Winner of the Scientific Exhibit Award of Excellence
2014 AAOS Meeting
New Orleans, LA

A Cost-Effective Junior Resident Training and Assessment Simulator for Orthopaedic Surgical Skills via Fundamentals of Orthopaedic Surgery (FORS)

Gregory Lopez, MD[a]; Rick Wright, MD[d]; David Martin, MD[e]; James Jung, BS[a]; Dan Bracey, MD[e]; Ranjan Gupta, MD[a,b,c*]

[a]Department of Orthopaedic Surgery
[b]Department of Biomedical Engineering
[c]Department of Anatomy and Neurobiology
University of California, Irvine, CA, 92697, USA

[d]Department of Orthopaedic Surgery
Washington University in St. Louis, St. Louis, MO, USA

[e]Department of Orthopaedic Surgery
Wake Forest University, Winston-Salem, NC, USA

Corresponding author:
Ranjan Gupta, MD
Department of Orthopaedic Surgery
University of California, Irvine
2226 Gillespie Neuroscience Research Facility
Irvine, CA 92697
Tel: 949.824.1405
Fax: 949.824.1462
E-mail: ranjang@uci.edu

Abstract

Background: Psychomotor testing has been recently incorporated into residency training programs to not only objectively assess a surgeons' abilities, but also to address current patient-safety advocacy and medico-legal trends. To date, orthopaedic surgery does not have a standardized, cost-effective psychomotor assessment tool that teaches basic orthopaedic motor skills that translate across a wide variety of operations. The purpose of this study was to develop and test a cost-effective psychomotor training and assessment tool— The Fundamentals of Orthopaedic Surgery (FORS) — for orthopaedic surgery junior resident education.

Methods: An orthopaedic skills board was made from supplies purchased at a local hardware store with total costs less than $350 so as to assess six different psychomotor skills. The six skills included fracture reduction, drill accuracy, simulated fluoroscopy-guided drill accuracy, depth-of-plunge-minimization, drill-by-feel accuracy, and suture speed and quality. Medical students, residents, and attending physicians from three ACGME accredited orthopaedic surgery residency programs participated in the study. At each program, replica FORS boards were built from local hardware stores. Additionally, twenty-five medical students were retained for longitudinal training and testing for 4 weeks. Each training session involved an initial exam followed by 30 minutes of board training. Time to perform each task was measured with accuracy measurements for the appropriate tasks. Statistical analysis was done with a one way ANOVA with significance set at $p<0.05$.

Results: 47 Medical students, 29 Attending physicians, and 58 Orthopaedic surgery residents participated in the study. Stratification between medical students, junior level residents, and senior level residents/attending physicians was found in five of the six categories. The twenty-five medical students who were retained for longitudinal training improved significantly above junior resident level in four of the six tasks.

Conclusions: The Fundamentals of Orthopaedic Surgery is an effective simulator of basic motor skills that translates across a wide variety of operations, and has the ability to train junior level participants to senior resident skill level.

Clinical Significance: The Fundamentals of Orthopaedic Surgery has demonstrable construct validity and may serve as a valuable tool for resident education.

Introduction

Significant changes to the classic models of surgical education and training are required secondary to an increased focus on patient safety, expanded skill requirements, restricted work hours, and financial constraints. To address some of these issues, several surgical specialties have adopted new educational modalities, including on-line curricula and surgical simulation, to educate and train residents in a safe, efficient, and cost-effective manner. [1,2] Surgical simulation has the promise to be an effective tool in resident education as it offers repetitive psychomotor training and immediate objective feedback in a learner–centered, risk-free environment.

Orthopaedic surgery simulation currently includes cadaveric labs, synthetic bone exercises, and virtual reality simulators that are costly and unaffordable for many residency programs. To circumvent this issue, our general surgery colleagues have successfully pioneered training tools that utilize low cost components to simulate real world exercises. The Fundamentals of the Laparoscopic Surgery (FLS) is a validated, cost-effective surgical simulation tool that trains and assesses residents' psychomotor skills in a variety of laparoscopic procedures. Moreover, there has been a recent push amongst other surgical disciplines to develop similar specialty-dependent training modalities to encourage early psychomotor skills and provide an objective measure for resident competency. [3,4] For example, urology has developed a cost-effective and risk-free simulator that is accessible to both small and large programs.

Orthopaedic surgery has followed the example of its surgical colleagues by both recognizing the need for increased patient safety[5] and realizing the utility and necessity of surgical simulation.[6,7] Most notably, the American Board of Orthopaedic Surgery has implemented surgical skills training modules for all first year orthopaedic surgery residents. Although recent studies have focused attention on surgical simulation in orthopaedic surgery,[8,9,10,11,12,13] there is currently no accepted standardized training and assessment tool analogous to general surgery's FLS program. The purpose of this study was to create and evaluate a cost effective, standardized resident training and assessment tool for orthopaedic surgery.

Materials & Methods

All procedures involving live human subjects was approved by the Institutional Review Board of the University of California, Irvine, Washington University in St. Louis, and Wake Forest University.

Development of FORS.

A questionnaire was initially distributed to twelve, board-certified (ABOS) orthopaedic surgeons. This survey aimed to identify the most essential skills that were necessary to become a competent orthopaedic surgeon (Figure 1). Once the surveys were completed, a surgical skills training (FORS) board was constructed to include the six basic and essential tasks previously identified and to assess these skills (Figure 2). The FORS board was constructed from supplies that were purchased at local hardware and home-improvement stores at a total cost of approximately $350. Although assembly of the FORS board is necessary, it is achievable with minimal effort in a reproducible manner. Each task sought to maximize operative face validity and content validity, as well as create a quantifiable and reproducible way of judging the participants performance. The six psychomotor tasks developed include simulation of the following: (1) fracture reduction, (2) minimizing drill depth of plunge, (3) drilling by haptic feedback (i.e. drill-by-feel), (4) fluoroscopy, (5) correct lag screw placement/3D drill control, and (6) suturing.

Description of FORS Tasks.

Fracture Reduction. The fracture reduction exercise utilizes a PVC-pipe with an obliquely-oriented chevron fracture. The PVC-pipe is mounted to a table vise grip on each end. Moreover, one of the table vise grips is placed on a translational board to allow for sliding. As such, these components allow for shortening and rotational forces to be applied to the simulated fracture (Figure 3). Fracture reduction clamps were utilized for the exercise. This exercise was timed until a successful reduction was completed with a maximum time of 240 seconds allowed.

Depth of Plunge. The depth-of-plunge-minimization task was created to simulate a soft tissue-bone interface by using a PVC pipe and a foam block as a backstop. The participant drills five consecutive holes through the PVC pipe, minimizing their plunge though the foam (Figure 4). The exercised is timed and penalized based on the depth of plunge in mm.

Drill by Feel. The drill-by-feel accuracy task simulates drilling in the absence of direct visualization of a target such as in external fixator pin placement. A flat 3.8cm wide board with a line bisecting the width was wrapped cylindrically with foam, thus hiding the board, and was mounted to the FORS testing board. The participants must use only the drill bit to accurately assess the center of the wooden board (Figure 5). This task was timed and penalized based on distance from the center of the board.

Fluoroscopy. The fluoroscopy simulation task requires the participant to aim a drill bit through a pre-marked 3.8cm thick block of wood with color-coordinated visible entry points vertically and horizontally (Figure 6). The participant triangulates the covered exit point by using color-coordinated guide-marks on perpendicular planes of the block. This exercise was timed and penalized based on the exit point’s distance from the pre-marked location. This task highlights the importance of using fluoroscopy to properly triangulate a point that cannot be visualized.

3D Drilling. The 3D drilling and lag screw placement task requires participants to aim a drill bit through a 3.8cm block of wood with three different color-coordinated entry and exit points (Figure 7). In this task, each color is drilled individually, with planning for each screw allowed. This exercise was timed and penalized based on the exit point’s distance from the pre-marked location. This tasks mimics correct lag screw placement.

Suturing. Suture speed and quality were assessed by giving each participant 240 seconds to place as many simple, interrupted sutures into a PVC-mounted foam incision (Figure 8). Sutures were required to have three throws per knot via instrument ties, as well as self-cutting and reloading of the suture. Only sutures were able to hold tension without unraveling were counted, although closure and approximation of the incision were not required. Scores were recorded as numbers of sutures.

Scoring. Each exercise was scored based on efficiency (time) or efficiency and accuracy (penalty). A maximum time was given for each task. A time score was calculated by subtracting the participant's time from the maximum time. Accuracy was assessed based on measured distances (in mm) from the desired point and multiplied by a constant factor. The accuracy score was subtracted from the time score to give the final result. When a negative score was received a recording of zero was used.

Forty-seven medical students, fifty-eight orthopaedic surgery residents, and twenty-nine attending orthopaedic surgeons from three ACGME accredited orthopaedic surgery residency programs participated in the study. At each training site, replica FORS boards were built from local hardware stores. Additionally, twenty-five medical students were retained for longitudinal training and testing weekly for 4 weeks. Each training session was thirty minutes long and instructed by a senior level orthopaedic surgery resident. Data is presented as the mean and standard error. One-way analysis of variance with Bonferroni post hoc comparison was performed unless otherwise indicated. A p value of < 0.05 was considered significant.

Results

Survey Results

Based on the questionnaire answered by orthopaedic surgeons (Figure 1), the highest rated skills necessary for a competent orthopaedic surgeon were: fracture reduction, minimizing depth of plunge, drilling by tactile feedback, directional control of the drill, fluoroscopic drilling, correct lag screw placement, and soft tissue closure. These skills were thought to be applicable across a wide variety of orthopaedic operations and sub-specialties. As a result of this questionnaire and survey, the Fundamentals of Orthopaedic Surgery (FORS) surgical skills board was created to incorporate these tasks for training and evaluation (Figure 2).

Fracture Reduction

Untrained medical students had difficulty reducing the fracture as compared to all other participants (98.78 ± 11.6; $p < 0.0001$; Table 1; Figure 9A). Furthermore, junior residents performed significantly slower than senior level residents (191.60 ± 6.18 vs. 219.80 ± 2.09; $p = 0.003$). Trained medical students significantly improved their scores and were also improved as compared to junior level residents (213.10 ± 8.55 vs. 191.60 ± 6.18; $p < 0.05$). For the fracture reduction exercise, novice participants were able to achieve scores significantly better than junior level residents and on par with senior level residents after four weeks of training.

Depth of Plunge

Novice medical students scored significantly lower than all groups when performing this task (9.10 ± 2.10; $p < 0.0001$; Table 1; Figure 9B). In addition, junior level residents scored significantly lower than senior level residents (24.50 ± 4.82 vs. 50.68 ± 4.05; $p < 0.0001$). Similarly, trained medical students were able to score significantly better than junior residents as well, with scores on par with senior level residents (46.78 ± 3.53; $p < 0.001$).

Drill by Feel

Medical students were initially unable to drill by tactile feedback accurately, and therefore, scored significantly below all other participants (20.91 ± 3.28; $p < 0.0001$; Table 1; Figure 9C). Moreover, senior level residents significantly outperformed junior residents in this task (62.90 ± 3.33 vs. 42.14 ± 3.66; $p < 0.001$). Similarly, once medical students were trained on how to perform this task properly, they scored significantly higher than junior level residents (65.32 ± 3.51; $p < 0.0001$). In fact, their score was higher than senior level residents as well.

Fluoroscopy

Medical students and junior residents scored significantly lower than senior residents (13.35 ± 2.12 & 10.22 ± 2.41 vs. 26.84 ± 2.90; $p < 0.01$; Table 1; Figure 9D). However, trained medical students were able to improve their scores significantly, not only above junior residents, but senior residents as well (39.10 ± 3.79; $p < 0.05$).

3D Drilling

On initial testing, both medical students and junior residents were significantly outperformed by senior residents (30.47 ± 2.74 & 35.52 ± 3.77 vs. 51.57 ± 1.88; $p < 0.01$; Table 1; Figure 9E). However, in this task, even when medical students were trained, they were unable to significantly improve their scores (39.80 ± 3.44). Thus, it is likely that certain tasks are unable to be replicated and simulated outside of real word experience and procedures.

Suturing

Upon initial assessment of medical students on their suturing ability, most students had not been previously taught how to properly suture and instrument tie. As such, medical students performed significantly lower than all other groups of participants (2.94 ± 0.27; $p < 0.0001$; Table 1; Figure 9F). Moreover, junior residents were able to tie significantly fewer sutures than senior residents in the allotted time period (7.47 ± 0.36 vs. 10.6 ± 0.31; $p < 0.0001$). After medical students were trained in proper suturing techniques, they were able to significantly improve their scores to the level of junior residents (7.27 ± 0.34).

However, they were unable to reach the levels of senior residents. Again, this is likely due to the experience residents gain in suturing throughout the operating room experience and this skill likely requires a longer time period to improve to that upper echelon of scores.

Discussion

The current medico-legal climate and public perception of patient safety all restrict the ability of the junior resident to learn basic operative skills inside the operating room (OR). As such, it is critical that there is appropriate training outside of the OR in a simulated and risk-free environment. [14,15,16,17] In regards to orthopaedic surgery, a simulator is an ideal tool for hands on learning. Simulation allows for repetitive practice of a particular skill with immediate feedback. As the task is repeated over an extended period of time, long-term structural modifications occur in the brain. [18,19] Furthermore, simulation allows for regular interval training to accelerate acquisition of correctly performed motor skills, thereby, increasing the learner's ability to retain those skills and building learner confidence in a low stress environment. [20,21]

There is ample evidence in surgical sub-specialties to support surgical simulation for the learning and acquisition of new skills as well as improving operative performance. In regards to simulation for orthopaedic surgery, there are a small number of virtual reality simulators outside of standard cadaver labs and synthetic bone exercises. [22,23] However, most programs do not have significant disposable income and must carefully scrutinize each training tool to determine if it will be maximally beneficial to resident education.

The FORS simulator was developed to help increase junior level resident practice of relevant orthopaedic tasks in a cost-effective manner and thereby allow universal access to all residents. The overall importance of the FORS simulator is that it allows for multiple repetitions of important orthopaedic skills in a short period of time with objective feedback. As many junior residents may have had limited access to an operative drill while on an orthopaedic surgery rotation, they will be able to perform multiple repetitions pertinent motor skills with minimal time investment with the use of this simulator. Once developed at a site, this simulator is available for use at any hour of the day and thereby allows residents to train at their own pace in a low stress environment.

The strength of the FORS simulator is the ability to train novice participants to improve above junior resident level performance on the simulator (PGY1 and 2). Although medical students had initially scored significantly lower than our more senior cohorts, our trained medical student data demonstrates overall improvement, as well as, significant improvement above junior resident level scores in four out of six exercises with only four weeks of training in short regular intervals. The two tasks that did not reach significance were three dimensional drill control and suturing. The three dimensional drilling task, although did not achieve significance, did trend in the overall correct alignment and significant scores would likely be achieved if the training period extended beyond the four-week block used in this study. Suturing, a task commonly performed by junior level residents, was the one of two tasks that the medical students were unable to improve beyond. This was expected as junior residents routinely suture in the operating room.

An important subjective observation was that our medical students confidence level in handling the drill and the other operative instruments was readily apparent. At the initial testing and training sessions for our novice cohort, they subjectively appeared timid and unsure as many had limited previous experiences with using a drill despite being Orthopaedic Surgery applicants. With short regularly spaced training modules, their confidence and ability to correctly perform drill control exercises had significantly increased.

Face validity, the ability for the simulator to contain realism, was most tested with the use of materials purchased from national hardware stores. Many of the tasks involve drilling through a material that is not hollow and does not contain the same density or thickness as bone. This distracts from a realistic operating room experience. Although cylindrical objects were used initially on most of the tasks, no significant accuracy difference was able to be ascertained. The blocks of wood help increase distance as well as increase participant error allowing for stratification within our testing population. The principles of triangulation and drilling which include spatial awareness and co-axial movements with the drill bit are maintained with these exercises. Also, with the use of these materials, the simulator cost is below $350, and all parts of each task are able to be resupplied at national hardware stores allowing for unlimited repetitions.

Lastly, although we had 130 total participants, the medical student group was the largest at 47. In order to draw more significant conclusions, higher numbers will need to be obtained. In regards to our attending physician population, nearly all of the attendings at each institution participated (those who were not available were not tested), however there were no community physicians within the testing group.

In conclusion, the Fundamentals of Orthopaedic Surgery Simulator (FORS), which includes six psychomotor tasks that cross over a multitude of orthopaedic surgeries, objectively demonstrated that attending physicians and senior level residents performed on average at a higher level junior level residents and novice medical students. Longitudinal training of medical students demonstrated this could be an important training tool for resident education. Ultimately, it is our hope that junior level orthopaedic surgery residents learn motor skills intrinsic to orthopaedic surgery on low cost simulators prior to operating on patients.

Acknowledgements

We would like to thank Nathanael Heckmann for his contributions in the initial data gathering for the project.

Figure 1:

FUNDAMENTALS OF ORTHOPAEDIC SURGERY

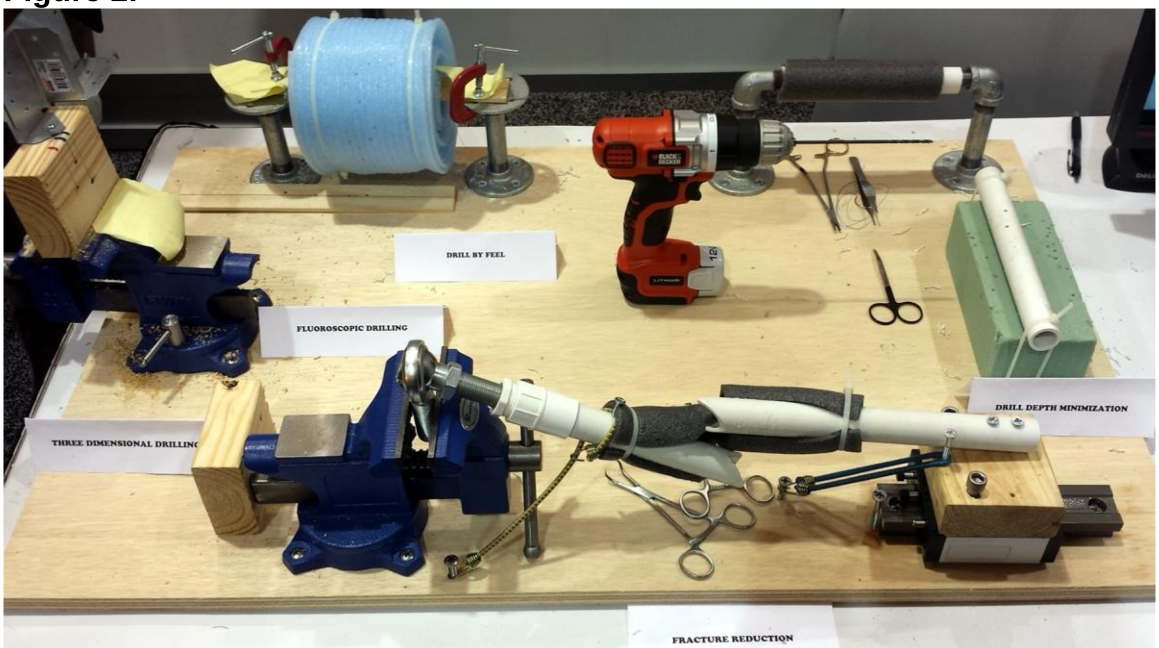
Thank you for taking part in our survey. The goal of this survey is to utilize your input to help build a curriculum in order to improve resident education and knowledge base. Please take the time to fill out the questionnaire below.

Name:
University Affiliation:
Position:

In order to provide quality patient care, what level of intraoperative skill proficiency is required for the graduating Orthopaedic Surgery resident to have in each of the following areas?
1 = Skill is mastered, able to provide guidance to others
3 = Able to perform task independently, but will occasionally need assistance
5 = Understands basic techniques/knowledge, but needs help performing task

Category: Surgical Skills	Value				
	Mastered		Intermediate		Novice
Patient Positioning	1	2	3	4	5
Correct placement of incision	1	2	3	4	5
Scalpel control	1	2	3	4	5
Soft tissue dissection of vessel/nerve	1	2	3	4	5
Fluoroscopy comprehension	1	2	3	4	5
Reduction techniques	1	2	3	4	5
Drill control under fluoroscopic view	1	2	3	4	5
Correct placement of lag screw	1	2	3	4	5
Drill control with lag screw placement	1	2	3	4	5
Appropriate placement/alignment of plate	1	2	3	4	5
Appropriate plating technique for fracture (Neutralization, bridging, etc.)	1	2	3	4	5
Intramedullary canal reaming/preparation	1	2	3	4	5
Appropriate blocking screw placement	1	2	3	4	5
Limiting plunge while drilling	1	2	3	4	5
Drilling by tactile feedback (Only able to feel drill location)	1	2	3	4	5
Spatial understanding of drill trajectory	1	2	3	4	5
Suture needle control	1	2	3	4	5
Able to perform tasks with both hands	1	2	3	4	5
Approximation of tissue	1	2	3	4	5

Figure 2:



The FORS training and testing board, consisting of six individual drills: fracture reduction (bottom right), drill accuracy (Bottom left), fluoroscopy simulation (left), drill-by-feel (top left), suture speed (top right), and depth-of-plunge minimization (right)

Figure 3:

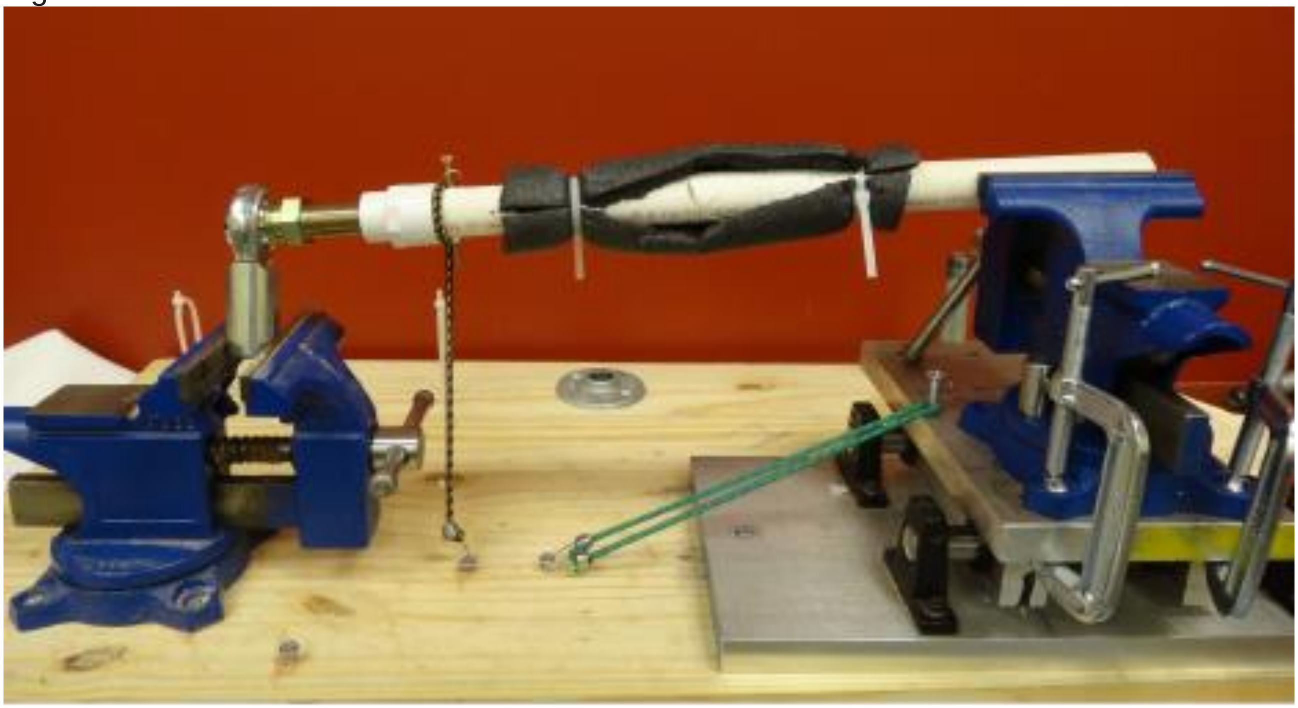


Figure 4:

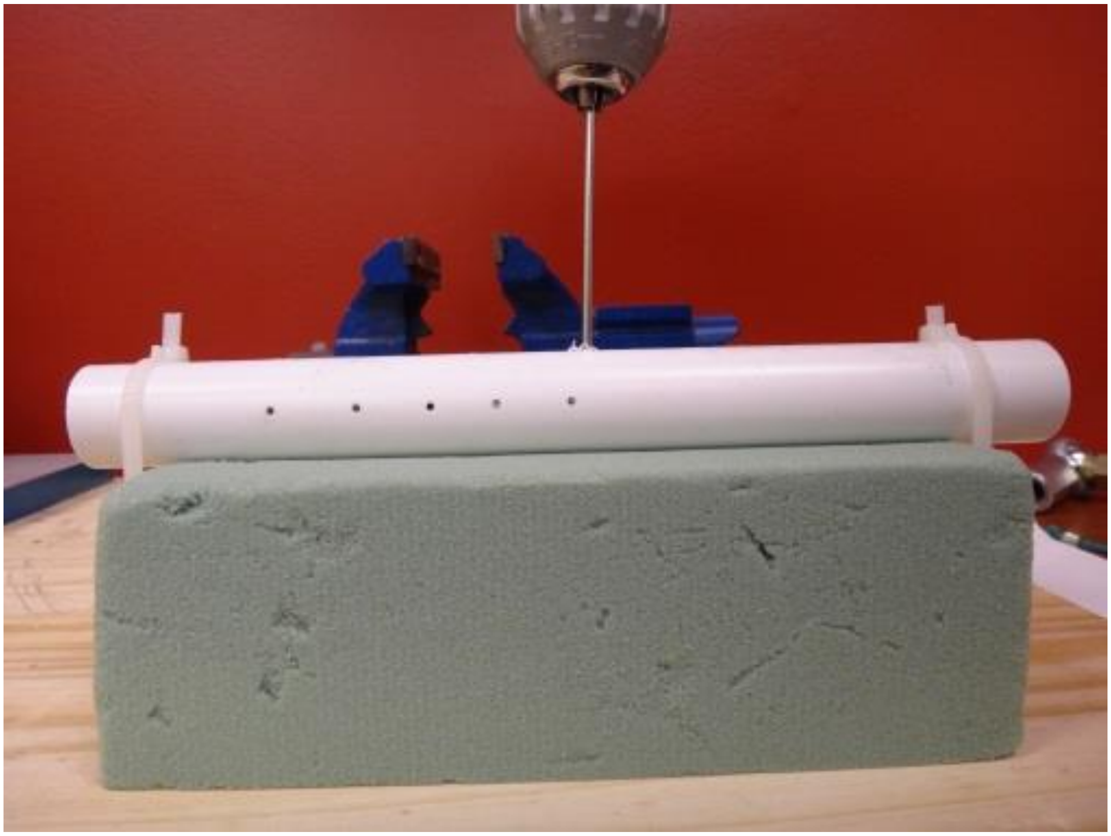


Figure 5:

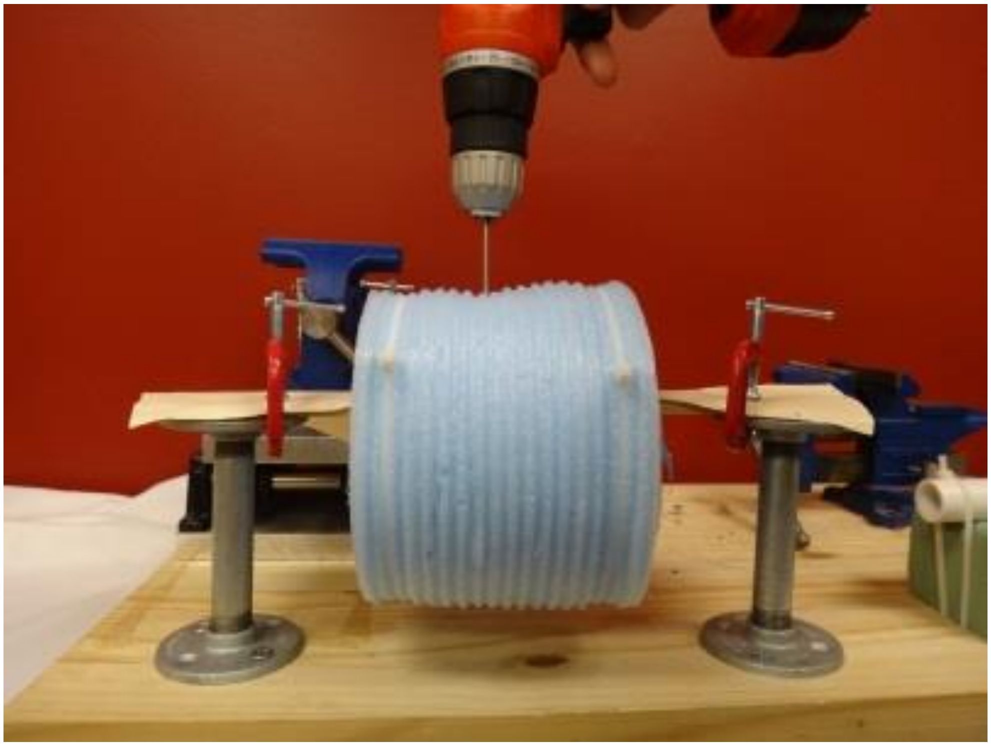


Figure 6A:

Figure 6B:

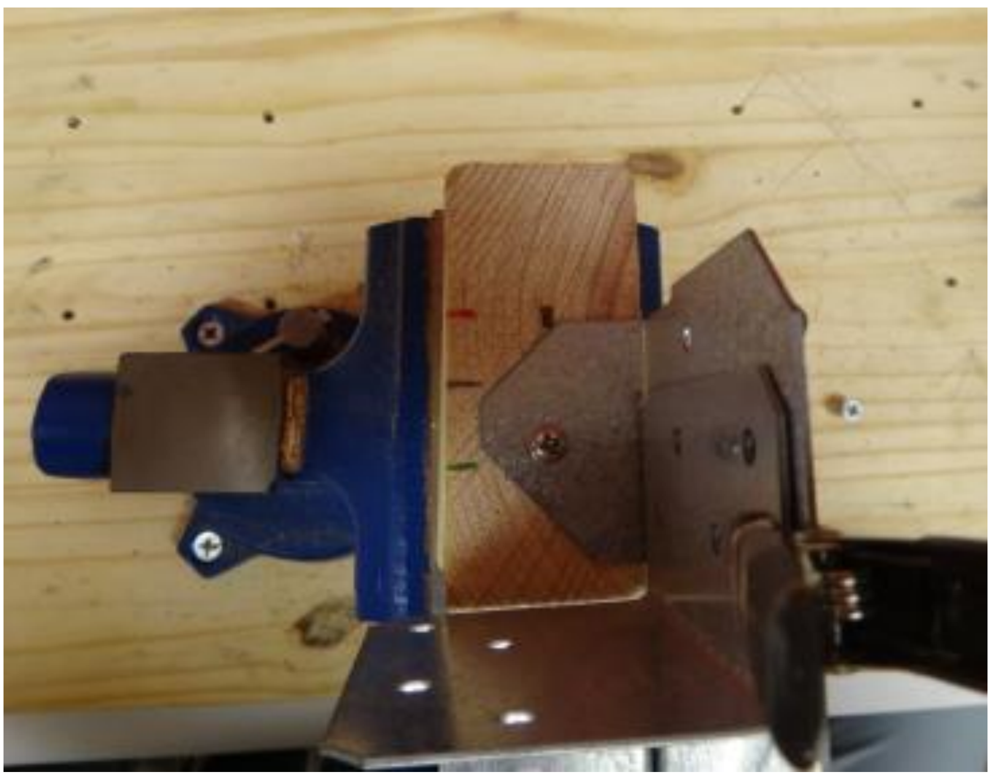
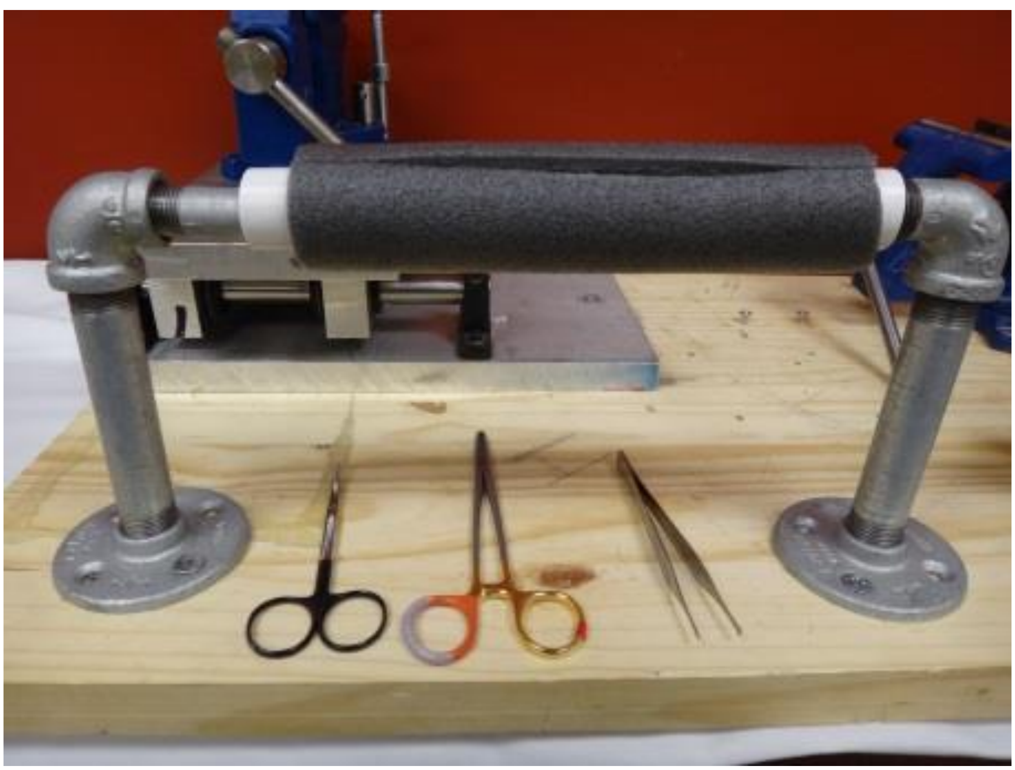


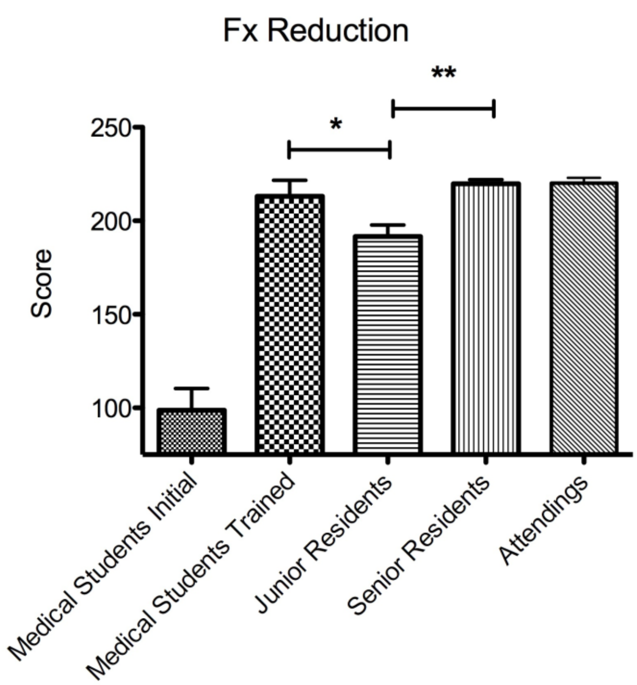
Figure 7:

Figure 8:



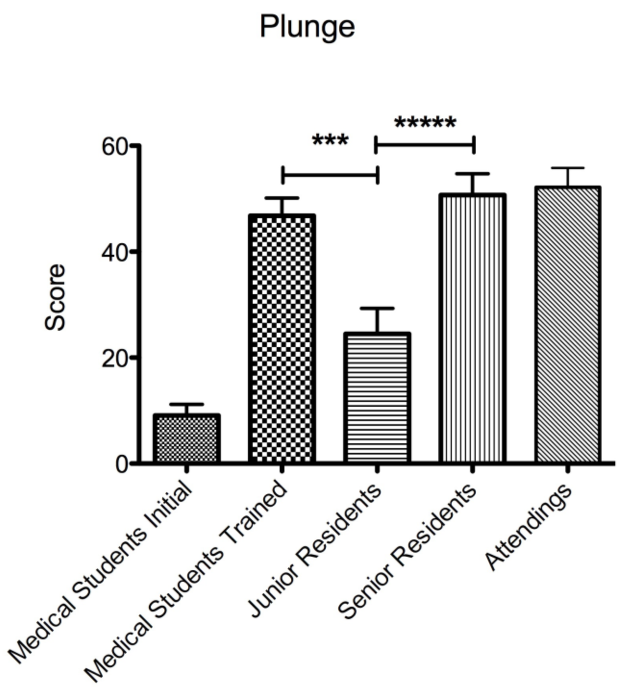
	Medical Students	Medical Students Trained	Junior Residents	Senior Residents	Attending Physicians
Fracture Reduction	98.78 ± 11.6	213.10 ± 8.55	191.60 ± 6.18	219.80 ± 2.09	220.10 ± 2.87
Depth of Plunge	9.10 ± 2.10	46.78 ± 3.53	24.50 ± 4.82	50.68 ± 4.05	52.14 ± 3.67
Drill by Feel	20.91 ± 3.28	65.32 ± 3.51	42.14 ± 3.66	62.90 ± 3.33	53.95 ± 4.13
Fluoroscopy	13.35 ± 2.12	39.10 ± 3.79	10.22 ±2.41	26.84 ±2.90	25.14 ±3.73
3D Drilling	30.47 ± 2.74	39.80 ± 3.44	35.52 ± 3.77	51.57 ± 1.88	48.85 ± 2.95
Sutures	2.94 ± 0.27	7.27 ± 0.34	7.47 ± 0.36	10.6 ± 0.31	10.48 ± 0.36

Figure 9A

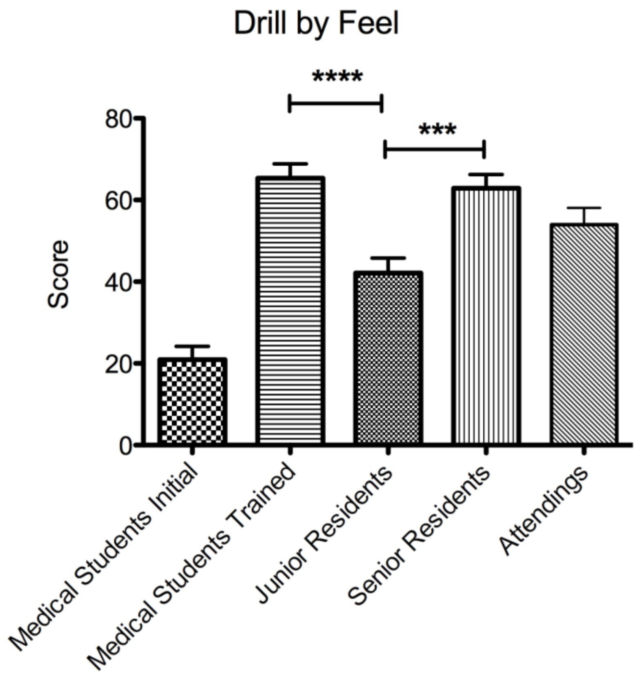


:

Figure 9B:


Plunge
***
*****
60
40
20
0
Score
Medical Students Initial
Medical Students Trained
Junior Residents
Senior Residents
Attendings

<u>Figure 9C</u>:



Drill by Feel
****
***
80
60
40
20
0
Score
Medical Students Initial
Medical Students Trained
Junior Residents
Senior Residents
Attendings

Figure 9D:

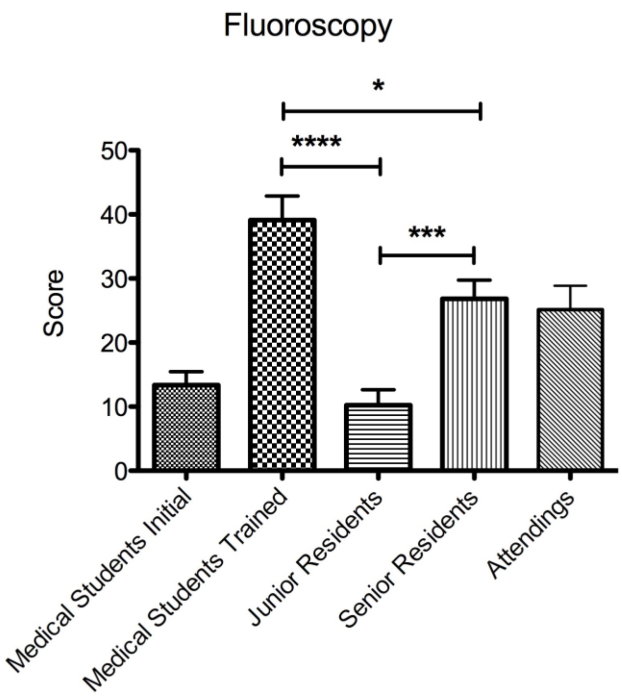

Fluoroscopy
*
****
***
Score
50
40
30
20
10
0
Medical Students Initial
Medical Students Trained
Junior Residents
Senior Residents
Attendings

Figure 9E:

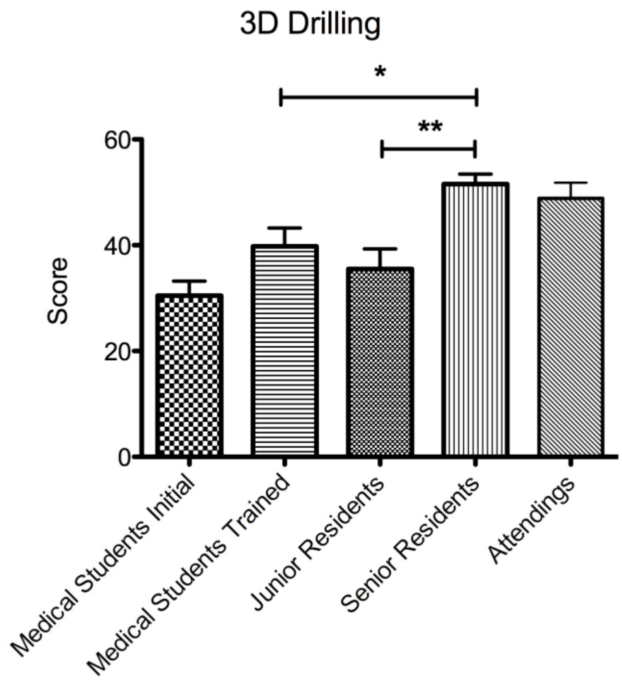
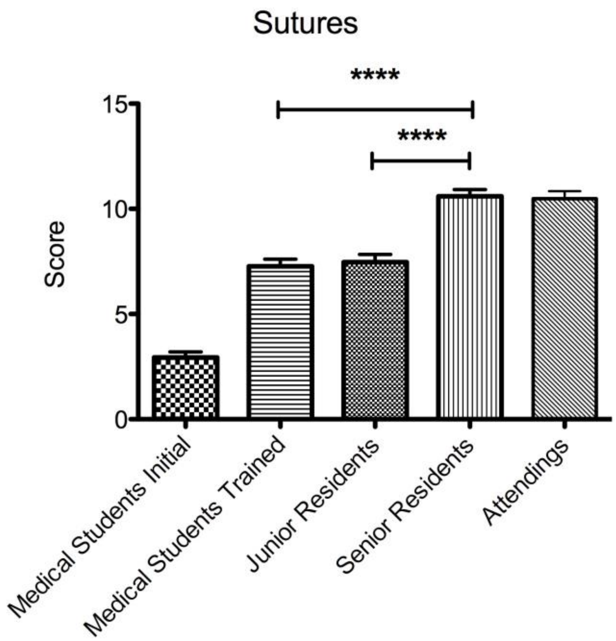

3D Drilling
*
**
Score
60
40
20
0
Medical Students Initial
Medical Students Trained
Junior Residents
Senior Residents
Attendings

Figure 9F:


Sutures
****
****
Score
15
10
5
0
Medical Students Initial
Medical Students Trained
Junior Residents
Senior Residents
Attendings

References:

[1] Peters JH, Fried GM, Swanstrom LL, Soper NJ, Sillin LF, Schirmer B, Hoffman K; SAGES FLS Committee. Development and validation of a comprehensive program of education and assessment of the basic fundamentals of laparoscopic surgery. Surgery. 2004 Jan;135(1):21-7. PubMed PMID: 14694297.

[2] Meier AH, Henry J, Marine R, Murray WB. Implementation of a Web- and simulation-based curriculum to ease the transition from medical school to surgical internship. Am J Surg. 2005 Jul;190(1):137-40. PubMed PMID: 15972187.

[3] Ahmed K, Amer T, Challacombe B, Jaye P, Dasgupta P, Khan MS. How to develop a simulation programme in urology. BJU Int. 2011 Dec;108(11):1698-702. doi: 10.1111/j.1464-410X.2011.010420.x. Epub 2011 Aug 22. Review. PubMed PMID:21871051.

[4] Friedell ML. Starting a simulation and skills laboratory: what do I need and what do I want? J Surg Educ. 2010 Mar-Apr;67(2):112-21. doi:10.1016/j.jsurg.2010.03.001. PubMed PMID: 20656609.

[5] Herndon JH. The patient first. Above all do no harm (primum non nocere). J Bone Joint Surg Am. 2013 Feb 20;95(4):289-90. doi: 10.2106/JBJS.9504edit. PubMed PMID: 23426762.

[6] Pedowitz RA, Marsh JL. Motor skills training in orthopaedic surgery: a paradigm shift toward a simulation-based educational curriculum. J Am Acad Orthop Surg. 2012 Jul;20(7):407-9. doi: 10.5435/JAAOS-20-07-407. PubMed PMID: 22751159.

[7] Karam MD, Pedowitz RA, Natividad H, Murray J, Marsh JL. Current and future use of surgical skills training laboratories in orthopaedic resident education: a national survey. J Bone Joint Surg Am. 2013 Jan 2;95(1):e4. doi: 10.2106/JBJS.L.00177. PubMed PMID: 23283381.

[8] Butler A, Olson T, Koehler R, Nicandri G. Do the skills acquired by novice surgeons using anatomic dry models transfer effectively to the task of diagnostic knee arthroscopy performed on cadaveric specimens? J Bone Joint Surg Am. 2013 Feb 6;95(3):e151-8. doi: 10.2106/JBJS.L.00491. PubMed PMID: 23389795.

[9] Hansen E, Marmor M, Matityahu A. Impact of a three-dimensional "hands-on" anatomic teaching module on acetabular fracture pattern recognition by orthopaedic residents. J Bone Joint Surg Am. 2012 Dec 5;94(23):e1771-7. doi: 10.2106/JBJS.K.00840. PubMed PMID: 23224397.

[10] Martin KD, Cameron K, Belmont PJ, Schoenfeld A, Owens BD. Shoulder arthroscopy simulator performance correlates with resident and shoulder

arthroscopy experience. J Bone Joint Surg Am. 2012 Nov 7;94(21):e160. doi: 10.2106/JBJS.L.00072. PubMed PMID: 23138247.

[11] Jackson WF, Khan T, Alvand A, Al-Ali S, Gill HS, Price AJ, Rees JL. Learning and retaining simulated arthroscopic meniscal repair skills. J Bone Joint Surg Am. 2012 Sep 5;94(17):e132. PubMed PMID: 22992861.

[12] Alvand A, Khan T, Al-Ali S, Jackson WF, Price AJ, Rees JL. Simple visual parameters for objective assessment of arthroscopic skill. J Bone Joint Surg Am. 2012 Jul 3;94(13):e97. doi: 10.2106/JBJS.K.01437. PubMed PMID: 22760398.

[13] Pollard TC, Khan T, Price AJ, Gill HS, Glyn-Jones S, Rees JL. Simulated hip arthroscopy skills: learning curves with the lateral and supine patient positions: a randomized trial. J Bone Joint Surg Am. 2012 May 16;94(10):e68. doi: 10.2106/JBJS.K.00690. PubMed PMID: 22617934.

[14] Sroka G, Feldman LS, Vassiliou MC, Kaneva PA, Fayez R, Fried GM. Fundamentals of laparoscopic surgery simulator training to proficiency improves laparoscopic performance in the operating room-a randomized controlled trial. Am J Surg. 2010 Jan;199(1):115-20. PubMed PMID: 20103076.

[15] Barsuk JH, Cohen ER, Feinglass J, McGaghie WC, Wayne DB. Use of simulation-based education to reduce catheter-related bloodstream infections. Arch Intern Med. 2009 Aug 10;169(15):1420-3. PubMed PMID: 19667306.

[16] Lee JY, Mucksavage P, Kerbl DC, Osann KE, Winfield HN, Kahol K, McDougall EM. Laparoscopic warm-up exercises improve performance of senior-level trainees during laparoscopic renal surgery. J Endourol. 2012 May;26(5):545-50. doi: 10.1089/end.2011.0418. Epub 2012 Jan 4. PubMed PMID: 22192095; PubMedCentral PMCID: PMC3552180.

[17] Calatayud D, Arora S, Aggarwal R, Kruglikova I, Schulze S, Funch-Jensen P, Grantcharov T. Warm-up in a virtual reality environment improves performance in the operating room. Ann Surg. 2010 Jun;251(6):1181-5. PubMed PMID: 20485133.

[18] Bailey CH, Kandel ER. Structural changes accompanying memory storage. Annu Rev Physiol. 1993;55:397-426. Review. PubMed PMID: 8466181.

[19] Amunts K, Schlaug G, Jäncke L, Steinmetz H, Schleicher A, Dabringhaus A, Zilles K. Motor cortex and hand motor skills: structural compliance in the human brain. Hum Brain Mapp. 1997;5(3):206-15 PubMed PMID: 20408216.

[20] Stransky D, Wilcox LM, Dubrowski A. Mental rotation: cross-task training and generalization. J Exp Psychol Appl. 2010 Dec;16(4):349-60. doi: 10.1037/a0021702. PubMed PMID: 21198252.

[21] Kerfoot BP, Fu Y, Baker H, Connelly D, Ritchey ML, Genega EM. Online spaced education generates transfer and improves long-term retention of diagnostic skills: a randomized controlled trial. J Am Coll Surg. 2010 Sep;211(3):331-337.e1. doi: 10.1016/j.jamcollsurg.2010.04.023. Epub 2010 Jul 13. PubMed PMID: 20800189.

[22] Pedowitz RA, Esch J, Snyder S. Evaluation of a virtual reality simulator for arthroscopy skills development. Arthroscopy. 2002 Jul-Aug;18(6):E29. PubMed PMID: 12098111.

[23] Poss R, Mabrey JD, Gillogly SD, Kasser JR, Sweeney HJ, Zarins B, Garrett WE Jr, Cannon WD. Development of a virtual reality arthroscopic knee simulator. J Bone Joint Surg Am. 2000 Oct;82-A(10):1495-9. PubMed PMID: 11057478.