Sugand et al (2016)[42]	Touch Surgery VR Platform App (TouchSurgery Labs, London, United Kingdom)	Intramedullary femoral nailing – four decision-making process modules: patient preparation and positioning; femoral canal preparation; proximal locking; and distal locking and closure	27 medical students	% correct decisions; time taken to complete; multiple choice test assessing the principal learning objectives	Median performance for all four modules demonstrated a significant improvement after six attempts

PGY, postgraduate year

group counterparts at probing scale scores and self-defined global rating scale scores during diagnostic knee arthroscopy *in vivo*. However, procedural checklist scores were not shown to be significantly different, which has been attributed to the influence of an extreme outlier. These benefits in knee arthroscopy were also assessed by Camp et al,[45] who compared the improvements in performance to those seen in another group trained on cadaveric specimens. Contrary to these promising results, Rebolledo et al[46] reported no significant benefit derived from two and a half hours of knee arthroscopy simulation training in orthopaedic residents whose performance was subsequently assessed on cadaveric models. This study did, however, show significant improvements in shoulder arthroscopy performance. Concurrent validity of VR simulation

Table IV. Studies assessing concurrent validity of virtual reality (VR) simulators

Study	Simulator	Skill	Intervention	Controls	Participants, intervention	Participants, control	Outcomes Measured	Results and Conclusions
Cannon et al (2014)[43]	ArthroSim VR Knee Simulator (ToLTech, Aurora, Illinois)	Diagnostic knee arthroscopy	Eight rounds of arthroscopy training using the simulator's curriculum (four for visualization and four for probing)	15-minute video depicting procedure and handbook detailing procedural tasks	27 PGY-3 residents	21 PGY-3 residents	Knee arthroscopy ability on a live patient including: procedural checklist, visualization scale, probing scale, self-defined global rating scale	Training on the simulator led to significant improvements in procedural checklist completion, probing scale scores and global rating scale scores when compared to controls
Rebolledo et al (2015)[46]	insight Arthro VR (3D Systems, Rock Hill, South Carolina.)	Diagnostic shoulder and knee arthroscopy	Two and a half hours of diagnostic arthroscopy training	Two hours of didactic lectures on basic arthroscopy	Eight PGY-1/2 residents	Six PGY-1/2 residents	Arthroscopy ability on a cadaveric model of both shoulder and knee arthroscopy including time taken and iatrogenic injuries	Residents trained on simulator significantly outperformed those in the control group in both time to completion and number of iatrogenic injuries
Waterman et al (2016)[45]	Arthro VR Shoulder Simulator (3D Systems, Rock Hill, South Carolina)	Diagnostic shoulder arthroscopy	One standardized evaluation session on the simulator and 4 × 1-on-1 simulation training sessions lasting approximately 15 minutes with one senior resident during a three-month period	1 standardized evaluation session on the simulator	12 orthopaedic trainees	10 orthopaedic trainees	Shoulder arthroscopic ability on a live patient assessed using the Arthroscopic Surgery Skill Evaluation Tool (ASSET) score [48]	Simulator trained group were assessed as competent by the ASSET score and were found to be significantly better than the control group
Camp et al (2016)[44]	ArthroSim VR Knee Simulator (ToLTech, Aurora, Illinois)	Diagnostic knee arthroscopy	Four hours of simulator training	Four hours of practice on a cadaveric specimen or no practice	15 orthopaedic residents	30 orthopaedic residents (15 cadaveric training and 15 no training)	Knee arthroscopic ability on a live patient assessed using the Arthroscopic Surgery Skill Evaluation Tool (ASSET) score [48] and time taken to complete the procedure	Significant improvements in both ASSET score and time by both the cadaveric control group and the simulator group; residents in the cadaveric control group improved their performance at twice the rate of the simulation group
Banaszek et al (2017)[47]	Arthro VR Knee Simulator (3D Systems, Rock Hill, South Carolina)	Diagnostic shoulder arthroscopy, probing examination and partial medial meniscectomy	Six to eight hours of simulator training over five weeks (in addition to the control groups video)	15-minute video of a basic, step-wise diagnostic arthroscopy and probing examination, or six to eight hours of training on a low-fidelity bench-top simulator	16 pre-clerkship level first- and second-year medical students	Video – eight pre-clerkship level first- and second-year medical students; low-fidelity simulator – 16 pre-clerkship level first- and second-year medical students	Knee arthroscopic ability on a cadaver knee in a simulated intra-operative environment using the validated Global Rating Scale,[49] arthroscopic checklist, and procedural time – for both diagnostic examination and probing examination; additionally, participants were given an untrained task (partial medial meniscectomy) to assess skill transfer, which was assessed using the same metrics as above	VR-trained participants outperformed both low-fidelity trained and control groups when assessed with the GRS, for diagnostic examination, probe examination, and partial medial meniscectomy; no difference was observed between arthroscopic checklist completion between the VR and low-fidelity trained groups for the diagnostic and probe examinations, although both groups outperformed the untrained controls; 31% of participants were able to complete the partial meniscectomy *vs* 0% in the low-fidelity and control groups; VR-trained and low-fidelity groups showed significantly lower procedural times *vs* controls, but were not significantly different from each other.

PGY, postgraduate year

of shoulder arthroscopy has also been demonstrated in a single-blinded study using 22 orthopaedic surgeons – 12 of whom received a total of one hour of VR training over three months, and 10 who received none. The VR trained group showed improved time, probe distance travelled and safety when compared with controls.[44]

Banasezek et al[47] assessed improvements in arthroscopic performance for 16 medical students trained for six to eight hours on either a VR knee arthroscopy simulator or a low-fidelity bench-top simulator, when compared with untrained controls. They reported higher validated Global Rating Scales scores in those who had undergone high-fidelity VR training than in the low-fidelity and untrained control groups when performing diagnostic and probe examinations on cadaveric knees. The study also assessed participants' ability to transfer arthroscopic skills with an "untrained surprise task" in the form of a partial medial meniscectomy, which 31% of the VR-trained group were able to complete, by comparison with 0% of the low-fidelity and untrained groups.

Discussion

Although the evidence of construct validity and progression with many simulators is promising, this neither confirms nor quantifies any benefit to trainees. To date, while those studies that have examined the effect of simulator training on performance in the operating theatre support the use of simulation, they are few in number.[43–46] It is in this area of transferability that supportive evidence is lacking when compared to other surgical specialties. Multiple studies have demonstrated a 'real-world' benefit from the use of laparoscopic simulators, resulting in their widespread use in the training of general surgeons.[50-53] Banasezek et al's[47] inclusion of a "surprise" task could, however, be argued to provide evidence of general benefits of VR in orthopaedic training. More investigation of costs and benefits of simulators of other orthopaedic procedures is required before their implementation into training curricula can be justified.

VR simulation may prove to be less cost-effective than other means of surgical education, such as the use of cadavers or low-fidelity simulators. Camp et al[44] found that a VR-trained group improved at half the rate of a cadaveric-trained group and suggested that the simulator would be cost-effective if used for a minimum of 300 hours per year. This supports the concept of centralized or shared VR training facilities. As technology advances and the price of simulators decreases, the cost efficiency is likely to increase. Furthermore, it should be noted that one of the tested simulators, TouchSurgery is a free application and so any benefits are inherently cost-efficient. It is, however, a non-haptic decision-making simulator, lacking the psychomotor fidelity of more sophisticated simulators, and is yet to be shown to have concurrent validity.

Despite limited evidence supporting orthopaedic VR simulators, cost efficiency of simulator systems in other specialities has already been demonstrated. Kunkler[54] argued that the cost of setting up a simulation centre was offset by the savings associated with reduced procedure time and reduced expenditure on instructors and equipment for traditional training. It was estimated that one simulator system saved in excess of $160 000 in six months, and another returned its investment within 131 days.

In order to evaluate VR simulation further in orthopaedic training, researchers should draw from the aviation industry's use of the 'Transfer Effectiveness Ratio' (TER), the only validated measure of cost effectiveness.[55,56] This is used to quantify the difference between virtual reality and real life in terms of the time required to achieve fully competent performance, with a ratio of 0.50 indicating that one hour of simulator training saves approximately 30 minutes of operative time. To allow direct comparison with other training techniques, TERs would have to be calculated for other training methods and analyzed in conjunction with the costs associated with each method.

Despite the fact that many of the simulators used in the cited studies were able to distinguish between 'experts' and 'novices', many found limited ability to differentiate between 'intermediates' and 'experts', suggesting limited verisimilitude to the real-world procedure. This may be because many studies used the cumulative number of procedures performed over a career (or several years) to differentiate 'experts' and 'intermediates', whereas 'intermediates' may have performed more arthroscopies in a more recent, shorter timeframe and therefore perform disproportionately well. There was also inconsistency in the objective measures used by the various simulators, with only a handful displaying discriminatory capacity (Table II). This highlights the importance of selecting appropriate measures of performance for assessment.

Although arthroscopic simulators have contributed to the majority of the studies discussed here, simulations of fracture fixation and orthopaedic drilling are also available. Studies of such simulators have also demonstrated construct validity and learning curve progression but evidence of concurrent validity is still lacking, but remains vital to demonstrate any postulated benefits.[18-20,24,34,40]

In conclusion, the demonstration of 'real-world' benefits to orthopaedic surgical training of two previously validated simulators for knee and shoulder arthroscopy is highly promising. More investigation of other simulators and of the cost efficiency of the two validated simulators is needed before their implementation into training curricula can be robustly championed. Future research should draw from the aviation industry's TER, allowing direct comparison of the cost efficiency of VR orthopaedic simulators and that of other means of surgical education.

Take home message:

- Increasingly complex procedures and reduced time in theatre makes for steep learning curves in modern surgery
- There is a growing body of evidence showing the benefits to the trainee of VR simulation
- Expanding the evidence base demonstrating improved operating theatre performance with VR simulation is mandated before its use can become widespread

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