Arthroscopic Simulation in Orthopaedic Surgery Training

EDWARD J. TESTA, MD; JACOB M. MODEST, MD; RORY A. BYRNE, BA; BRETT D. OWENS, MD; RAYMOND HSU, MD

ABSTRACT

Surgical simulation has become a commonly utilized and well-researched training adjunct in nearly all surgical specialties. Balancing high-quality orthopaedic surgical training in the face of work hour restrictions and efficiency pressures has become a challenge to educators and trainees alike. Surgical simulation is an opportunity to enhance such training and potentially permit trainees to be better equipped for the operating room. In orthopaedics, various low-fidelity, high-fidelity, and virtual reality simulation platforms are readily available to almost all trainees and permit simulation of a wide array of arthroscopic surgeries. In this review, we seek to highlight the potential utility of simulation-based training in orthopaedic surgery, the various types of available simulators, and review the evidence for simulator use.

KEYWORDS: surgical simulation, orthopaedic education, arthroscopic simulation, virtual reality

INTRODUCTION

Surgical simulation has become an important tool for graduate surgical education in recent decades, in response to paradigm shifts in the training landscape. Mastery following the traditional Halstedian approach of "see one–do one–teach one" is no longer feasible in modern surgical education, despite a growing need for competent, efficient surgeons.[1] It is increasingly difficult for trainees to strike a balance between prioritization of patient safety and satisfaction, and the volume constraints of resident duty hour restrictions and operating room efficiency.[1–3] To improve high-quality, efficient, and patient-centered care, interest in evidence-based, formal curricula to address core competencies of surgical training using models and simulators has grown.[4,5] Orthopaedic surgical simulation offers a promising adjunct to the apprenticeship model, providing an accessible, controlled environment without the risk of patient harm.[5] Simulation to improve surgical skills hinges on the concepts of pedagogic consistency and deliberate practice, the latter defined as focused, effortful skill repetition in progressive exercises that provide informative, immediate feedback.[5] Surgical simulation allows residents to advance through appropriately challenging skills at their own pace, with progress tracked based on clearly defined outcome measures.

There is a growing body of evidence demonstrating the considerable benefits of simulation in orthopaedic training, especially arthroscopy, though the incorporation of these methods into orthopaedics has lagged somewhat behind other disciplines.[6–8] Frank et al conducted a meta-analysis of 57 studies published between 1999–2016 concerning validated arthroscopic simulation models; the authors reported improvement in simulator task performance (24 of 25 studies that analyzed this metric; 96%) and improvement in operative performance after simulator training (4 of 4 studies; 100%), although they cautioned that the evidence for improved *in vivo* performance was limited.[8] A more recent 2021 systematic review from Lakhani et al added to this base with 44 studies regarding use of physical or augmented/virtual reality (AR/VR) arthroscopic models for ankle, knee, shoulder, and hip environments.[6] Similarly, they concluded that simulation is beneficial for orthopaedic trainees, with the majority of included studies demonstrating construct and transfer validity – important measures of the capability of the simulator to differentiate between levels of expertise, and the ability of the simulator to achieve learning and improvement outside of the simulation, respectively.[6,9] Although small scale studies have demonstrated improvement of technical performance and patient safety measures following a simulator training regimen for procedures such as diagnostic shoulder arthroscopy, there remains a question of how well simulator skills can transfer to operative performance and ultimately improve patient outcomes.[10]

Within orthopaedics, several simulator models are available, existing on a spectrum from low-fidelity self-made workstations to augmented and virtual reality environments. Despite evidence regarding the validity and success of these simulators, there is no consensus on a gold standard option for orthopaedic surgical simulation. We aim to provide evidence on the accessibility, validity, and success of various simulators, to inform residency training programs on how to best incorporate simulation into orthopaedic training.

PROFIDENCY-BASED TRAINING

As minimally invasive surgery became more prevalent in the late 20th century, surgical training programs were faced with the challenge of training surgeons in procedures that required distinctly unique skillsets from those utilized in open surgeries.[11] Historically, competency in surgical skills was assessed through either successful completion of a predetermined number of cases (i.e., a case minimum) or observation and evaluation by a more senior surgeon.[12] Unfortunately, these methods are inherently flawed due to subjectivity and variability in trainee skill level (i.e., some residents may need more than minimum case numbers to become proficient in a given procedure), as well as variability in the feedback provided to trainees. Thus, proficiency-based progression (PBP), or proficiency-based training (PBT), was born. This training strategy focuses solely on performance, using goal-directed and deliberate practice in the form of simulation to achieve competency, with the goal of developing a uniform skill set for all trainees to improve safety and efficiency in the operating room.[13]

PBT utilizes simulation-based training to allow learners to acquire specific skills, then uses objective measures to evaluate progress, and correct errors through direct feedback.[14] In orthopaedic surgery, PBT has been studied primarily within the realm of shoulder arthroscopy.[15–17] Arthroscopy is a minimally invasive skill that requires unique technical proficiencies compared to open surgeries, such as instrument triangulation, bimanual dexterity, and the ability to manipulate three dimensional images on a two-dimensional screen. Therefore, to maintain operative efficiency and patient safety, mastering these skills prior to the operating room is certainly ideal. In his pivotal work, Angelo et al broke down the steps of an arthroscopic shoulder labral repair into the core "phases" and "steps."[15] Arthroscopic portal placement, mobilization of the capsule and labrum, and glenoid preparation for anchor placement were denoted as "phases" of the repair, while each arthroscopic view or instrument manipulation was a "step." This training technique thus permits a metric-based system to provide a grading system for a trainee's performance, creating the opportunity to denote a trainee as competent at a given procedure if they can achieve certain metrics. Angelo et al demonstrated that PBT led to significant decreases in surgical error rate, as well as greater likelihood of achieving proficiency, when compared to traditional training techniques in arthroscopic Bankart repairs.[16] When coupling the metrics of arthroscopic Bankart repair performance with cadaveric shoulder training, Angelo et al found the ability to accurately measure surgeon skill.[17] These findings, which are in accordance with those of other authors,[10,18] can potentially provide useful metrics for surgeons to possess to ensure they are proficient in the necessary skills to safely perform arthroscopic surgery. Continued research into PBT and other arthroscopic and open orthopaedic surgeries would be a useful next step in advancing orthopaedic surgery simulation-based training.

VALIDATION OF ARTHROSCOPIC SIMULATOR

Necessary to any discussion of surgical simulators is the principle of validity. For a surgical simulator to be truly useful, it must strive to replicate the surgical experience as closely as possible to reality. Therefore, any orthopaedic surgery simulation platform should ideally be validated in several different ways, including construct, content, transfer, and face validity (**Table 1**).[7] Construct validity is defined as the extent to which a simulator can differentiate the performance between users of various skill levels.[19] For example, an arthroscopic surgical simulator would have high construct validity if it can discern an expert arthroscopist with years of experience from a medical student, who is a novice. Content validity instead refers to an estimate of a surgical simulator's skill testing ability based upon a thorough assessment of the contents of the test items. Generally speaking, content validity is determined by opinions of those deemed experienced or expert in the field.[15] Transfer validity instead is an assessment of the ability to translate technical performance on a simulator to the operating room for a specific procedure.[8] Finally, face validity measures how real a simulator feels, evaluating how its performance looks and feels relative to reality. While these are relatively subjective measures, they remain important tools to critically assess surgical simulators prior to application within a training program.

Table 1. Types of Validity Related to Orthopaedic Surgery Simulation

Terms	Definition
Construct Validity	The extent to which a simulator can differentiate the performance between users of various skill levels
Content Validity	Measurement of a surgical simulator's skill testing ability based upon a thorough assessment of the contents of the test items
Transfer Validity	The ability to translate technical performance on a simulator to the operating room for a specific procedure
Face Validity	How true a simulator feels to the surgical experience

LOW-FIDELITY SIMULATORS

The term fidelity describes the ability of a certain simulator to adequately mimic the real surgical environment or skill set being tested, similar to the aforementioned concept of face validity.[20,21] Low-fidelity simulators therefore are physical models that may be associated with simulation modules that replicate aspects of surgical procedures, but with limited functionality and realism. According to a recent systematic review, these simulators are notably less expensive than their high-fidelity counterparts, and simpler to set-up, operate, and transport.[21] Therefore, low-fidelity simulators are often a good option for novices and basic skills training. Low-fidelity models may be self-made or can be purchased commercially. Ling et al compared the effectiveness of a self-made arthroscopic training camera versus a commercial camera, devices that cost roughly $30 and $50,000 USD, respectively.[20] The self-made construct was composed of an endoscopic camera fixed at 30 degrees of inclination to two parallel Kirschner wires, in addition to a small training box constructed using splint material; other "homemade" models are similarly composed of small USB cameras with built-in lights. Significant technical improvement was seen with both models, with no significant difference between the groups for any tests, suggesting equivalent learning effectiveness using the low-cost model.[20] As first described by Ferras-Tarrago et al, 3-dimentional (3D) printing of an arthroscopic simulator device offers a low cost, accessible alternative; the simulator model pattern can be downloaded for free and printed easily on any domestic 3D printer, and combined with an inexpensive ($14 USD) endoscopic camera.[22] The physical model is combined with an open-source, validated, practical training program, through which seasoned surgeons can virtually provide instruction and feedback to novices. This construct currently lacks evidence of transfer validity.

The Fundamentals of Arthroscopic Surgery Training, or the FAST workstation (Pacific Research Laboratories, Inc., WA, USA) is a relatively low-cost, low-fidelity commercial option, consisting of a computer-controlled arthroscopic box construct, various surgical instruments, and a computer interface to record movement and provide real-time feedback on performance.[23] This device is designed to develop the cornerstone skills of arthroscopy such as bimanual dexterity, grasping, triangulating, and knot tying; trainees can progress through the 6-module paired program consisting of various exercises, including visualization and probing, ring transfer, maze navigation, tissue biting, suture passing, and knot tying. Several studies have demonstrated the effectiveness of the FAST workstation and associated models in improving novice task performance. Goyal et al reported reliable construct validity, as well as improvement in performance with sequential tasks in a group of 20 orthopaedic surgeons of various skill levels.[24] Similarly, Meeks et al demonstrated significantly decreased time to completion of task modules after 6 weeks of FAST training in medical students.[25] Notably, the mean time to completion and number of errors did not change following 12- or 24-week intervals of inactivity, suggesting promising psychomotor retention of tested skills. Additionally, this study among others posits the feasibility and success of formal teaching for true novices, which would allow for earlier access to competency training.[25,26] However, there is some opposing evidence that several of the FAST modules have low construct validity – a multicenter study from Vaghela et al reported no demonstratable correlation between true arthroscopic experience and ambidextrous performance, as well as an inability of the modules to discriminate between participants' experience levels; this suggests the inadequacy of the construct for assessing advanced arthroscopic proficiency.[27] A similar study reported that the FAST simulator could discriminate between activities and training year, but not case experience as measured by score, path length, and time.[28] The authors still maintain the importance of the FAST workstation in building crucial but novice-level arthroscopic skills, despite conflicting evidence regarding its construct validity.

ArthroBox™ (Arthrex, Inc., Naples, FL, USA) is another example of a low-fidelity commercial training system for triangulation skills, comprised of a collapsible arthroscopy box with combined LED camera and light source that plugs directly into a personal computer.[29] Bouaicha et al demonstrated significant improvement in task performance following novice use of an ArthroBox trainer, and also found it to have construct validity.[30,31] Not only did they demonstrate improvement between baseline to follow-up on the low-fidelity model, subjects also showed subsequent improvement on high-fidelity, validated virtual knee simulators, suggesting that training on a more accessible device is beneficial for future performance on a higher fidelity construct and potentially in the operating room itself. A recent systematic review found that low-fidelity workstations improve novice trainee performance in arthroscopic tasks, and are likely more cost effective and simple to implement than higher fidelity simulators.[32] Ultimately, the cost effectiveness and potential training benefits of low-fidelity workstations make them a viable consideration for a training program's armamentarium.

HIGH-FIDELITY SIMULATORS

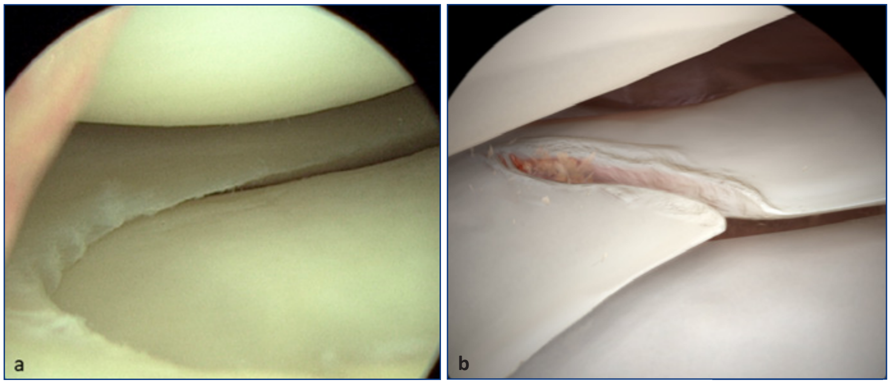
In comparison with low-fidelity simulators, high-fidelity simulators are more expensive but have improved realism and feel to the real world and operating room (**Figures 1A, 1B**). A common improvement in these simulators is the use of augmented reality (AR). Proprietary examples of high-fidelity simulators include ArthroS® (VirtaMed),[33] ARTHRO Mentor™ (Symbionix),[34] and InsightARTHRO VR® (3D Systems).[35] These products have the components of a mannequin, an arthroscopic video monitor, and simulated arthroscopic equipment. The arthroscopic equipment is nearly identical to operating room instruments and the majority of simulators provide tactile and haptic feedback for the instruments to simulate resistance and vibrations associated with their real use.

Several studies have sought to validate high-fidelity simulators for use in orthopaedic surgery resident training given the advantages of ease of use and demands for patient safety and quality control. These studies have examined both the validity of these simulators as well as their impact on surgical training. Various arthroscopic simulators have been validated both with face and construct validity and the general construct of the various proprietary simulators is overall similar amongst systems.[36] To examine the impact of these

Figures 1A, 1B.

[**A**] An intraoperative arthroscopic image of a right knee demonstrating a lateral meniscal tear after debridement.

[**B**] An image of a right knee with a large radial tear of the lateral meniscus from a high-fidelity arthroscopic simulator. Note the high-quality graphical comparison to a true arthroscopic image.



[Images from ArthroS® (VirtaMed) simulator video. Reproduced with permission of VirtaMed AG Switzerland]

simulators on surgical training, Rebolledo and colleagues compared high-fidelity arthroscopic simulation using the InsightARTHRO VR to didactic lectures, finding that the residents assigned to the surgical simulator group had significant improvement over those in the didactic session group in performing cadaveric diagnostic knee and shoulder arthroscopy.[18] Wang and colleagues designed a randomized controlled trial to assess the impact of simulation training on performance of cadaveric arthroscopy using a high-fidelity workstation. These researchers randomized novice participants to simulation training or no simulation training (control group) prior to assessing arthroscopic skills on a cadaver. After the use of the simulator 1 time per week for 3 weeks, the simulation group had significantly improved task-time completion scores for all tasks. However, when these groups practiced on a cadaveric models, these skills did not have significant transferable benefit as they found no difference between the groups in performing standard diagnostic arthroscopy of a knee and a shoulder.[37] Interestingly, they discuss a ceiling affect for task improvement that occurs after 3 trials for most of the tasks analyzed, concluding that there is some measurable improvement in coordination and efficiency for AR training models and that this improvement is rapidly obtained.

The validity of high-fidelity simulators has been assessed through various studies. Lakhani et al performed a thorough systematic review of arthroscopic simulators synthesizing the body of available literature related to arthroscopy simulation.[6] These authors found many studies which determined that several commercially available high-fidelity arthroscopic simulators demonstrate construct, transfer, and face validity, while only 3 studies assessed these simulators for content validity.[6] These have been validated for use in several joints, including the knee, shoulder, and hip. It remains essential that all commercially available arthroscopic simulators undergo evaluation of validity to ensure that the simulators can truly provide a realistic benefit to orthopaedic trainees. Furthermore, residency program directors should scrutinize the literature regarding specific simulators when considering the purchase of an expensive high-fidelity simulator to train their residents.

A meta-analysis of arthroscopic simulator training by the same group reviewed 57 studies with 1698 participants.[8] Twenty-five studies compared pre-simulator training to post-simulator tasks and 24, or 96%, of these studies showed significant improvement after simulator use. Four studies examined results on live-patient arthroscopy of which all 4 showed improvements after simulator use. High-fidelity simulators likely will continue to have a growing role in resident education. However, they may be cost prohibitive in many situations as they can cost tens to hundreds of thousands of dollars; therefore, training programs should carefully consider their options to determine if high-fidelity simulators are a cost-effective means to improve resident education.

While the aforementioned arthroscopy simulators utilize a form of virtual reality (VR), in which a mannequin and computer are utilized to experience an arthroscopic environment, commercially available VR headsets are emerging as another form of workstation. These headsets offer a wireless, computer-based simulation in which the user wears a VR headset and utilizes two controllers to manipulate a virtual environment, such as the operating room, without the need for a computer. For example, PrecisionOS® has created a complete hip arthroscopy VR experience in which trainees can immerse themselves in the operating room to simulate the steps of this technically demanding procedure.[38] While this platform has demonstrated good face and content validity, it has incomplete construct validity; further research on this type of VR arthroscopy simulation is necessary, but it remains an important emerging training tool to consider.

CONCLUSIONS

Surgical simulation platforms, which have been well-studied in techniques such as arthroscopy, remain a viable and proficient tool for improving an orthopaedic surgery trainee's skillset prior to entering the operating room. Low-fidelity simulators are a relatively low-cost, accessible option for training certain basic skills, while high-fidelity simulators afford an experience with higher face validity, but also substantially greater cost. Arthroscopic surgical simulators should be thoroughly evaluated for validity. While various studies have evaluated construct, face, and transfer validity in specific arthroscopic simulators, content validity is infrequently reported. The future of orthopaedic surgical simulation includes continued work on these aforementioned simulators, and expansion of true VR experiences that encompass all realms of orthopaedics from arthroplasty to trauma surgery. Future work in validating various VR modules and platforms will be useful to help elucidate this expansile technology's role in orthopaedic surgical training.

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Authors

Edward J. Testa, MD, Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Jacob M. Modest, MD, Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Rory A. Byrne, BA, Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Brett D. Owens, MD, Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Raymond Hsu, MD, Department of Orthopaedic Surgery, Alpert Medical School, Brown University, Providence, RI.

Disclosures

BDO: Consultant to Mitek, Miteck, Miach; financial disclosures: Conmed, Vivorte

Correspondence

Edward J. Testa, MD
Rhode Island Hospital
2 Dudley Street, Providence RI 02909
Edward.j.testa@gmail.com