Current Concepts

Evaluation of a Virtual Reality Simulator for Arthroscopy Skills Development

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Abstract: We evaluated a virtual reality shoulder arthroscopy simulator using a standardized skills-assessment algorithm in 3 specific groups with various degrees of surgical expertise. The simulator (Mentice Corp, Gothenberg, Sweden) consists of a computer-based, dual-force feedback system with video monitor. Modeled structures include cartilage, labrum, ligaments, biceps tendon, and rotator cuff. The study included 3 groups of volunteers: group 1, medical students interviewing for orthopaedic residency (n = 35); group 2, orthopaedic residents interviewing for sports medicine fellowship (n = 22); and group 3, experienced faculty at a shoulder surgery course (n = 21). Data were collected anonymously and subjects completed a standardized test protocol designed to assess accuracy and efficiency. Subjects used the probe to "touch" a sphere that appeared at various locations within the joint (11 positions total). The sphere changed location immediately on contact with the tip of the probe. The following parameters were calculated by the computer: time (from touching the first ball until touching the eleventh ball), path ratio (percent of measured path length relative to the ideal path), collisions (number of times the probe / arthroscope contacted any tissue), and injuries (collisions beyond a threshold force). Test time and path ratio differed significantly as a function of surgical experience. There was no significant difference in probe collisions between the groups. Arthroscope collisions and injuries averaged 2 or less in all of the groups. There was significant correlation between path ratio and time to complete the test in groups 1 and 2 ($r = .527$ and $r = .827$, respectively, $P < .001$), but not in group 3 ($r = .376$, $P = .10$). There was essentially normal distribution of time performance in groups 1 and 2. Time was shorter and more consistent in group 3, suggesting greater consistency in the experienced surgeons. These data suggest that this arthroscopy simulator facilitates discrimination of arthroscopic skills. Computer-based simulation technology provides a major opportunity for surgical skills development without morbidity and operating room inefficiency. **Key Words:** Arthroscopy—Education—Virtual reality—Simulation—Computer—Surgical skills.

Traditional methods of surgical education use apprenticeship models after acquisition of basic knowledge during medical school.[1-3] Major changes in surgical technology and recent research in adult education suggest reconsideration of current educational paradigms. Arthroscopy is a very common orthopaedic procedure. Low morbidity, diagnostic accuracy, and therapeutic efficacy suggest that arthroscopy will continue to play a major role in orthopaedic practice. Rapid changes in video technology and instrument sophistication require continual adjustment of educational approaches. It is essential to review the state of the art of arthroscopy education as a foundation for potential methodological improvement.

Arthroscopy training usually begins during orthopaedic residency. Competency in surgical arthroscopy typically develops during completion of the residency curriculum as defined by the residency review com-

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Supported in part by an Arthroscopy Association of North America Research Grant. Technical support provided by Mentice Corporation, Gothenburg, Sweden.

1526-3231/02/1806-3201$35.00/0
doi:10.1053/jars.2002.33791

mittees, with standard of care as defined by community norms. Additional training is often provided by focused fellowships in arthroscopy and sports medicine.

Arthroscopic skills are particularly difficult for some surgeons. This may be in part due to its inherent challenge, because current arthroscopic visualization is 2-dimensional representation on a video monitor with 3-dimensional manipulation of camera and instruments. In addition, arthroscopic technique demands different psychomotor skills than those used during open surgical procedures. This is particularly important because many of the open surgical techniques use psychomotor skills that are rooted in early childhood. For example, eating with utensils, tying a shoelace, and working with basic household tools are psychomotor skills that can be built upon for more advanced surgical techniques. Some believe that the next generation of medical students will have a more natural propensity for arthroscopy because of their experience with computer games (the Nintendo generation).

Current educational approaches include written materials such as textbooks and journals, didactic teaching in lectures and seminars, and observational learning via videotape and computer presentations.[4,5] Rudimentary psychomotor tasks may be learned using a simple "black box," whereby basic triangulation skills are practiced within an abstract environment. Newer teaching models include anatomically appropriate knee and shoulder models (for example, Alex the Shoulder Model). Some surgeons also have an opportunity to practice on cadaver specimens, which is a valuable learning opportunity given proper preparation and supervision. However, inherent costs and practical considerations make cadaveric practice somewhat limited.

Most arthroscopic education occurs in the operating room under the watchful eye of a mentor who is qualified in arthroscopic surgery. Teaching progresses from role modeling of arthroscopic techniques to controlled practice under direct supervision, with a significant component of unsupervised education. Unfortunately, unsupervised education involves significant trial and error, whereby new techniques are learned individually by self-evaluation. This approach is neither the most efficient from an educational perspective nor particularly safe in terms of the associated patient morbidity.

There are important inherent limitations of the current educational paradigm. Early skill acquisition is often associated with significant patient morbidity, particularly to articular cartilage, which has an extremely limited reparative capacity. Arthroscopy education is relatively inefficient from a clinical perspective because it usually adds significant time (and therefore delivery expense) to the surgical procedure. Trial and error teaching can also be detrimental for the learner because it provides a real opportunity to learn and reinforce poor surgical technique.[4] Current approaches may not be the most efficient and beneficial educational paradigms for arthroscopic training.

It is interesting that the airline industry has embraced computer simulation technology for decades, whereas medical education has been relatively slow to use such technology.[6] This is probably due to 2 major factors. First, surgical traditions are hard to break. Second, the aviation industry has long recognized the potential adverse consequences of mistakes in aviation training. Loss of life and loss of expensive aircraft provided the critical motivation for developing low-risk simulation paradigms, particularly for the military. The positive cost-benefit analysis of this approach is evidenced by dramatic investments in simulator realism and broad application of simulators in the commercial airline industry.

Advances in computer technology and developments in 3-dimensional force feedback systems suggest that similar investments are appropriate for surgery.[6,7] These advances should allow the price of arthroscopy simulators to fall within reach for general orthopaedic education. Appropriate development of this technology requires step-wise validation and careful integration of modern educational theory. Other medical subspecialties have described recent efforts at simulation training.[8-27] Unfortunately, similar development and validation has not been completed for orthopaedic applications.

A virtual reality shoulder arthroscopy simulator was introduced recently (Mentice Corp, Gothenburg, Sweden); this platform could be developed for arthroscopy education. The device incorporates 3-dimensional force feedback systems for the "camera" and for the "probe." These elements provide physical feedback, for example, when the camera bumps the virtual cartilage surface or when the probe pulls on the virtual biceps tendon. Anatomic modeling is based on 3-D reconstruction of human imaging data. The software provides continuous monitoring and adjustment of camera image and orientation, as well as probe position within the virtual joint. The physical setup allows simulation of patient size, portal position, and surgical positioning.

The purpose of this study was to examine the potential utility of this platform for eventual development of a valid surgical arthroscopy simulator. Our goal was to evaluate motor performance using a standardized skills-assessment algorithm in 3 specific groups with various degrees of surgical expertise. We hypothesized that there would be considerable variation of motor performance within these groups, and that performance would improve as a function of experience.

METHODS

The simulator consisted of a computer-based, dual-force feedback system with video monitor. Anatomically modeled structures include cartilage, labrum, ligaments, biceps tendon, and rotator cuff. The study included 3 groups of volunteers: group 1, medical students interviewing for orthopaedic residency (n = 35); group 2, orthopaedic residents interviewing for sports medicine fellowship (n = 22); and group 3, experienced faculty at a shoulder surgery course (n = 21). Data were collected anonymously.

After orientation and 5 minutes of practice, subjects completed a standardized test protocol designed to assess accuracy and efficiency. Subjects used the probe to "touch" a sphere that appeared at various locations within the joint (11 positions total). The sphere changed location on contact with the tip of the probe. The computer calculated the following parameters:

Time: From touching the first ball until touching the eleventh ball.
Path Ratio: Percentage of measured path length relative to the ideal path.
Collisions: Number of times the probe/arthroscope contacted any tissue.
Injuries: Collisions beyond a threshold force.

Data Analysis: Data are presented as mean ±SD. Analysis of variance, linear regression, and unpaired *t* tests were used to evaluate parametric variables. Significance was considered at $P < .05$. To evaluate distribution of time data within groups, time was stratified in 25-second epochs and the percentage incidence performance within each epoch was determined.

RESULTS

Time, path ratio, and probe collision data are presented in Table 1. There were significant differences in test time and path ratio between the groups, with the best overall performance observed in the group of experienced surgeons. There was no significant difference in probe collisions between the groups. Arthroscope collisions and injuries averaged 2 or fewer in all of the groups (statistical evaluation not relevant due to low incidence).

TABLE 1. *Performance on the Shoulder Arthroscopy Simulator*

	Group 1 (n =35)	Group 2 (n = 22)	Group 3 (n = 21)
Time (sec) (ANOVA, $P < .001$)	140 ± 46	110 ± 74	53 ± 22
Path Ratio (% of optimal path) (ANOVA, $P < .001$)	529 ± 247	383 ± 334	214 ± 79
Probe Collisions (no.) (NS)	83 ± 50	78 ± 67	60 ± 28

NOTE. Data presented as mean ± SD.
Group 1, Medical students interviewing for orthopaedic residency.
Group 2, Orthopaedic residents interviewing for sports fellowship.
Group 3, Experienced faculty at a shoulder arthroscopy course.

There was significant correlation between path ratio and time to complete the test in groups 1 and 2 ($r = .527$ and $r = .827$, respectively, $P < .001$), but not in group 3 ($r = .376$, $P = .10$). There was essentially normal distribution of time performance in groups 1 and 2 (Fig 1). Time was shorter and more consistent in group 3, suggesting greater performance consistency in the experienced surgeons.

DISCUSSION

Motivation of This Work

Arthroscopic techniques have changed the face of orthopaedic practice, and there is little doubt that scientific and technical advances in arthroscopy will continue to revolutionize the surgical management of articular disorders. Knee and shoulder arthroscopy are 2 of the most commonly performed general orthopaedic procedures. It is incumbent on our profession to develop strategies for facilitation of competency in surgical arthroscopy.

However, development and maintenance of basic and advanced arthroscopic skills can be a daunting challenge for novice trainees and for practicing surgeons, even for those who are skilled at open techniques. Arthroscopy training is difficult, time consuming, and expensive.

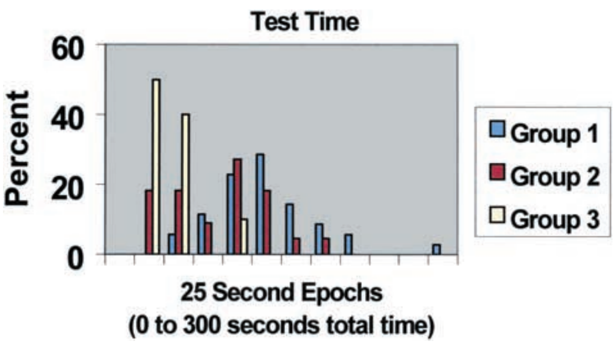

FIGURE 1. Distribution of simulator test time performance. Group 1, Medical students interviewing for orthopaedic residency. Group 2, Orthopaedic residents interviewing for sports fellowship. Group 3, Experienced faculty at a shoulder arthroscopy course.

Unfortunately, arthroscopy training is sometimes associated with significant morbidity related to damage of delicate intra-articular structures. Few would argue that the incidence of significant cartilage injuries decreases as one progresses along the arthroscopic learning curve, although this assumption should be carefully validated. Articular cartilage is of particular concern due to its limited intrinsic capacity for tissue repair. From an ethical perspective, surgeons should implement educational paradigms and exploit new technologies that minimize patient morbidity.

Excellence in arthroscopy requires a broad knowledge base, accurate diagnostic skills, positive patient rapport, and outstanding technical ability. Whereas some open surgical skills come naturally because of life-long experience with basic tools and utensils, many arthroscopic skills are difficult for surgeons-in-training. Arthroscopy requires synthesis of 2-dimensional video feedback (via the eyes) with physical/spatial information (via the hands) in order to create 3-dimensional control of a host of delicate instruments (via the brain). This is a very difficult task for many surgeons. From an educational perspective, it is desirable to develop realistic surgical simulators that facilitate practice and progression in a controlled and non-threatening environment. The educational paradigm should reflect sound application of validated theories of adult psychomotor education.

Current reimbursement conditions do little to compensate hospitals or physicians for the additional surgical time required for acquisition of these skills. From a financial perspective, development of basic surgical skills in a simulator setting would be preferable so as to maximize the efficiency of surgical environments. Obviously, the cost-benefit ratio of a new educational method must be considered carefully. However, as computer technology explodes and 3-dimensional force feedback mechanisms become smaller and more affordable, computer-based surgical simulation should become an integral and cost-effective element of surgical education.

Educational Theory

Surgical performance can be broken into cognitive, psychomotor, and affective domains. As such, the purpose of surgical training is to foster skills development in each domain in order to facilitate safe, effective, and ethical patient management both inside and outside of the operating room.

Computer technology has been applied extensively to the cognitive domain; examples include CD-ROM resources and internet-based search engines. Clearly, a vast amount of cognitive information should be dovetailed eventually into surgical simulation strategies as part of a comprehensive educational package. However, initial efforts should focus on validation and development of the psychomotor elements of virtual reality simulation.

Technological advances in arthroscopy have revolutionized the diagnosis and treatment of intra-articular disorders. However, surgical education has yet to exploit the same technological opportunities to maximize the safety and efficiency of arthroscopy training. A virtual reality shoulder arthroscopy simulator has been developed for this purpose. The long-term goal of this work is to develop, validate, and implement a realistic and versatile shoulder arthroscopy simulator that can be used for basic surgical training as well as for advanced arthroscopy education.

Recent research suggests that we should reconsider some of our basic paradigms for surgery education. Teaching and learning in surgery typically is achieved using one of 4 major modes of learning.[4] These modes include: (1) self-directed or autonomous learning, (2) receptive learning from reading, hearing, and or observing, (3) guided intervention or guided inquiry, and (4) cognitive apprenticeship. The first 3 modes are inherently risky and inefficient and are "relatively contraindicated for surgical training."[28]

Cognitive apprenticeship is a relatively new model of instruction that is particularly efficient for teaching of clinical orthopaedics.[29-32] Cognitive apprenticeship can be broken into 5 major phases (Table 2). Phase 1 involves someone who is proficient demonstrating the technique and explaining the principles, tricks, and pitfalls. Phase 2 involves the learner imitating the gold

TABLE 2. *Cognitive Apprenticeship*

	Role of Learner	Role of Teacher	Key Activities
Phase I	Observe performance of skills. Develop mental model or schema.	Model the procedure proficiently. Talk about pitfalls and tricks.	Modeling Explaining
Phase II	Approximate doing the real thing. Reflect on teacher's performance.	Provide coaching. Provide support when needed.	Scaffolding Coaching
Phase III	Continue approximating the real thing (individually or in groups).	Decrease coaching and scaffolding, but maintain close supervision.	Fading
Phase IV	Practice task independently, meeting acceptable standards of proficiency.	Provide assistance only when requested.	Internalization
Phase V	Discuss the generalizability of what has been learned.	Explain and discuss general relationships for what was learned.	Generalizing

Data from Lippert and Farmer.[4]

standard under carefully scaffolded conditions. The teacher coaches as necessary during this phase and provides remedial instruction. Phase 3 requires gradual fading of the coach as the learner demonstrates increased ability. Phase 4 involves independent practice with teacher backup available as requested. Phase 5 involves discussion, integration, and generalization of the surgical techniques to other areas of clinical practice. The theory of cognitive apprenticeship provides a progressive framework for surgical education that relies on significant interaction between teacher and learner. This theory also provides a framework for development for virtual reality simulators for arthroscopic surgery training. Each of the phases of cognitive apprenticeship could be mimicked by interactive, computer-based virtual reality simulation.

Implications of the Current Study

We assumed that arthroscopic skills would be better in group 3 than in group 2 than in group 1 (as a function of surgical training and experience). The testing paradigm used in the present study allowed for performance discrimination between these groups. Although there was significant variation of the tested parameters, performance was more consistent for the experienced surgeons. This finding is shown well in the test time histogram (Fig 1), with shorter test times and narrower performance distribution noted in group 3.

These data suggest that the virtual reality shoulder arthroscopy simulator facilitates discrimination of psychomotor skills. To develop the simulator into a relevant educational tool, future efforts will focus on creating and validating educational paradigms that are rooted in modern educational theory. Although this simulator is designed for shoulder procedures, the conceptual framework of this work may be relevant to arthroscopy education in general. Virtual reality arthroscopy simulation may present an effective, safe, and cost-effective educational alternative.

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