SOAJ Scientific Open Access Journals

Journal of Medical Education and Training

Research Article Open Access

Virtual Reality Surgical Simulation for Arthroscopy Training

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Received: 27 February 2017; **Accepted:** 03 May 2017; **Published:** 10 May 2017

Introduction

There is little doubt that the medical profession stands at a major crossroads with regards to the fundamental structure of surgical education. Although the apprenticeship model has been used for centuries, we are rapidly moving toward a new era of proficiency-based education. This transition is motivated by several important factors, including greater emphasis upon patient safety, increased focus on educational efficacy, and a shift toward objectively measured performance outcomes (i.e., demonstration of clinical proficiency). At the same time, the paradigm shift is challenged by limitations imposed by trainee work hour restrictions and by the initial investments and ongoing expenses associated with implementation of new training paradigms.

None of these considerations change the fundamental prediction; it is no longer a question of if, but when. Surgical education is rapidly moving toward greater utilization of simulation technology. How can this transition be managed most efficiently by surgical leaders and key decision-makers? What is the role of virtual reality in the larger picture? This paper will review these important questions, with a specific focus upon current knowledge pertaining to virtual reality simulation in the field of arthroscopic surgery.

What is Simulation?

Simulation is the imitation of the operation of a real-world process or system over time. From the medical perspective, simulation provides an opportunity to learn and to rehearse in any environment that doesn't involve direct patient care. Simulation experiences must be relevant and based in reality, but they need not be perfect representations to be educationally effective [1]. For example, specific elements of a procedure, derived from careful task deconstruction, can be emphasized to develop motor skills that might be needed for overall technical development. Benchtop task trainers are good examples of this type of surgical simulation. To be effective, task trainers must enhance an important motor skill, but they need not be high fidelity, high technology, or expensive. Simulation utilizing physical anatomy models, animal structures or human cadavers can facilitate integration of surgical skills and operative procedures, but again they need not be perfectly realistic to be educationally effective. Virtual reality (VR) surgical simulation facilitates a wide range of objectives, from task training through full operations, with varying degrees of fidelity that are associated with the hardware and software characteristics of a given VR platform.

It is important to emphasize that the value of any form of surgical simulation reflects the quality of the curriculum that precisely defines core content, educational sequence, learning objectives and feedback mechanisms, and the specific metrics that are used to measure performance and, thereby, the process of learning [2]. Over the past couple of decades, orthopaedic educators have placed substantial emphasis upon simulation fidelity, which is natural given the excitement created by new computer technology and our seemingly innate preference for realism. Much less attention has been paid to careful development of detailed educational curriculum and to meticulous validation of objective and useful performance metrics. Gallagher [2] provides an excellent overview of surgical simulation definitions, compares competency training with proficiency progression, and explains metric and benchmark development. The article emphasizes the very important principle of deliberate practice as opposed to repeated practice (a common but relatively inefficient and unpredictable educational approach).

Current Situation

Simulation training in arthroscopy

Arthroscopy is a technically challenging orthopedic sub-specialty, and it is a particularly difficult skill set for many learners. Arthroscopy requires three-dimensional, ambidextrous actions that are guided by a two-dimensional representation on a video monitor. The surgeon must be able to switch hands, which can be especially difficult for trainees. There are multiple variables that need to be managed simultaneously, for example camera position, directional control of the angled arthroscope, image horizon, centering and steadiness, instrument triangulation using the contralateral hand, fluid control, and foot pedal interactions. Toss in the addition demands of patient management, procedural planning and sequencing, and constant awareness of three-dimensional anatomic structures at risk: It is easy to understand how learners can be rapidly overwhelmed by these stressors. From an educational perspective, it is therefore logical to break down arthroscopy into its most fundamental elements using meticulous task deconstruction, which facilitates sequential training and rehearsal as the learner gradually moves toward integrated surgical procedures.

Unfortunately, we still utilize the "see one, do one" training approach, whereby the learner observes an expert and tries to mimic a set of complicated, integrative tasks. It makes much more sense to focus during early training upon mastery of fundamental, deconstructed surgical skills. Furthermore, the "see one, do one" method risks development and subsequent reinforcement of poor technical habits. Poor surgical habits can be very hard, and at times, impossible to remediate. It is safer, more efficient, and more predictable to build surgical skills from the "ground up". This principle is reflected in orthopaedic training curriculum that start with a "surgical boot camp", and is clearly reflected by 2013 changes that were mandated by the American Board of Orthopaedic Surgery (ABOS) requiring simulation-based motor skills training for all PGY-1 orthopaedic surgery residents in the United States.

Various forms of simulation have been used for arthroscopy training over the years, including cadaver labs, benchtop skill trainers, anatomic dry models, and virtual reality simulation [3]. Although orthopedic educators are very comfortable with use of these modalities, relatively little is available in terms of validated performance metrics that could be used for proficiency progression training.

Training on cadavers has been a core educational element since the advent of arthroscopy. Cadaveric surgery offers the advantage of anatomic fidelity, even though many of these procedures are limited by the poor tissue quality imposed by the aging process. Training on cadavers is expensive, can be associated with disease transmission, and requires a dedicated wet-lab teaching space. In some parts of the world, this type of training is simply unavailable due to cultural norms, and/or local regulations. Some arthroscopy simulation systems have been based upon task deconstruction. For example, the Fundamentals of Arthroscopic Surgery Training (FAST) Program provides various modules for training of basic arthroscopy skills, including image management, basic triangulation, tissue resection, suture anchor placement and suture delivery, and arthroscopic knot tying. The FAST Program was a collaborative effort of AANA, AAOS, and ABOS, that addressed the new educational mandates implemented by the ABOS in 2013. The modular FAST workstation was developed to facilitate training of these skills (Sawbones, Pacific Design Labs). Proficiency benchmarks have been developed for several FAST modules, including arthroscopic knot tying, based upon measurements of expert surgeon performance [4]. Elements of the FAST program have been incorporated into the ArthroS virtual reality platform, which offers the advantage of computerized measurement of motion control (i.e., instrument path length) and task time. Similar in concept to the FAST workstation, Lopez and co-workers [5] demonstrated construct validity for a low-cost benchtop arthroscopy simulator that can be built by end users with parts available at most hardware stores.

Virtual reality arthroscopy training has developed into a valuable and efficient alternative for motor skills development. Rudimentary VR arthroscopy trainers emerged about 20 years ago, but they were severely limited by computer technology, haptics and tracking methodology, software design, and cost. Recent advances in these areas make VR training feasible, affordable, and effective. Furthermore, VR platforms allow for automatic generation of feedback metrics for learners and supervisors and they facilitate integration of curriculum into learning management system. It is likely that we will see a rapid transition toward greater use of VR arthroscopy training and computer-based assessment of motor skills proficiency in the very near future.

Innate Motor Skills and the Arthroscopy Learning Curve

Just as children are born with a wide range of innate intellectual and athletic abilities, adult learners arrive for surgical training with variable psychomotor skills, which are rarely tested during the residency selection process. Surgical skills develop at a variable pace, but development follows a predictable overall sequence [6,7]. Trainees move from an initial cognitive stage (the surgeon learns to understand the task but performs erratically) through an integrative stage (knowledge is translated into appropriate behavior) toward an autonomous stage (motor performance is smooth and the surgeon no longer needs to concentrate on specific aspects of the new skill). This last level is very important because cognitive capacity is freed up when motor skills become automated. Autonomous activity is a key element of genuine surgical expertise that is facilitated by deliberate and repeated practice.

Alvand and associates [8] demonstrated variation in innate arthroscopy skills and learning curves in medical students. Variable learning curves infer disparity of training time required to reach acceptable levels of technical proficiency. In other words, some learners achieve proficiency very quickly and should be allowed to move forward, whereas other learners require more time prior to safe progression. Historically, surgical training has been based upon sub-specialty rotation time (i.e., a pre-determined number of months on a surgical service), as opposed to progression based upon acquisition of well-defined levels of knowledge and technical skill. This traditional approach slows down gifted learners and encourages progression of some who are not quite ready to take the next step. Obviously, this is neither efficient nor does it optimize patient safety.

Without practice, complex surgical skills also deteriorate over time. Howells and co-workers [7] demonstrated motor skills improvement in a group of experienced non-arthroscopic surgeons who were learning a new skill using a bench top shoulder model. They demonstrated *loss of skill* in the absence of deliberate practice. This is a particularly important value of structured VR training. Learners can return to the VR trainer at regular intervals for timely and deliberate practice to discourage loss of psychomotor skills. Trainees can practice on an arthroscopy VR simulator while on rotation in other surgical sub-specialties, guided by their own performance metrics.

Atesok and colleagues [9] reviewed retention of skills after simulation-based training in orthopaedic surgery. The available literature did not offer highest-level scientific evidence, but it did support the notion of repeated, intermittent practice to retain skills, particularly for difficult motor tasks such as arthroscopy. The observations support incorporation of VR platforms into a structured curriculum that schedules repeated practice to mitigate skill loss, particularly when residents are NOT working in a key area (i.e., when they are going to be away from arthroscopy for an extended amount of time).

Hodgins and co-workers [10] used a task specific check list (TSCL) and a global rating scale (GRS) to assess the arthroscopy learning curve for residents doing diagnostic knee arthroscopy in patients (average 16.5 procedures per resident). Surprisingly, only 40% achieved competency on the TSCL and 5% (one resident) achieved the competency benchmark for the GRS during their study. O'Neill and co-workers [11] performed a survey of orthopaedic department chairs and sports medicine fellowship directors regarding the number of arthroscopic cases needed to become surgically proficient. There was wide variation of these estimates, particularly between educators who did and those who did not perform arthroscopy in their surgical practice. The overall means for number of requisite cases to achieve "proficiency" were impressive: 45 diagnostic knee arthroscopies, 50 meniscectomies, 61 ACL reconstructions, 48 shoulder arthroscopies, 58 sub-acromial decompressions.

Middleton and colleagues [12] evaluated skills performance as a function of experience level for a simple diagnostic shoulder arthroscopy task and a more complex Bankart labral repair task. The investigators evaluated receiver operating characteristic curves, and concluded that 52 previous arthroscopies were needed to perform at a competent level at the diagnostic task and 248 to be competent at the complex task. To perform at an expert level, 290 and 476 previous arthroscopies, respectively, were needed. The authors noted that the number of arthroscopic cases associated with basic competence on a simple shoulder task exceeded the current minimum number required during residency training in some countries.

In the United States, ACGME "case logs" are used as a surrogate for surgical experience. Unfortunately, resident case logs do not delineate whether the resident surgeon actually performed the operation or served as a more passive surgical assistant. Therefore, while case logs reflect *exposure*, they tell us nothing about *proficiency*. Recently, Hinds and co-workers [13] and Gil and co-workers [14] noted wide variation in the number of arthroscopy cases documented by ACGME case logs across various institutions. Although arthroscopy case numbers have been gradually increasing over recent years, both articles emphasized the same critical limitation: Case logs provide no information about acquisition of technical proficiency. Pelligini and associates [15] noted that work hour restrictions have exacerbated the challenges associated with time-based learning in surgical residency, and they emphasized the importance of *deliberate practice* to facilitate development of technical skills.

Key Training Challenges

Clearly, multiple and formidable challenges are associated with modern surgical training [16,17]. Stakeholder perceptions are affected by specific roles within the clinical and educational system. From a societal perspective, we strive to train the next generation of excellent, ethical surgeons in a time-efficient and cost-effective manner. But for a given patient, it is critical that the surgical training process not impose unwarranted risk and unnecessary clinical morbidity. Every surgical trainee wants to achieve levels of technical proficiency and clinical confidence to facilitate professional development, without excessive psychological stress or unwarranted sleep deprivation. For hospital administrators, department chairs, and residency program directors, the goal is optimization of education with minimal disruption of other core missions, at the lowest possible cost. Clearly, surgical training is a delicate balancing act. The question, as we move forward: Does simulation make the process safer and more efficient?

Ferguson and colleagues [18] estimated a cost of $100,000 Canadian dollars per year of surgical training. They argue that decreasing total training time, for example with earlier graduation via competency-based progression, could create enough savings to justify new forms of educational expenditure. The surgical learning curve is associated with some degree of additional clinical morbidity when trainees (rather than experienced attending surgeons) perform part or all of an operation. This learning curve can add short-term cost and/or long-term expense, depending upon the severity of the complication. Furthermore, operating rooms and faculty time are a valuable hospital resource that should be used efficiently. Extra time spent for training costs direct dollars, and the added time also affects opportunity cost, whereby more surgeries could potentially be performed during the same hospital day.

Farnworth and co-workers [19] compared surgical time for anterior cruciate ligament reconstruction done by one attending faculty surgeon (mean 95 minutes) with surgeries performed by residents under his direct supervision (mean 137 minutes). The authors calculated the costs associated with additional operating room time and anesthesia time. On average, costs increased $662 per case. They did not, however, calculate the associated loss of productivity for the faculty member, nor did they address increased patient morbidity associated with the resident learning curves (for example, increased articular cartilage injury). From a financial perspective, and considering our obligation to optimize patient safety, surgical educators must exploit efficient methods for bringing trainees up the learning curve *prior* to the performance of operative procedures on patients. This is a distinct divergence from a longstanding surgical tradition: The “see one, do one” approach. Surgical simulation, in concert with proficiency-progression training, makes the change feasible, today.

Proficiency-Progression & Surgical Performance Metrics

What is available for arthroscopy?

Medicine has traditionally trained doctors to be “*competent*”, a standard that reflects minimum levels of knowledge and skill [2]. “*Proficient*” reflects a higher level of clinical performance, as trainees move up the learning curve toward “*expert*” skills levels. Proficiency-progression training involves the creation of well-defined curriculum, objective interval testing with timely learner feedback, and systematic advancement as the learner demonstrates sufficient acquisition of knowledge and skills based upon appropriate benchmarks [1]. To objectively stratify the learning curve, it is absolutely critical to utilize thoughtful, detailed, and well-validated *metrics*. Historically, surgical skills have been assessed by subjective methods, which can be substantially affected, positively or negatively, by interpersonal relationships between master and apprentice.

In terms of knowledge acquisition and cognitive performance, medicine has a strong history of metrics and benchmark setting via standardized testing. Much less is available regarding objective assessment of surgical and arthroscopic skills [20,17]. There are some important criteria for development of performance metrics: They must be relevant to the task at hand, they must precisely define what should *and should not* be done for a given procedure, and they must not inadvertently encourage inappropriate behavior. For example, procedural metrics must not emphasize raw speed over surgical safety. Over-reliance on “time to completion” is therefore an important pitfall, especially when not counter-balanced by safety and/or error metrics.

Simulation strategies and associated metrics must be validated prior to broad implementation. *Intra-observer variability* and *inter-observer variability* must be measured to confirm that metrics are well-defined and operationally consistent. *Face validity* means that the metrics are acceptable representations of the skills to be trained. Though important, face validity is a subjective and relatively weak descriptor. *Construct validity* is a more robust parameter demonstrating that simulation metrics differentiate performance across various groups by skill and experience level, for example, measured differences between novices, residents, and experienced surgeons. *Transfer validity and predictive validity* are perhaps the most difficult steps in the overall process, whereby better skills in the simulation environment correlate with improved performance in the clinical setting. Transfer of training can be demonstrated by correlation of simulator performance with surgical skill during cadaveric procedures. However, cadaver surgery is an imperfect surrogate for live clinical performance.

Current surgical skill assessment strategies fall broadly into a few general categories. Some systems utilize visual analog scales to define *quality* for various categories, typically on scales from one to five or one to ten. Other systems utilize task checklists that record completion of specific *procedural steps*, with simultaneous recording of *technical errors*. This assessment strategy creates a string of binary measures, in other words, steps and errors either did or did not happen. Another alternative is motion analysis via external motion sensors or by direct motion analysis within a VR platform, whereby *efficiency* of hand and/or instrument motion and *procedural time* are measured by the computer system.

There are pros and cons to each of these assessment methods, and the optimal approach is yet to be defined. A significant issue continues to be the amount of time, requisite expertise, and commitment for experts (i.e., surgical faculty) to complete interval performance assessments. Assessment time takes faculty away from research activity, administrative work, clinical care and other revenue-generating opportunities. This is a major advantage of computerized metrics combined with a proficiency-progression curriculum that exploits computer-based mentorship, if and when appropriate. *Faculty time* is often overlooked during financial analyses of simulation alternatives. This issue cannot be understated from a cost-efficiency perspective.

Defined and validated metrics can be used to set *performance benchmarks*, which are critical for proficiency-progression programs. Benchmark setting is a challenging and controversial process [1]. Cognitive benchmarks often utilize mean performance minus two standard deviations, derived from a relevant reference group; this strategy has been used for surgical skills benchmarks as well [21]. This approach makes the “passing score” relatively easy, reflecting a minimal level of competence without demonstration of surgical proficiency. Therefore, some groups have utilized the mean performance of an experienced cohort to define the performance benchmark for surgical motor skills, thereby raising the bar for acceptable performance by trainees [2]. Others utilize the “contrasting groups method”, setting the benchmark at the intersection of Z-score curves for novices and experts [22]. This approach places the benchmark somewhere between the mean and two standard deviations below the mean of expert performance. Complete discussion of metrics and benchmark setting are beyond the scope of the current paper. Clearly these are critical prerequisite processes for proper implementation of simulation-based training curriculum.

Validation of Simulation Training in Other Surgical Specialties

Simulation training has been validated and adopted in other surgical specialties, and it is useful to extrapolate when appropriate. In a landmark study, Seymour and co-workers [23] demonstrated transfer validity to clinical performance for VR training in laparoscopic surgery, following three to eight training sessions on the MIST- VR platform. They observed fewer errors and better efficiency in the operating room after VR training to criterion performance in the simulation lab. Grantcharov and colleagues [24] also demonstrated transfer validity for VR training in laparoscopic surgery, with ten repetitions on six different task exercises on the MIST-VR platform. Based upon blinded review of surgical videos, there was more improvement in procedural speed, fewer surgical errors, and better economy of movement in the VR trained subjects compared to controls. Fried and co-workers [25] summarized a large series of experiments, proving that the MISTELS Fundamentals of Laparoscopic Surgery (FLS) benchtop training system is both valid (face, construct, and transfer validity) and educationally effective. The MISTELS-FLS system was created by scrupulous task deconstruction, underwent rigorous scientific validation, and was subsequently adopted by the American Board of Surgery as a requirement for all general surgery training programs in the United States.

Evidence for the Use of Simulation in Arthroscopy Skills Training

Simulation training has been used for decades in orthopaedic surgery, incorporating task trainers, anatomic models, and cadaveric surgery in the overall educational process. Recently VR simulation has become a feasible and attractive option in the field of arthroscopy. What is the validation evidence for arthroscopy simulation, and for VR arthroscopy training specifically?

In 2002, Pedowitz and colleagues [26] demonstrated construct validity for basic shoulder arthroscopy skills on the Mentice VR platform, comparing performance of medical students, advanced residents, and experienced attending surgeons. Howells and co-workers [27] demonstrated transfer validity for a benchtop non-VR knee simulator, with improved operative skills during diagnostic knee arthroscopy for residents trained on the simulator compared to a standard training group. In 2012, Atesok et al. [28] published a review article about simulation in orthopaedic skills training. At the time, these authors found limited scientific data to definitively prove the educational advantages of simulation, and described a need for improved global rating scales to measure arthroscopy performance.

Butler and colleagues [29] demonstrated positive effects of training on knee dry models prior to training in cadaver knees for medical student novices, with performance assessed by blinded observers using the BAKSS (Basic Arthroscopy Knee Scoring System). Baseline performance shifted up in the dry model trained group, and the difference persisted over eight training trials on the cadaver. In 2013, Alvand and co-workers [30] demonstrated correlation between motion analysis and global rating scale video-assessment of meniscus repairs performed in a benchtop environment. Frank and co-workers [31] published a systematic review of available evidence, noting moderate construct validation but little information about clinical transfer of arthroscopy simulation training to the operating room. When Frank et al. [31] conducted their review, an important paper by Cannon and co-workers [32] had not yet been published. Cannon et al. demonstrated transfer validity for a knee VR simulator (ToLTEC), whereby training on the VR simulator resulted in improved clinical performance of knee arthroscopy, compared to a control group that did not participate in VR training. Of interest, time to perform a diagnostic knee arthroscopy was not different between the groups because the control group tended to be less thorough. This observation emphasizes the importance of combining speed with quality metrics to promote clinical safety. Around the same time, Fucentese and co-workers [33] demonstrated face and construct validity for the VirtaMed ArthroS knee simulator, comparing novices, intermediates, and expert surgeons.

Publication has accelerated in the last two years, and we should expect more information demonstrating transfer of VR to OR in the field of arthroscopic surgery. In 2015, Kirby et al. [34] cross-correlated the VirtaMed ArthroS shoulder simulator against motion sensors worn on the wrist and elbow, with good path length correlation for the two methods. They also demonstrated construct validity for the ArthroS VR platform. Coughlin and co-workers [35] demonstrated construct validity for a benchtop model designed to teach basic arthroscopic skills in six modules (triangulation and probing, grasping and transferring objects, tissue resection, tissue shaving, tissue liberation and suture passing, tissue approximation and knot tying). Rebolledo and colleagues [36] demonstrated transfer validity from VR to cadaveric surgery, with improved performance of shoulder arthroscopy after 2.5 hours of VR training (ArthroVR, GMV) compared to traditional didactic training. There were similar but not statistically-significant trends for VR to cadaver knee arthroscopy in that study.

Reppenhagen [37] presented a study that found similar improvements in skills learning for medical students when guidance was provided by experts compared to guidance by the ArthroS VR platform's autodidactic program. This study is important, because it supports the notion that the VR computer program can act as an effective mentor, thereby decreasing faculty time and associated costs. In 2015, Rose and Pedowitz [38] demonstrated construct validity for several fundamental arthroscopy motor skills on a VR platform (Swemac Arthrovision). A novel observation of this study was that experienced surgeons demonstrated greater motor skills consistency and better *ambidextrous* arthroscopy performance, measured by symmetry between dominant and non-dominant hands.

In 2016, Martin et al. [39] demonstrated improvement of arthroscopy skills after a four day AANA resident arthroscopy fundamentals course, as measured on a VR arthroscopy platform (Simbionix ARTHRO Mentor VR). Camp et al. [40] compared improvement in cadaver knee arthroscopy performance measured by ASSET scores between three training groups: No additional training pre-test to post-test, four hours of simulator training (ToLTEC VR knee platform), or four hours of training on a cadaver knee. They showed greater improvement in residents trained on the cadaver knee than the VR trained subjects, with no improvement in the control subjects. However, the training sessions in this study were unstructured and advancement was not proficiency-based.

Garfjeld Roberts and colleagues [41] demonstrated face validity and construct validity for the second-generation VirtaMed ArthroS simulator for knee and shoulder modules. Time for task completion and instrument path length were reliable metrics for differentiating experience level, though some of the novel metrics did not demonstrate construct validity. In a similar study, Rahm and co-workers [42] demonstrated good face and construct validity for the ArthroS shoulder VR simulator. In another paper, Rahm et al. [43] studied the learning curves of novice medical students trained on the VirtaMed ArthroS knee simulator. They noted a plateau of improvement after the fourth training session, with little performance change from sessions five through eight.

In an interesting study, Middleton et al. [44] compared three global rating scales for arthroscopy that was performed on the VirtaMed ArthroS knee and shoulder modules, comparing groups of novices, orthopaedic trainees, and experts. There were no discriminatory differences between the global rating scales, and there was good correlation of those scales with the computer-generated metrics (time to task completion and path length). Thus, VR metrics can be used to objectively measure surgical performance. Scoring algorithms should probably introduce quality measures or procedural error penalties to encourage clinical safety over raw speed.

Tofte and colleagues [45] cross-correlated performance on a knee module, a shoulder module and several VR FAST modules using the VirtaMed VR arthroscopy platform. The authors found significant correlations between composite score, camera path length and operation time. Better VR performance was associated with greater arthroscopy training experience.

Jentzsch and co-workers [46] noted significant correlations between 3D video game performance and arthroscopy skills measured on the VirtaMed ArthroS knee platform in novice volunteers. In this study, performance on a strategy game did not correlate with arthroscopy motor skills. They infer that some trainees have better innate 3D skills and/or there could be positive effects of prior 3D video game practice that translate to enhanced arthroscopy performance. In 2016, Reppenhagen et al. [47] presented a study of three training protocols with medical students, each of which involved a total of five training sessions. Training was performed on the VirtaMed ArthroS platform (five times in one week, 2 times per week for 2.5 weeks, or once a month for 20 weeks), with outcomes assessed three months after the final VR training session. The best learning occurred with VR training twice per week, and it was associated with preservation of motor skills three months later. Martin and co-workers [48] assessed face validity for three arthroscopic VR simulators (Simbionix, VirtaMed, TolTEC) with questionnaires to medical students, residents, and faculty after exposure to each simulator. VirtaMed ArthroS had the highest face validity.

In summary, scientific evidence demonstrates positive effects of simulation training upon surgical performance in the field of arthroscopy and beyond. VR platforms can serve as effective educational mentors when used in conjunction with a well-structured curriculum. Furthermore, VR programs can assess arthroscopy performance objectively, with good correlation of computerized metrics with global rating scales. To discourage fast but careless surgical habits, VR performance assessments should blend speed and efficiency metrics with measures of quality and/or procedural errors.

Relevant Focus Areas and Opportunities for Improvement

Curriculum development and simulation fidelity

For many surgeons, a big appeal of VR is the "coolness" of the technology, in and of itself. VR is genuinely amazing, and it is rapidly growing in the consumer arena through gaming, VR headset displays, and new experiences that are highly engaging. Unfortunately, in surgery the "cool factor" has resulted in over emphasis upon ultra-high fidelity, with relatively less emphasis on the quality and educational impact of the simulation. Meticulous development of the teaching curriculum, with well-defined learning objectives and mechanisms for performance feedback, should ***precede*** simulation development (also integral for continuous process improvement). We have seen multiple examples of simulators that were built in the reverse order, thereby creating "neat" experiences that have little educational merit or assessment value.

How should educators and developers approach the challenging process of curriculum development? Curriculum templates are an effective way to structure this exercise. The American College of Surgeons (ACS) created a detailed curriculum template that emphasized metric development. This template was subsequently adapted by the ABOS to provide a consistent format for the 2013 PGY-1 orthopaedic surgery motor skills curriculum, which is comprised of multiple surgical skills modules. In general, curriculum templates should include these core elements: (1) Problem identification, (2) Goals and objectives, (3) Syllabus development, (4) Learner evaluation and feedback, and (5) and Metric validation and periodic review.

Once the teaching curriculum and performance metrics are well-defined, educators can decide upon the best ways to incorporate simulation into the overall training process. For example, surgical skills can be broken down into fundamental elements using task deconstruction. In some cases, benchtop task trainers are most appropriate and cost-effective for training of fundamental skills, for example for development of arthroscopic knot-tying skills [4]. As trainees progress toward more integrated and complex surgical procedures, it may be appropriate to utilize anatomic simulation models or cadaveric training. VR simulation platforms can be used at any stage of the surgical training process, gearing the exercises toward well-defined educational objectives. It is very important to emphasize that simulation fidelity should be *sufficient* to achieve the educational goals of each specific exercise. It is neither necessary nor appropriate to strive for perfect procedural fidelity in every case. Excessive emphasis on simulation fidelity over educational quality can be counterproductive, creating simulations that are ineffective and cost prohibitive.

Proficiency progression

Historically, surgical training has been based upon time intervals of topic *exposure*, for example a certain number of months of training in a sub-specialty area. Ideally, progression through the surgical curriculum should be based upon demonstration of cognitive and technical proficiency (or competency, which is a somewhat lower standard, as described above). It makes sense from educational and patient safety perspectives for the trainee to advance based upon demonstration of knowledge and technical skill. When it comes to performance of surgery *on live patients*, residents should preliminarily reach sufficient levels of motor skill *using simulation* to minimize clinical morbidity, optimize expensive surgical resources, and maximize the training experience for trainees and educators.

Ferguson and co-workers [18] described a major transition in the Toronto orthopaedic training program toward a "competency-based resident curriculum". They deliberately and steadily changed from the traditional time-based, service-provision approach toward a program structure that is educationally-focused and heavy on objective performance evaluations. They were motivated by the major gap in experience level and proficiency for key orthopaedic procedures in the traditional educational format, exacerbated by limitations in available training hours. They estimated that orthopaedic training at their institution costs about $100,000 (Canadian dollars) per trainee per year. Implementation of a competency-based curriculum can allow training to happen *faster* in some individuals (thereby saving dollars), since they are potentially able to move through the competency-based curriculum more efficiently. Ferguson et al. [18] documented a high level of satisfaction with the new educational format, for residents and faculty alike, although the assessments added cost because the global rating scales required substantial faculty time.

A few years ago, the Arthroscopy Association of North America (AANA) embarked on a series of studies that were coined the "Copernicus project", so named because it was an effort by AANA to change the educational paradigm. Initial research efforts focused upon teaching of an arthroscopic Bankart procedure for the treatment of anterior shoulder instability, as described in a series of papers published by Angelo and co-workers [49]. The development process involved task deconstruction of the surgical procedure, meticulous definition of the steps and errors involved in the operation, vetting of these procedural definitions by a Delphi process, and detailed validation of the performance metrics when procedures were performed on anatomic shoulder models and cadaveric shoulders. Ultimately, a proficiency-progression curriculum was defined and compared with standard AANA resident teaching approaches in a large multi-center, blinded, randomized prospective study. These studies demonstrated, unequivocally, that the proficiency-progression method was associated with *much* greater probability (> 5 times) of acquisition of surgical skills that exceeded the proficiency benchmark, compared to traditional training methods.

Pathways for broader adoption

Surgery has been taught the same way for many, many years (centuries, to be precise). It is hard to shift from the traditional surgical apprentice model, which despite its many limitations, is at the very least a time-tested educational approach. However, the traditional system is under substantial pressure in terms of patient safety, restrictions on resident training hours, and cost. Simultaneously, surgical simulation (particularly with VR) is undergoing rapid technologic advancement, whereby excellent educational quality and objective performance assessment are now, literally, within grasp. The regulatory environment has also changed, with rules and mandates enacted by residency review committees and board certification bodies and new pressures applied by political entities and public expectation. Surgical education, it seems, has arrived at a "tipping point". What do surgical educators need to make the paradigm shift? Where is the key resistance to change?

Karam and co-workers [16] explored the major barriers to broad implementation of simulation in orthopaedic surgery training in a large survey of US orthopaedic faculty and residents. They noted that lack of available funding was the most important *perceived* barrier, followed by lack of available curriculum, lack of faculty/instructor interest, and lack of dedicated space for simulation training. Clearly simulation cost is a major issue, but generally financial impact is considered at a relatively "knee-jerk" and superficial level (ie., "How much does the simulator cost?"). A complete cost-benefit analysis by educational decision-makers should include other factors that are rarely considered. For example, as noted above, a substantial portion of surgical education must be transitioned out of the direct patient care arena. How does the change improve operating room efficiency? Will surgical faculty be responsible for educational delivery and proficiency-assessment when education is provided in the simulation lab? Faculty time is extremely valuable, particularly when surgeons are taken away from the operating room and clinic. If VR simulation platforms can be used as surrogate mentors to deliver high quality education per a well-defined curriculum, they can facilitate faculty productivity. Motor skills evaluations should utilize validated and objective performance metrics, and they must be performed carefully and consistently. This is *critical*, particularly when it comes to high stakes examinations that affect trainee progression through the surgical program. Computer-based performance metrics can make the motor skills evaluation process objective, discriminative, reproducible, and efficient, with less faculty time and associated expense.

To summarize, surgical decision-makers should start by careful delineation of educational curriculum that are optimized for their learning environments, faculty and trainees. Simulation strategies can then be tailored to serve specific needs, thereby maximizing patient safety and enhancing overall educational quality. Proficiency metrics must be clearly defined, using objective approaches that can be implemented consistently and effectively. Finally, financial analyses should account for changes in operating room efficiency and for faculty time associated with simulation teaching and surgical skill assessment. These are high-value variables that can substantially swing the cost-benefit analysis.

Disclosure

Dr. Pedowitz is Chair of the Fundamentals of Arthroscopic Surgery Training Program (a collaborative effort of AANA, AAOS and ABOS). Dr. Pedowitz is a paid consultant for Virtamed and he received financial support for preparation of this manuscript.

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