Observational Learning During Simulation-Based Training in Arthroscopy: Is It Useful to Novices?

Marie-Eve LeBel, MD, MHPE, FRCSC[a], John Haverstock, MD, FRCSC[a,1],
Sayra Cristancho, PhD[b], Lucia van Eimeren, MSc[c,2], Gavin Buckingham, PhD[d,3]

[a] Division of Orthopaedic Surgery, Western University, London, Ontario, Canada.
mlebel4@uwo.ca, john.haverstock@gmail.com
[b] Centre for Education, Research & Innovation, Western University, London, Ontario, Canada.
Sayra.Cristancho@schulich.uwo.ca
[c] Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada.
lvaneimeren@gmail.com
[d] The Brain and Mind Institute, Western University, London, Ontario, Canada.
G.Buckingham@exeter.ac.uk

Corresponding author:

Dr. Marie-Eve LeBel, MD, MHPE, FRCSC

Associate Professor,
Division of Orthopaedic Surgery
Roth-McFarlane Hand and Upper Limb Centre (HULC)
St-Joseph's Health Care
268 Grosvenor St., Suite D0-202
University of Western Ontario
London (ON)
Canada
N6A 4V2

phone: 1-519-646-6153
fax: 1-519-646-6049
email: mlebel4@uwo.ca

Conflict of Interest:
No conflict of interest.

---

[1] Present address: Halton Healthcare, 3075 Hospital Gate, Suite 310, Oakville, ON, L7M 1M1

[2] Present address: Department of Psychology, Streatham Campus, University of Exeter, Exeter, United Kingdom, EX4 4QG

[3] Present address: Department of Sport and Health Sciences, St. Luke's Campus, University of Exeter, Exeter, United Kingdom, EX1 2LU

Structured Abstract

Objective: Observing experts constitutes an important and common learning experience for surgical residents before operating under direct guidance. However, studies suggest that exclusively observing experts may induce suboptimal motor learning, and watching errors from non-experts performing simple motor tasks may generate better performance. We investigated whether observational learning is transferrable to arthroscopy learning using virtual reality (VR) simulation.

Setting/Design: In our surgical simulation laboratory, we compared students learning basic skills on a VR arthroscopy simulator after watching an Expert video demonstration of VR arthroscopy tasks or a Non-Expert video demonstration of the same tasks to a Control group without video demonstration. Ninety students in three observing groups (Expert, Non-Expert, Control) subsequently completed the same procedure on a VR arthroscopy simulator. We hypothesized the Non-Expert-watching group would outperform the Expert-watching group, and both groups to outperform the Control group. We examined performance pre-test, post-test and one week later.

Participants: Participants were recruited from the final year of medical school and the very early first year of surgical residency training programs (orthopaedic surgery, urology, plastic surgery, general surgery) at Western University (Ontario, Canada).

Results: All participants improved their overall performance from pre-test to retention ($p<.001$). At initial retention testing, Non-Expert-watching group outperformed the other groups in Camera Path Length $p<.05$ and Time to completion, $p<.05$, and both the Expert/Non-Expert groups surpassed the Control group in Camera Path Length ($p<.05$).

Conclusion: We suggest that error-observation may contribute to skills improvement in the Non-Expert-watching group. Allowing novices to observe techniques/errors of other novices may assist internalization of specific movements/skills required for effective motor performances. This study highlights the potential impact of observational learning on surgical skills acquisition and offers preliminary evidence for peer-based practice (combined non-experts and experts) as a complementary surgical motor skills training strategy.

Key words:

Observational learning, motor learning, surgical simulation, arthroscopy, orthopaedic surgery, error observation.

ACGME competencies:

Patient Care, Practice Based Learning and Improvement

Source of Funding

This project was supported by a Physicians' Services Incorporated (PSI) Foundation grant. Funds were used to pay for salary and employee benefits (LvE). The PSI Foundation did not play a role in the investigation.

Introduction

Surgical skills training has a direct and significant impact on patients' well-being and quality of care [1, 2], as surgical outcomes directly relate to a surgeon's skills [3, 4]. Adequate training results in improved efficiency [4, 5], improved quality of surgery [6], superior outcomes [1, 4, 7], efficient use of healthcare resources [7], decreased complications [1, 4, 7-9] and reduced costs [1, 10].

Arthroscopy is a complex skill that can be challenging for trainees to learn efficiently in a busy teaching centre. Successful arthroscopists require excellent hand-eye coordination [11-13], three-dimensional visualization [12-14], knowledge of anatomy and pathophysiology, knowledge of different procedures, good surgical judgment and experience [13]. In contrast to laparoscopy, successful acquisition of arthroscopy skills presents challenges due to the constrained and variable surgical fields relative to the different joints, each with slightly differing morphologies and limited space available for maneuvering. In addition, the various patient positions that are used during arthroscopy can alter the learner's frames of reference [15, 16]. Because of this complexity, effective arthroscopic training is critical, as the learning curve is steep, the visuospatial demands for arthroscopy are high and trainees require many hours of practice and mentors' feedback to gain basic competence [17, 18].

Traditional surgical education practices, which continue to rely on the traditional apprenticeship model of instruction and the modus operandi: "See one, Do one, Teach one", are being scrutinized [19-21]. Changes in work hours, increased subspecialization and increased concerns about patient safety have motivated surgical educators to explore alternative educational strategies [22].

Recently, Wulf and colleagues [23] identified that observational practice, external focus of attention, feedback and self-controlled practice were, together, effective methods for enhancing motor skill learning in medical education. Learning through observation has been a growing area of interest in neuroscience and motor control literature [24]. Several studies have demonstrated that individuals may learn a variety of simple visuomotor skills by watching the skills being executed by another individual [25, 26]. Moreover, the processes that underlie this learning appear to be automatic, persistent and unaffected by distraction [25]. Recent unexpected evidence has shown that learning basic motor skills is enhanced by the observation of errors, rather than the observation of a flawless performance [27]. Brown and colleagues [28] demonstrated that observing trials which contained high degrees of error facilitated more rapid learning of a pointing task than observing trials which contained minimal error. Similarly, Buckingham et al. [27]demonstrated that individuals learn to apply the correct gripping and lifting forces to objects which have an unexpected weight after observing lifting errors, whereas they did not benefit from observing error-free lifts. The goal of the current study was to test these lab-based findings of error-based observational learning by introducing peer observation in the sensorimotor tasks of basic arthroscopic training.

Surgical learning needs innovative techniques to meet the modern challenges of skill acquisition. Learning by observation of error-laden performances done by other novices is a novel idea that contradicts the commonly held belief that motor skills are best learned by observing and imitating experts [28, 29]. The purpose of this study was to examine the learning of surgical skills by measuring and comparing basic arthroscopic skills performance on a VR surgical simulator by students who observed either an expert or non-expert demonstrating the task (Expert-watching or Non-Expert-watching), versus a control group who received no such intervention. We hypothesized enhanced learning and superior performance metrics of simulated knee arthroscopy following the observation of Non-Expert (high error) performance in comparison to the control group (no observation) or the observation of Expert (low error) performance.

Materials and Methods

Participants

Eligible participants were recruited from the final year of medical school and the very early first year of surgical residency training programs (orthopaedic surgery, urology, plastic surgery, general surgery) at Western University (Ontario, Canada). All subjects were between the ages of 18-40, spoke English fluently and were screened to ensure that they had no prior experience with arthroscopic surgery, endoscopic surgery or any form of surgical VR simulation. Most participants had baseline understanding of arthroscopic surgery, but had not seen or used the arthroscopic instruments or an arthroscopy simulator. The sample size was estimated from previously published study, which examined the effect of active observation on the learning of a simple motor task [27]. After informed consent, research assistants randomly assigned subjects to either the Expert-watching, or Non-Expert-watching groups by coin toss. A Control group was added later to account for the effect of practice alone without observational learning. The study included two testing sessions (see description in sections below). Session 1 included a pre-test (Test 1), intervention/rest and post-test (Test 2). Session 2 occurred one week later and included a retention test (Tests 3-4-5). The retention test was performed three times to evaluate the maintenance and recovery of skills after a resting period.

Simulator and Videos

The *insight*ARTHRO-VR (GMV, Spain, now called ArthroMENTOR, Symbionix, Ohio, USA) is a validated virtual-reality arthroscopy simulator that was used in the creation of the Non-Expert and Expert instructional videos (**see “Novice” and “Expert” videos**) and for data collection during this study [30-32]. This simulator uses phantoms of a leg and a shoulder as well as a set of instruments (camera, probe, shaver and grasper) that are very similar to real surgical instruments. The simulator’s library includes 40 knee and shoulder arthroscopy modules. The modules are designed to develop bimanual coordination and navigation skills by providing visual and haptic feedback and increasing task complexity. Variables and performance measures recorded by the simulator included: 1) Camera Path Length (distance covered by the camera, in millimeters [33]), 2) Camera Roughness (intensity of contact of camera with simulated tissues in newtons [33]), 3) Probe Path Length (distance covered by the probe, in millimeters [33]), 4) Probe Roughness (intensity of contact of probe with simulated tissues in newtons [33]) and 5) Time to Completion (seconds) [30, 34].

Video 1: Novice video

Video 2: Expert video

For this study, an introductory module, the “Knee -Diagnostic Arthroscopy - Locate and palpate” module, was selected for the creation of the instructional videos (Expert and

Non-Expert). The instructional videos provided a viewpoint that was akin to standing as a surgical assistant and displayed the hands of the surgeon on the arthroscope (camera) and probe, along with the patients' knee and the arthroscopy monitor (Figure 1). The arthroscope was held in the left hand (lateral portal), and a probe held in the right hand (medial portal) was used to palpate targets located in various locations throughout a right knee joint.

Subjects randomized to the Non-Expert-watching group observed a video of one of the authors (GB), an academic psychology researcher with no arthroscopic (simulated or real) training, completing the selected module on the simulator. Subjects randomized to the Expert-watching group were assigned to watch a video showing one of the authors (ML), an experienced fellowship-trained expert arthroscopist and expert on the simulator, completing the same task. The outcomes of both videos were the same and the module was completed but the performances were different: compared to the video of the Expert, the video of the Non-Expert was about three times longer (3 minutes-12 seconds vs 58 seconds). At times, the Non-Expert video demonstrated more erratic camera and probe motion, slower progression and inadequate visualization of both the probe and target. These translated in an increased camera and probe path length, increased camera and probe roughness, increased time to completion as well as the probe and target seen off center on the arthroscopy monitor.

Figure 1: Screenshot of a video watched by participants.

Testing sessions

Baseline knowledge disparities among subjects were addressed by providing all subjects with a standardized introduction on knee anatomy, an orientation to the simulator and tasks to perform and, most importantly, safe and efficient use of the arthroscope (rotating optics, triangulation, avoidance of collisions). The subjects were encouraged before each of the testing sessions to do the tasks efficiently, as accurately and as quickly as possible with no imposed time limit. To learn basic camera maneuvering techniques, a “warm-up” module entitled “Operating Room” followed the standardized introduction. This module provides standardized and scripted instructions (visible at the bottom of the simulator monitor) on the concepts of withdrawing the arthroscope to widen the field of view and on maintaining a leveled perspective for ease of safe and efficient navigation. After completion of the “Operating Room” module, all subjects received instruction on the use of an arthroscopic probe.

The knee arthroscopy module “Knee -Diagnostic Arthroscopy - Locate and palpate” was used for the pre-test (or Test 1) and all the subsequent tests (Tests 2-5). No assistance or feedback was provided during or after any trial and subjects were instructed to complete the tasks independently. The tasks were explicit and the trials were identical each time. Each test began with the leg in extension to allow the subject to place the arthroscope into the patello-femoral joint; then the knee was flexed for the remainder of the task. To successfully complete the task, subjects were prompted in a standardized manner by the simulator software to visualize and palpate targets (using the tip of the probe) in the patello-femoral groove, medial tibial plateau, trochlear notch, lateral tibial plateau, insertion of ACL and femoral attachment of the PCL. Targets responded to palpation by changing color, then disappearing and prompting instructions to locate the next target.

Following the pre-test, participants assigned to the Non-Expert-watching or Expert-watching video groups watched their respective demonstration video three times. To standardize the protocol, the same “Knee -Diagnostic Arthroscopy - Locate and palpate” module was watched. The Control group was given a period of rest instead of a video observation. After the playback of the three video demonstrations ended, participants completed the knee arthroscopy module once again (post-test, or Test 2). During each test, the spheres were located and presented in the same position, with a fixed path model, so that the sequence was not modified. Again, no feedback was provided to participants following the conclusion of the second testing session. Five to seven days following the first testing session, participants completed the retention test, consisting of three repetitions (Tests 3 to 5) of the same task, without video stimuli or feedback.

Outcomes

The primary outcome evaluated in this project was whether enhanced learning (i.e. improved performance and retention of skills) would occur following the observation of novice performance in comparison to the observation of expert performance. Trainee performance was assessed using validated performance measures generated by the VR simulator [30, 34].

Statistical Analysis

Subjects whose initial attempt at the task was outside 2.5 standard deviations from the mean of any performance measure for all subjects were removed as outliers from the final analysis. The data were initially examined with separate 3 (group membership) by 5 (testing session) mixed design ANOVAs for each dependent variable. Greenhouse-Geisser corrections were applied to account for inhomogeneity of the variance across sessions where necessary. To directly compare performance across the groups, the omnibus analyses were followed up with post-hoc one-way ANOVAs and independent samples 2-tailed t-tests at each level of the Testing Session variable.

Institutional ethics review was obtained prior to initiation of the study and informed consent was acquired from each participant.

Results

Ninety participants were recruited to take part in this study and were assigned to one of the three groups (Control, Expert-watching, and Non-Expert-watching). The demographics of all three groups were comparable. After removing the outliers (± 2.5 SD) from the data analysis, 28 subjects were left in both the Non-Expert-watching and Expert-watching video observation groups, and 26 subjects in the Control group (Table I).

Table I: Participants' demographic data.

	Non-Expert-watching group n = 28	**Expert-watching group n = 28**	**Control group n = 26**
Age (SD)	25.1 (3.86)	25.7 (2.4)	26.3 (4.6)
Sex	9 females 19 males	10 females 18 males	4 females 22 males
Hand Dominance	2 left 26 right	2 left 26 right	4 left 22 right
Days between sessions 1 & 2	5.5 (2.5)	6.1 (1.9)	5.5 (2.2)

We initially examined the change in participants' performance over the course of the five tests. All participants improved from Tests 1 to 5 in all measures, with significant main effects of testing session number for Camera Path Length (F(2.66,209.97)= 22.43; p<.001; Figure 2A), Camera Roughness (F(4, 316)= 11.07; p<.001; Figure 2B), Probe Path Length (F(2.75,217.41; Figure 2C)= 13.81; p<.001), and Time to Completion (F(2.66,210.49; Figure 2E)= 40.75; p<.001). Additionally, there was a modest significant main effect of Probe Roughness (F(3.55,280.65)= 2.46; p=0.05; Figure 2D). These findings, demonstrate that all participants significantly improved their performance on every measure provided by the simulator over the course of the multiple testing sessions. No significant Group x Testing session interactions were observed for any of the study variables (see Table II). However, as visual inspection of the plots showed that most of the significant improvements were observed between Tests 3 and 4, we undertook a series of planned comparisons to examine main effects at each level of the Testing session variable.

Figure 2. Participants' mean performance across all tests as a function of observation group. Error bars indicate standard error of the means. 2A) Camera Path Length; 2B) Camera Roughness; 2C) Probe Path Length; 2D) Probe Roughness; 2E) Time to Completion. Error bars indicate standard error of the means.

Table II: ANOVA summary table for the 3 (group membership) by 5 (testing session) mixed design ANOVAs for each dependent variable.

Variable	Testing session	Group x Testing session
Camera path length	F(2.7,209.9)=22.4, p<.001	F(5.3, 209.9)=1.2, p=.29
Camera roughness	F(4, 316)=11.1, p<.001	F(8, 316)=0.5, p=.85
Probe path length	F(2.8,217.4)=13.8, p<.001	F(5.5,217.4)=0.8, p=.84
Probe roughness	F(2.7,210.5)=2.5, p=.05	F(7.1,210.5)=0.4, p=.94
Time to completion	F(3.6,280.7)=40.7, p<.001	F(5.3,280.7)=1.0, p=.43

We then confirmed that all three groups were similar (demographics and pre-test VR performance metrics) at pre-test, before the video intervention. No main effect of group was found in Test 1 for any of the dependent variables (all p values > .25), with the exception of the Probe Path Length (F(2,79) = 5.36, p<.005; Figure 2C).

We subsequently studied group differences in the sessions following the video intervention (Tests 2, 3, 4, & 5). For this final analysis, we did not take into consideration the Probe Path Length variable as any further found differences may not have been due to the intervention and thus would have been difficult to interpret. In Test 2, we observed no significant effects for any dependent variables (all p values > .07). In Test 3, one week after the video intervention, we observed a significant effect for Camera Path Length based on group assignment (F(2,79)=3.1, p=.05; Figure 2A). Post-hoc analysis indicated that the Non-Expert-watching group outperformed both the Expert-watching (t(42.28)=2.05; p<.047) and Control (t(36.22)=2.45; p<.019) groups. No difference was observed between the Control group and the Expert-watching group (p=.55). Significant effects for Camera Path Length (Figure 2A) were also observed at both Test 4 (F(2,79)=7.1, p<.005), and Test 5 (F(2,79)=5.0, p<.01). These main effects (at Tests 4 and 5) were a consequence of the Control group being outperformed by the Non-Expert-watching (t(52)=2.16; p<.034; t(28.92)=2.44; p<.021) and Expert-watching groups (t(34.67)=3.67; p<.001; t(40.69)=2.36; p<.023). Finally, a significant group effect was observed for the Time to Completion variable in Test 4 (F(2,79) = 4.6, p<.037). As with the Camera Path Length variable, this effect was a consequence of the Control group being outperformed by the Expert-watching (t(52)=2.64; p<.011) and Non-Expert-watching (t(52)=1.99; p=.05) groups. No significant group effects were observed for Camera Roughness or Probe Roughness in any of the five tests and no other effects on Test 5 were significant.

Discussion

Surgery is a complex multi-step procedure that incorporates different cognitive processes. At early stages, those processes focus on the acquisition of motor skills. As Blandin et al. stated [35]: “it is generally agreed that the first determinant of motor learning is physical practice. However, physical practice is not always a suitable first step, nor is it always possible.” In line with previous literature on the effectiveness of video-based observational learning [36, 37], our study results emphasize the importance of combining the observation of others’ performance with dedicated practice of motor skills (in this study, repetition of skills without explicit feedback) to enhance the acquisition of surgical technical skills. Specifically, our study suggests that observing errors may provide learners with more useful visual information beyond that obtained by observing expert performance alone due to minimal variability from one expert performance to the next. Similar to findings in psychology [27-29, 38, 39], our study indicates that observation of both experts and non-experts results in improved performance over a control group [38, 39]. In particular, our study suggests potential benefits in learning motor skills by the observation of novice performance at the very early stages of the training. Junior trainees may benefit more from the observation of new tasks with error prone performance because it transmits important information about the coordination of unfamiliar movements or motor skills [40, 41]. In order to enable inexperienced trainees to recognize key features of specific motor tasks [35, 36, 42], observing others' performance and peer-to-peer practice may be worthwhile additions to current surgical teaching methods [23], particularly when the learning curve is steep [36, 41, 42].

An improvement in Camera Path Length at Test 3 by the Non-expert watching group that exceeded the improvements noted in both the Expert watching and control groups is the most significant and positive result of our study. While it is the main positive result in a stepwise comparison against both other groups, we feel that it is an indicator that the observation of errors can improve learning compared to standard methods of demonstration and observation. As novices learn arthroscopy, controlling the camera to visualize the appropriate target is the most fundamental skill, from which probe coordination and other bimanual skills are developed. For these reasons, we believe that specific improvements in Camera Path Length for the Non-Expert group are meaningful and important as the camera is always active and every movement is hence visible. In comparison, the probe can go out of the view of the camera field and its movements may or may not be visible at all times, therefore impacting the Probe Path Length and Probe Roughness. Improvements noted at Test 3 are also the most significant as they represent learning that has occurred and is maintained after a retention period, and are unlikely to be influenced/overwhelmed by the effects of repeated physical practice.

Furthermore, our data shows that study participants seemed to imitate components of surgical techniques or strategies displayed in either the Expert or Non-Expert videos, demonstrating that the observation of errors is not the only enhancer of surgical expertise. For example, Figure 2B shows an Expert-watching advantage for reducing Camera Roughness during the session immediately following the intervention (Test 2). The Expert video featured smooth, purposeful and accurate bimanual motion, which some of the subjects incorporated in order to maintain focus on the targets. This contrasts with the more random motion-based searching technique demonstrated in the Non-Expert video, where localization of the probe and target was attempted by visualizing a broader zone of interest, covering more distance with both the camera and probe, and inevitably making more contact with tissues, increasing the Camera Path Length as well as Camera and Probe Roughness. The simulator did not/could not capture all the nuanced actions that are potentially clinically important. Many of the measures were quite crude compared to, for example, the performance rating from an expert surgeon, but they have obvious face validity and capture many facets of good performance.

While this study did not permit us to offer firm conclusions regarding the hypothesis, it has provided some useful lessons to continue to build further research in the area, as follows. For instance, though we were able to determine that a beneficial learning effect occurs when novice trainees observe other novices, it is unknown which specific visual cues promoted the improvement in subjects' performance and why some measures have shown little difference. It is possible that the benefit observed is a result of the natural differences in the length of observation for each group. The duration of the Non-Expert demonstration was almost three times greater than the Expert demonstration, allowing more time to observe the dynamics of the task, the performance and the errors, and build an internal representation of the structure of the joint. Additionally, it is possible that "probing" is a task that may be more challenging for certain participants and may require more advanced skills because of its bimanual nature (holding the camera and maneuvering it at the same time as holding and maneuvering the probe), explaining the Probe Path Length differences. We also noted a practice effect, where the multiple repetitions of the tasks resulted in uniformly higher scores for Tests 4 and 5, limiting our ability to detect differences between the experimental groups (Expert, Non-Expert and Control).

Limitations of this study include the small number of participants per group relative to the high degree of variability in how participants could complete the tasks, as well as the different durations of the video demonstrations. Further investigations with larger groups are required to build upon the preliminary findings of this study, and better understand 1) how trainees can most effectively learn complex surgical skills through observation with or without feedback and 2) the informational content in each of the videos which had the greatest influence on the motor skills learning. By focusing on studying specific visual cues (e.g. field of view or camera roughness) or a variety of haptic feedback options, future studies will be able to control the duration of the visual exposure to better understand learning strategies during observation and promote faster skills' acquisition.

In the context of this experiment, what can be seen as “repeated learning activities” were actually “repeated testing sessions”. Study participants probably learned because of the multiple testing sessions, and we fully acknowledge that physical practice with feedback would lead to far more consistent improvements than through sole observation of either expert or novice video models. Additionally, giving no feedback and having a one-week gap between Tests 2 and 3 may have minimized “learning through repetition” and focused on “learning through observation” in Test 3. Rather than suggesting that observational learning, combined with repetition of surgical skills without feedback is “best practice”, this project explored one possible supplementary training method to assist surgical skills training.

In conclusion, with high costs of surgical training and time pressure from restricted work hours, more efficient and cost-effective ways to train residents are necessary [23, 43, 44]. Is observational learning a useful teaching method for novice arthroscopists? The answer is: “probably”. Observational learning from models with a range of skillsets, combined with physical practice/repetition without feedback, may improve the training of basic surgical skills that are difficult to learn. This exploratory project is one of the few surgical studies that suggest that conventional teaching of surgical skills could benefit from the addition of observation of a novice committing errors. This counterintuitive finding may have an impact on surgical training, redefining how surgical skills are taught. Complementary to current apprenticeship training methods, improvements in performance may be hastened by observing other individuals who are also at early training stages to provide a basis for comparison between experts and non-experts. These preliminary findings may be valuable and may lead to improvements in teaching surgical skills that involve the learning of bimanual coordination of endoscopic instruments. Gains in surgical skills acquisition can certainly be made outside the operating room with simulation-based training, and further research is necessary to explore the value of implementing cost-effective, efficient peer learning and observational learning to improve surgical skills.

Bibliography

1. Barnes, R.W., *Surgical handicraft: teaching and learning surgical skills.* Am J Surg, 1987. **153**(5): p. 422-7.
2. Scalese, R.J., V.T. Obeso, and S.B. Issenberg, *Simulation technology for skills training and competency assessment in medical education.* J Gen Intern Med, 2008. **23 Suppl 1**: p. 46-9.
3. Chami, G., et al., *Haptic feedback can provide an objective assessment of arthroscopic skills.* Clin Orthop Relat Res, 2008. **466**(4): p. 963-8.
4. Birkmeyer, J.D., et al., *Surgical skill and complication rates after bariatric surgery.* N Engl J Med, 2013. **369**(15): p. 1434-42.
5. Reznick, R.K. and H. MacRae, *Teaching surgical skills--changes in the wind.* N Engl J Med, 2006. **355**(25): p. 2664-9.
6. Sutton, D.N., J. Wayman, and S.M. Griffin, *Learning curve for oesophageal cancer surgery.* Br J Surg, 1998. **85**(10): p. 1399-402.
7. Sosa, J.A., et al., *The importance of surgeon experience for clinical and economic outcomes from thyroidectomy.* Ann Surg, 1998. **228**(3): p. 320-30.
8. Tashiro, Y., et al., *Evaluation of skills in arthroscopic training based on trajectory and force data.* Clin Orthop Relat Res, 2009. **467**(2): p. 546-52.
9. Puhaindran, M.E., et al., *Wrist arthroscopy: beware the novice.* J Hand Surg Eur Vol, 2009. **34**(4): p. 540-2.
10. Ziv, A., et al., *Simulation-based medical education: an ethical imperative.* Acad Med, 2003. **78**(8): p. 783-8.
11. Barrett, D.S., R.G. Green, and S.A. Copeland, *Arthroscopic and endoscopic skills: a method of assessment.* Ann R Coll Surg Engl, 1991. **73**(2): p. 100-4.
12. Hanna, G.B., S.M. Shimi, and A. Cuschieri, *Randomised study of influence of two-dimensional versus three-dimensional imaging on performance of laparoscopic cholecystectomy.* Lancet, 1998. **351**(9098): p. 248-51.
13. Alvand, A., et al., *Innate arthroscopic skills in medical students and variation in learning curves.* J Bone Joint Surg Am. **93**(19): p. e115(1-9).
14. Ghandi, A. *Arthroscopy Skills test.* [cited 2012 June 30th]; Available from: http://www.shoulderdoc.co.uk.
15. Byrd, J.W., *Hip arthroscopy by the supine approach.* Instr Course Lect, 2006. **55**: p. 325-36.
16. Keren, E., et al., *[Wrist arthroscopy].* Harefuah, 2008. **147**(5): p. 428-32, 477.
17. Pedowitz, R.A., J. Esch, and S. Snyder, *Evaluation of a virtual reality simulator for arthroscopy skills development.* Arthroscopy, 2002. **18**(6): p. E29.
18. Gallagher, A.G., et al., *Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training.* Ann Surg, 2005. **241**(2): p. 364-72.
19. Carter, B.N., *The fruition of Halsted's concept of surgical training.* Surgery, 1952. **32**(3): p. 518-27.
20. Wigton, R., *See one, do one, teach one.* Academic Medicine, 1992. **67**: p. 743.
21. Torkington, J., et al., *The role of simulation in surgical training.* Ann R Coll Surg Engl, 2000. **82**(2): p. 88-94.

22. Michelson, J.D., *Simulation in orthopaedic education: an overview of theory and practice.* J Bone Joint Surg Am, 2006. **88**(6): p. 1405-11.
23. Wulf, G., C. Shea, and R. Lewthwaite, *Motor skill learning and performance: a review of influential factors.* Med Educ, 2010. **44**(1): p. 75-84.
24. Malfait, N., Valyear, K.F., Culham, J.C., Anton, J-L., Brown, L.E., & Gribble, P.L. , *fMRI activation during observation of others' reach errors.* . Journal of Cognitive Neuroscience, 2009. **22**: p. 1493-1503.
25. Mattar, A.A. and P.L. Gribble, *Motor learning by observing.* Neuron, 2005. **46**(1): p. 153-60.
26. Trempe, M., Sabourin, M., Rohbanfard, H., & Proteau, L., *Observation learning versus physical practice leads to different consolidation outcomes in a movement timing task.* Experimental Brain Research, 2011. **209**: p. 181-192.
27. Buckingham, G., et al., *Observing object lifting errors modulates cortico-spinal excitability and improves object lifting performance.* Cortex, 2014. **50**: p. 115-24.
28. Brown, L.E., et al., *Effect of trial order and error magnitude on motor learning by observing.* J Neurophysiol, 2010. **104**(3): p. 1409-16.
29. Xeroulis, G.J., et al., *Teaching suturing and knot-tying skills to medical students: a randomized controlled study comparing computer-based video instruction and (concurrent and summary) expert feedback.* Surgery, 2007. **141**(4): p. 442-9.
30. Bayona, S., Fernandez-Arroyo, J.M., Martın, I., Bayona, P., *Assessment study of insightARTHRO VR arthroscopy virtual training simulator: face, content, and construct validities.* J Robotic Surg, 2008. **2**: p. 151–158.
31. Martin, K.D., et al., *Arthroscopic basic task performance in shoulder simulator model correlates with similar task performance in cadavers.* J Bone Joint Surg Am, 2011. **93**(21): p. e1271-5.
32. Martin, K.D., et al., *Shoulder arthroscopy simulator performance correlates with resident and shoulder arthroscopy experience.* J Bone Joint Surg Am, 2012. **94**(21): p. e160.
33. *ARTHRO Mentor*, 2012, Symbionix Ltd. p. 2.
34. Funk, L., Awan, A., Gandhi, M. *Validation of a virtual reality arthroscopic shoulder simulator*. Validation studies-abstracts ArthroMentor, 2007.
35. Blandin, Y., Lhuisset, L., Proteau, L., *Cognitive Processes Underlying Observational Learning of Motor Skills.* The Quarterly Journal of Experimental Psychology, 1999. **52A**(4): p. 957-979.
36. Blandin, Y. and L. Proteau, *On the cognitive basis of observational learning: development of mechanisms for the detection and correction of errors.* Q J Exp Psychol A, 2000. **53**(3): p. 846-67.
37. Anthony G. Gallagher, G.C.O.S., *Human Factors in Acquiring Medical Skills; Learning and Skill Acquisition in Surgery*, in *Fundamentals of Surgical Simulation: Principles and Practice*. 2012, London : Springer-Verlag London Limited. p. 89-121.
38. Rohbanfard, H. and L. Proteau, *Learning through observation: a combination of expert and novice models favors learning.* Exp Brain Res, 2011. **215**(3-4): p. 183-97.
39. Andrieux, M. and L. Proteau, *Observation learning of a motor task: who and when?* Exp Brain Res, 2013. **229**(1): p. 125-37.

40. Grierson, L.E., et al., *The role of collaborative interactivity in the observational practice of clinical skills.* Med Educ, 2012. **46**(4): p. 409-16.
41. Ashford, D., S.J. Bennett, and K. Davids, *Observational modeling effects for movement dynamics and movement outcome measures across differing task constraints: a meta-analysis.* J Mot Behav, 2006. **38**(3): p. 185-205.
42. Scully, D.M., & Newell. K.M., *Observational learning and the acquisition of motor skills: Towards a Visual Perception perspective.* Journal of Human Movement Studies, 1985. **11**: p. 169-186.
43. Atesok, K., et al., *Surgical simulation in orthopaedic skills training.* J Am Acad Orthop Surg, 2012. **20**(7): p. 410-22.
44. Pedowitz, R.A. and J.L. Marsh, *Motor skills training in orthopaedic surgery: a paradigm shift toward a simulation-based educational curriculum.* J Am Acad Orthop Surg, 2012. **20**(7): p. 407-9.