An Assessment of Fine Surgical Knot Tying

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OBJECTIVE: Operating room simulation exercises have been well established as an effective means of improving confidence, task engagement, and learning retention among surgical residents. We have established a cost-effective model and scoring system assessing resident skills to tie secure surgical knots with minimal tension.

DESIGN: A circular grid divided into 18 segments was placed underlying an aluminum can. Trainees tie 20 surgical square knots scored for time and total knot length. Movement of the can outside the grid served as a scoring penalty. Recorded were time, length of the 20 knots, and number of segments exposed at exercise end. A score was developed to identify a progression of skills with PGY level. All outcomes were compared between classes using ANOVA.

SETTING: Brown University/Rhode Island Hospital Department of Surgery.

PARTICIPANTS: Surgical residents (PGY1-PGY5) and participating attending surgeons employed by Rhode Island Hospital.

RESULTS: Knot length and exposed segments showed trends of improved scores with ascending PGY level. Only average time attained statistical significance. Overall scores improved with PGY level:

	PGY1 (N = 9)	PGY2 (N = 3)	PGY3 (N = 6)	PGY4 (N = 3)	PGY5 (N = 3)	Attending (N = 4)
Composite	100.5	116.4	152.7	138.1	169.9	162.8

Composite scores significantly improved when comparing PGY1 to PGY3, PGY5, and Attending surgeons (p = 0.016, 0.011, and 0.011, respectively). Time significantly improved when comparing PGY1 to PGY3 and Attending surgeons (77 vs. 50 and 47 seconds, p = 0.019 and 0.022 respectively). Composite scores were not significantly different above PGY3.

CONCLUSIONS: A low fidelity, high impact knot tying model has been developed to assess the ability to securely tie surgical knots while minimizing tension, with linear increases in scores that appear to plateau at the PGY3 level. (J Surg Ed 76:808−813. Published by Elsevier Inc. on behalf of Association of Program Directors in Surgery.)

KEY WORDS: Surgical education, knot tying, surgery simulation, learning techniques, resident education

COMPETENCIES: Medical Knowledge, Practice-Based Learning and Improvement, Systems-Based Practice

INTRODUCTION

With the Accreditation Council for Graduate Medical Education Milestones and Core Entrustable Professional Activities initiatives, there has been a notable shift toward merit and competency-based curricula in general surgery training.[1,2] Program directors and surgical educators thus seek the development of effective teaching tools and reliable assessment methods to evaluate resident progression. Utilization of operating room simulation exercises with clear goals and reproducible results has been well established as an effective means of improving confidence, task engagement, and learning retention.[3] Those tasked with training the next generation of surgery residents have thus looked toward practical, cost-effective techniques with the aim of increasing proficiency during bedside and clinic interventions as well as in the operating room.[4,5] A fundamental skill one acquires is the ability to secure surgical square knots while minimizing upward tension, as unnecessary force may inadvertently avulse tissue and even cause damage at the microscopic level.[6,7] While immediate feedback simulation exercises have been developed thus far, costs associated with force sensor usage and graphical display technology

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may impede their widespread integration.[8,9] To this end, the general surgery program at Brown University now requires residents to undergo an evaluation of their fine knot tying skills in a PGY-stratified, challenge scenario using a low-cost, low-fidelity model. We aim to effectively discriminate surgical residents' abilities at varying degrees of experience to perform the task of fine knot tying.

MATERIALS AND METHODS

Participants

The knot challenge is a low-cost simulation exercise developed by residency educators at the Brown University general surgery program aiming to train the surgical resident to tie square knots while minimizing unnecessary tension. As of the 2017 academic year, the exercise will be a required part of the residency training program, with participants from each year represented (PGY to PGY5). Attending surgeons will be participating in the exercise voluntarily with the intention of providing the "benchmark" score to which the residents will aim to reach. Attending surgeons will be provided with an informational waiver of consent confirming their voluntary participation in the exercise, with all scores obtained remaining confidential and deidentified.

Data Collection

The participants were introduced to the exercise beforehand, with their performance used to generate scores to validate the exercise. The exercise was conducted, and scores collected, by a third party with deidentified data collected prospectively by the investigators. As the experience level of the participant increased, from PGY1 to Attending level, the scores generated were used to distinguish between those proficient at the given task vs. those requiring additional training. Investigators only received a participant subject number and PGY level, with all information stored on an encrypted, password protected USB storage drive. The study design obtained approval by the Rhode Island Hospital Institutional Review Board and was determined to follow Good Clinical Practice and FDA/DHHS regulations.

Exercise Design

The simulation exercise consists of a circular grid divided into 18 triangular segments (Fig. 1a), which underlays an aluminum can filled with a predetermined amount of water (200 mL, Fig. 1b). The tab of the can is hitched vertically at 90 degrees functioning as a tying post. Participants stand at an exercise table adjusted to operating room table height, using 2-0 silk suture to perform the exercise. Movement of the aluminum can outside the underlying circular grid will expose the triangular segments and serve as a scoring
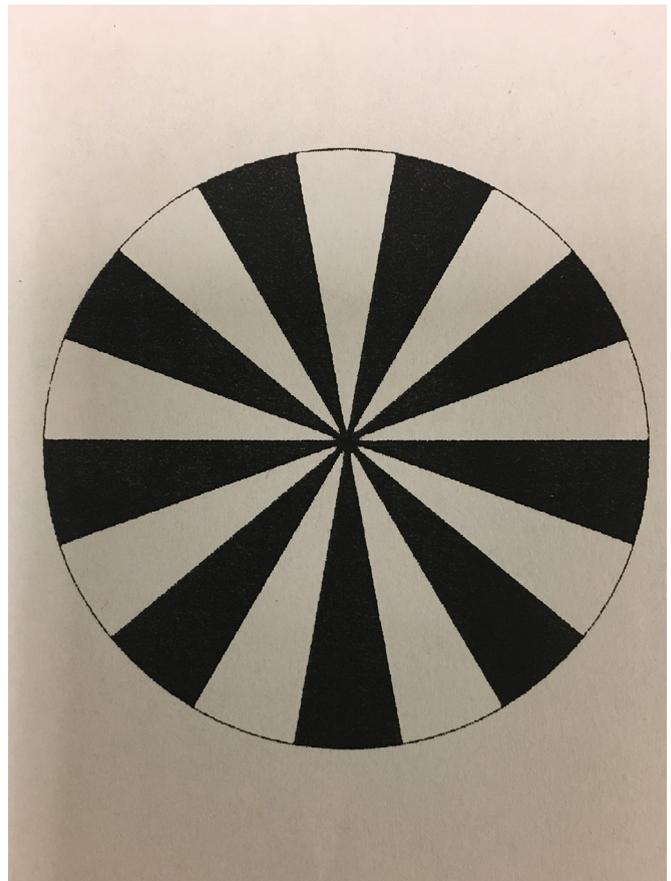

FIGURE 1A. Circular scoring grid composed of 18 triangular segments. Movement of the can outside this grid exposes the segments and acts as a scoring penalty.

penalty. The participants are introduced to the exercise beforehand and are allowed 2 minutes of practice time prior to score collection. After proceeding to tie twenty surgical square knots, 3 variables are recorded: time (seconds), length of twenty square knots (mm), and number of exposed underlying segments. The overall score (Table 1) was calculated as follows: $300 - [\text{Time (seconds)} + (4 \times \text{Length of Twenty Knots (mm)}) + (10 \times \text{Number of exposed segments})]$. Throughout the exercise the bottom of the aluminum can must remain, in some portion, in contact with the table and underlying scoring grid. Should the entire can leave the table surface, the score is discarded, and the participant is instructed to restart the exercise.

Data Analysis

Following an introduction to the exercise, the participants performed the simulation 3 times, with their average score contributing to the cumulative PGY class score. The average scores were compared between PGY levels using ANOVA, with a p value <0.05 being used to determine statistical significance.
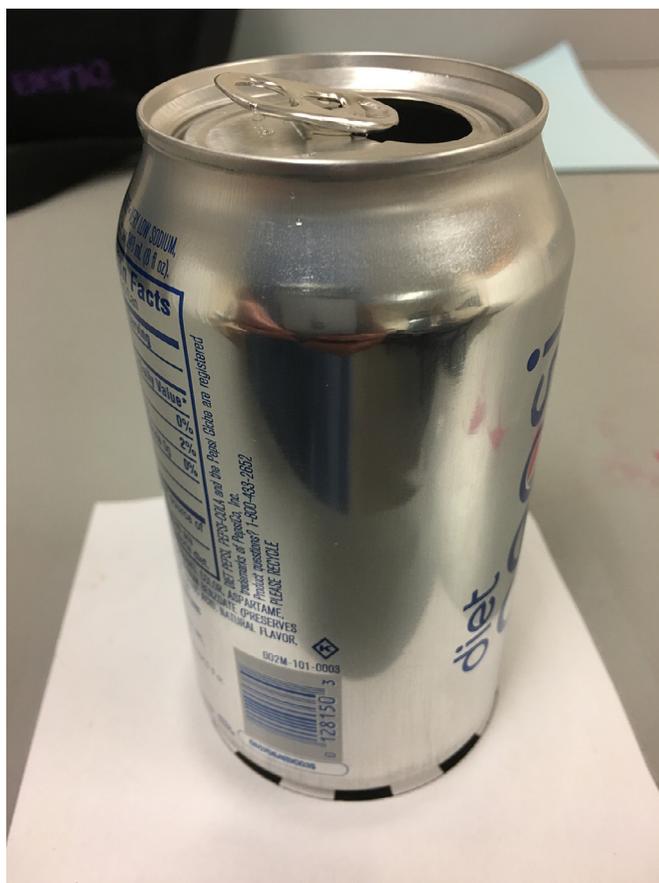
FIGURE 1B. An aluminum can filled with 200 mL water perfectly overlies the scoring grid. The participant is instructed to tie 20 square knots to the tab of the can using 2-0 silk ties.

TABLE 1. Exercise Composite Score Calculation. Penalties Including Time (Second) to Exercise Completion, Length of Twenty Knots (mm), and Number of Segments Exposed are Each Subtracted From a Starting Value of 300

Exercise Scoring System

Overall Score = 300 − [Time (seconds) + (4 × Length of Twenty Knots (mm) + (10 × Number of Exposed Segments)]

RESULTS

Twenty-eight surgical residents and 4 attending physicians participated in the study (n = 28). Resident case logs were collected at the time of this study (average cases/PGY level − PGY1 131.2, PGY2 298.6, PGY3 748.9, PGY4 1075.6, and PGY5 1344.8) and are illustrated in Table 2. Average knot length and number of exposed segments showed trends of improved scores with ascending PGY level (data not included), but only average time (seconds) demonstrated statistical

TABLE 2. Resident Case Demographics by PGY level

Activity Report	Min	Max	Average
PGY 1	102	164	131.2
PGY 2	266	326	298.6
PGY 3	603	1036	748.9
PGY 4	996	1262	1075.6
PGY 5	1280	1426	1344.8

significance. There was a notable improvement in overall score with ascending PGY level (Fig. 2): 100.5 (PGY1), 116.4 (PGY2), 152.7 (PGY3), 138.1 (PGY4), 169.9 (PGY5), and 162.8 (Attending). Composite scores significantly improved when comparing PGY1 to PGY3, PGY5, and Attending surgeons (p = 0.016, 0.011, and 0.011, respectively). Time (Fig. 3) significantly improved when comparing PGY1 to PGY3 and Attending surgeons (77 vs. 50 and 47 seconds, p = 0.019 and 0.022, respectively). Composite scores were not significantly different when comparing levels above PGY3.

DISCUSSION

Program directors and resident educators have long been faced with the daunting challenge of imparting a rapidly expanding body of knowledge and operative skills to surgical trainees, an incentive that has adapted in response to the 80-hour work week. The Accreditation Council for Graduate Medical Education milestones have demonstrated the ability to detect differences among PGY levels with regard to achievements and
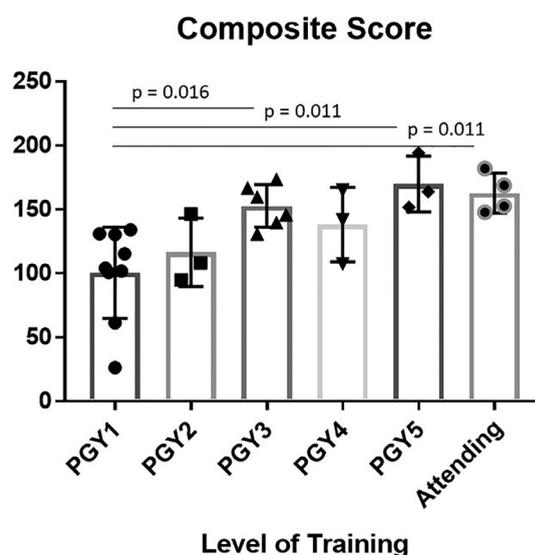

FIGURE 2. Composite exercise scores stratified by PGY level.

FIGURE 3. Time (second) to exercise completion stratified by PGY level.

resident growth, while fostering an environment of self-reflection and self-evaluation.[2,10] Furthermore, the Medical Knowledge milestone rating has been shown to predict scores obtained for the American Board of Surgery In-Training Examination, assisting program leadership in identify residents in need of additional support when needed.[11] With these milestones in mind, our department found it prudent to adopt a cost-effective, reproducible operating room simulation exercise to complement an existing, robust curriculum which includes Fundamentals of Laparoscopic/Endoscopic Surgery (FLS/FES), Vascular Anastomoses, as well as Robotic Surgery training.[12] Bench models and simulation training have continued to gain traction over the last decade as a means of improving residents' technical skills. Literature has shown a positive correlation between bench model training and technical competency in the operating room and has also been associated with improving patient related outcomes.[13,14]

While operating room simulation exercises have their limitations, engaging in dedicated practice and self-evaluation supplemented with one-on-one coaching may function to enhance confidence and learner engagement across a range of specialties.[15-17] Feins et al. established training modules to simulate resident competency regarding cardiopulmonary bypass, coronary artery bypass grafting, aortic valve replacement, and various notable complications. They not only demonstrated notable improvement with practice repetition, but also a transient detrimental effect of time away from training, reinforcing the value of spaced repetitive learning, and deliberate practice.[15] Vaughan et al. developed a simulated vaginal hysterectomy trainer and demonstrated its ability to distinguish differences between "junior" and "senior" resident level performance, suggesting its utility in improving junior resident skills prior to their

first case.[16] Our challenge exercise demonstrated the most notable improvement in scores when comparing PGY1 to PGY3 level, suggesting its primary utility as a junior-resident assessment and education tool. Future iterations of our model will decrease the volume of water used for senior residents and attendings to increase difficulty and help better stratify scores above PGY3. Furthermore, fostering program camaraderie in the form of friendly competition has garnered a sense of improved morale among participants, with junior residents practicing during downtime to achieve the benchmark chief resident and attending scores.

While knot tying models with the ability to provide real-time feedback have been developed, we feel their widespread implementation into resident curricula has been hindered by the need to invest in force sensors and digital software.[8,9] Upfront costs for our exercise are virtually nonexistent, with the almost immediate ability to undergo trials at any residency program. The findings from our project echo what has been previously studied regarding transfer of learning and skill acquisition. In order to maintain skills, intermittent, or distributive training schedules produce better results than massed training sessions and surgical skills decline with nonuse.[18] Junior residents, particularly interns, typically have longer intervals of nonuse due to less frequent operative exposure, as compared to senior residents and attending surgeons who spend most of their clinical time operating. This relationship between time and skill degradation has significant implications regarding how we should be scheduling training sessions and simulation workshops with surgical residents.[19,20]

LIMITATIONS

It is important to note the limitations of our study, to include its single-center design, nonvalidated scale of knot tying assessment, and limited number of exercise trials among residents. To encourage distributive knot tying practice and assessment within our surgical residency program, we plan to standardize this exercise into the academic year simulation curriculum. While the initial scoring modalities show significant score improvement with ascending PGY level, further iterations with multiple, spaced repetitions may elucidate a learning curve difference and a theoretical "peak score" among residents. Additionally, the exercise design and scoring system is limited by capturing primarily 2-dimensional, horizontal, movements. Instances where the aluminum can was lifted completely off the practice table served as a disqualification prompting repeating of the exercise. To capture vertical movement, the exercise may benefit from factoring this event into the existing scoring system as an additional penalty.

CONCLUSION

A low fidelity, high impact knot tying model has been developed to assess a resident's ability to securely tie surgical knots while minimizing unnecessary tension, with linear increases in scores that appear to plateau at the PGY3 level.

FUNDING

REFERENCES

1. Gardner AK, Scott DJ, Choti MA, Mansour JC. Developing a comprehensive resident education evaluation system in the era of milestone assessment. *J Surg Educ*. 2015;72:618–624. https://doi.org/10.1016/j.jsurg.2014.12.007.

2. Meier AH, Gruessner A, Cooney RN. Using the ACGME milestones for resident self-evaluation and faculty engagement. *J Surg Educ*. 2016;73:e150-e157. https://doi.org/10.1016/j.jsurg.2016.09.001.

3. Gardner AK, Jabbour IJ, Williams BH, Huerta S. Different goals, different pathways: the role of metacognition and task engagement in surgical skill acquisition. *J Surg Educ*. 2016;73:61–65. https://doi.org/10.1016/j.jsurg.2015.08.007.

4. Ruder JA, Brighton BK, Vander Have KL, Turvey BR, Hsu JR, Scannell BP. Effectiveness of a low fidelity cast removal module in orthopaedic surgical simulation. *J Surg Educ*. 2018. https://doi.org/10.1016/j.jsurg.2018.01.020.

5. Jabbour N, Snyderman CH. The economics of surgical simulation. *Otolaryngol Clin N Am*. 2017;50:1029–1036. https://doi.org/10.1016/j.otc.2017.05.012.

6. Högström H, Haglund U, Zederfeldt B. Tension leads to increased neutrophil accumulation and decreased laparotomy wound strength. *Surgery*. 1990;107:215–219.

7. Raut VN, Takaori K, Uemoto S. Optimal tissue tension for secure laparoscopic knots. *Med Hypotheses*. 2011;76:269–270. https://doi.org/10.1016/j.mehy.2010.10.019.

8. Hsu JL, Korndorffer JR, Brown KM. Force feedback vessel ligation simulator in knot-tying proficiency training. *Am J Surg*. 2016;211:411–415. https://doi.org/10.1016/j.amjsurg.2015.09.009.

9. Rafiq A, Tamariz F, Boanca C, Lavrentyev V, Merrell RC. Objective assessment of training surgical skills using simulated tissue interface with real-time feedback. *J Surg Educ*. 2008;65:270–274. https://doi.org/10.1016/j.jsurg.2008.05.012.

10. Goldman RH, Tuomala RE, Bengtson JM, Stagg AR. How effective are new milestones assessments at demonstrating resident growth? 1 year of data. *J Surg Educ*. 2017;74:68–73. https://doi.org/10.1016/j.jsurg.2016.06.009.

11. Kimbrough MK, Thrush CR, Barrett E, Bentley FR, Sexton KW. Are surgical milestone assessments predictive of in-training examination scores? *J Surg Educ*. 2018;75:29–32. https://doi.org/10.1016/j.jsurg.2017.06.021.

12. Okhah Z, Morrissey P, Harrington DT, Cioffi WG, Charpentier KP. Assessment of surgical residents in a vascular anastomosis laboratory. *J Surg Res*. 2013;185:450–454. https://doi.org/10.1016/j.jss.2013.04.090.

13. Wilasrusmee C, Phromsopha N, Lertsitichai P, Kittur DS. A new vascular anastomosis model: relation between outcome and experience. *Eur J Vasc Endovasc Surg Off J Eur Soc Vasc Surg*. 2007;33:208–213. https://doi.org/10.1016/j.ejvs.2006.09.026.

14. Brydges R, Hatala R, Zendejas B, Erwin PJ, Cook DA. Linking simulation-based educational assessments and patient-related outcomes: a systematic review and meta-analysis. *Acad Med J Assoc Am Med Coll*. 2015;90:246–256. https://doi.org/10.1097/ACM.0000000000000549.

15. Feins RH, Burkhart HM, Conte JV, et al. Simulation-based training in cardiac surgery. *Ann Thorac Surg*. 2017;103:312–321. https://doi.org/10.1016/j.athoracsur.2016.06.062.

16. Vaughan MH, Kim-Fine S, Hullfish KL, Smith TM, Siddiqui NY, Trowbridge ER. Validation of the simulated vaginal hysterectomy trainer (Simvaht). *J Minim Invasive Gynecol*. 2018;25(6):1101–1106. https://doi.org/10.1016/j.jmig.2018.02.022.

17. Boody BS, Rosenthal BD, Jenkins TJ, Patel AA, Savage JW, Hsu WK. The effectiveness of bioskills training for simulated open lumbar laminectomy. *Glob Spine J*. 2017;7:794–800. https://doi.org/10.1177/2192568217703337.

18. Adams JA. Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychol Bull*. 1987;101:41–74.

19. Moulton C-AE, Dubrowski A, Macrae H, Graham B, Grober E, Reznick R. Teaching surgical skills: what kind of practice makes perfect?: a randomized, controlled trial. *Ann Surg*. 2006;244:400–409. https://doi.org/10.1097/01.sla.0000234808.85789.6a.

20. Mitchell EL, Lee DY, Sevdalis N, et al. Evaluation of distributed practice schedules on retention of a newly acquired surgical skill: a randomized trial. *Am J Surg*. 2011;201:31–39. https://doi.org/10.1016/j.amjsurg.2010.07.040.

SUPPLEMENTARY MATERIAL

Supplementary data are available in the online version of this article at https://doi.org/10.1016/j.jsurg.2018.10.017.