The American Journal of Surgery 220 (2020) 100–104

Contents lists available at ScienceDirect

The American Journal of Surgery

journal homepage: www.americanjournalofsurgery.com

Feedback based simulator training reduces superfluous forces exerted by novice residents practicing knot tying for vessel ligation

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A R T I C L E I N F O

Article history:
Received 28 September 2019
Received in revised form
18 November 2019
Accepted 18 November 2019

Part of a presentation at the 2019 Association for Surgical Education (ASE) Annual Meeting, April 26, 2019, Chicago, IL

Keywords:
Knot tying
Education
Feedback
Simulator
Training
Residency

A B S T R A C T

Background: Technological advances have led to the development of state-of-the-art simulators for training surgeons; few train basic surgical skills, such as vessel ligation.

Methods: A novel low-cost bench-top simulator with auditory and visual feedback that measures forces exerted during knot tying was tested on 14 surgical residents. Pre- and post-training values for total force exerted during knot tying, maximum pulling and pushing forces and completion time were compared.

Results: Mean time to reach proficiency during training was 11:26 min, with a mean of 15 consecutive knots. Mean total applied force for each knot were 35% lower post-training than pre-training (7.5 vs. 11.54 N (N), respectively, $p = 0.039$). Mean upward peak force was significantly lower after, compared to before, training (1.29 vs. 2.12 N, respectively, $p = 0.004$).

Conclusions: Simulator training with visual and auditory force feedback improves knot-tying skills of novice surgeons.

Introduction

Proficiency in knot tying for vessel ligation has traditionally been acquired in the operating room, based on the apprenticeship model. The skill is learned through trial and error, with failure due to excessive force often leading to tissue avulsion and or tear of thread. The advantages of simulation-based training and the limited exposure to operations, particularly open surgery, have led to the widespread incorporation of the former in residency programs.[1,2] An increasing number of studies suggest force feedback simulations facilitate training of tissue handling skills in novices.[3–7]

Technological advances have led to the development of state-of-the-art simulators that employ virtual reality combined with force feedback mainly focuses on laparoscopic or robotic surgery. Advanced simulators to develop and refine basic surgical skills, such as vessel ligation, are lagging behind.[8] Simulators for this purpose are needed in residency programs to train fledgling surgeons in this basic surgical skill.

We developed a simulator for the task of vessel ligation that incorporates a visual and auditory force feedback feature. The purpose of this study was to examine its ability to train novice residents to reach proficiency in knot tying using the appropriate force. We hypothesize that trainees given immediate visual and auditory feedback on their performance will learn to use less force while tying a knot for vessel ligation.

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https://doi.org/10.1016/j.amjsurg.2019.11.027

Material and methods

The study was approved by the Sheba Medical Center Internal Review Board (IRB). Participants signed written informed consent to analysis of the recorded data.

Participants

Fourteen surgical residents, postgraduate year (PGY) 1 and 2, were recruited to the study from the institution's 'surgical boot camp', a comprehensive five-day simulation-based preparatory course that included, among other skills, surgical knot tying. The 9 male and 5 female trainees ranged in age from 27 to 37 years (mean 32 ± 3 years). Twelve were right-handed and two left-handed. Four were residents in gynecology (29%), three in general surgery (22%), two in urology (14%), two in oral and maxillofacial surgery (14%), one in orthopedic surgery (7%), one in otolaryngology (7%), and one in thoracic surgery (7%). Trainees reported prior clinical experience of tying 50 to 100 knots. Only 4 reported spending time at hospital or home the previous year practicing knot tying.

Instrument

A novel benchtop simulator, Knoti, that measures forces exerted during knot tying for vessel ligation (Fig. 1 and figs1) is described in detail in previous studies.[9,10] It was put into routine use in our hospital after being tested on surgical residents in 2017 and 2018. The simulator logs to a designated computer software and records a set of performance parameters, including vertical forces and time for task completion.

In a prior study that compared metrics between novice residents and experienced surgeons,[10] we identified 1.3 N (N) as the maximum force exerted when experts tie a knot on the simulator. The expert group included 15 experienced surgeons from general surgery, vascular surgery, cardiothoracic surgery and gynecology; they had 201 years of cumulative surgical experience since receiving their board certification, with an average of 13.4 ± 7 years each.

Following this study, we added to the simulator colored LED lights (green and red) and an alarm circuit that produces a beep sound in different frequencies. The visual and auditory systems were added to signal any excessive force exerted during knot tying. The following threshold values were defined: Red light and persistent beep when the reaction force exceeds 1.3 N. Green light and intermittent beep when the reaction force is lower than 1.3 N.

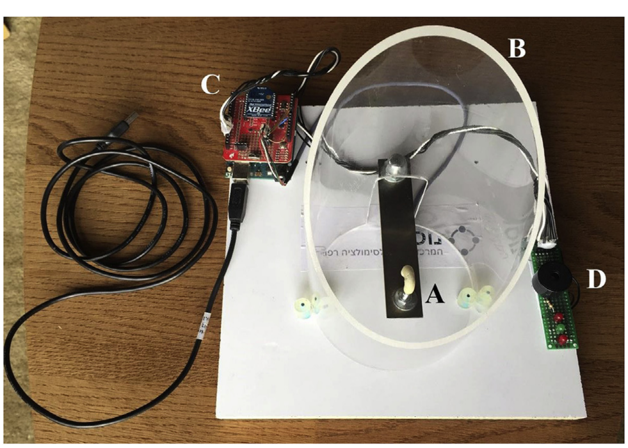

Fig. 1. The bench top knot tying simulator (KNOTI), with the additional visual and auditory feedback system. A – the hook for knot application, B – plexiglass tube to simulate deep knot tying. The top of the tube was 3 cm above the top of the hook. C – data sensor that connects to any personal computer via USB cable. D – the feedback appliance with red and green LED lights. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Study design

The study design (Fig. 2) consisted of three segments: a pre-training test, a training session with the feedback system, and a post-training test. The knot tying procedure and set-up in all three segments were identical. The pre- and post-training tests consisted of tying 11 knots without feedback. Using surgical gloves, the participants were instructed to perform a square knot in a one-handed technique at a deep setting, simulating a vessel ligation. They were not informed of the parameters being tested, being told only to avoid tissue rupture or loose knots. All ties were 3-0 silk (Sofsilk™ 3.0, MEDTRONIC, Minneapolis, Minnesota, US). Instructions were given by the same examiner and residents were allowed to ask questions only during the training segment. During that segment, they were instructed to practice until proficiency (the ability to tie five consecutive knots within the requisite force metrics) was achieved. The duration of the segments depended on the time it took to complete the task required. Total exerted force, maximum pulling and pushing forces, and completion time of each knot were compared between pre- and post-training tests.

Knot integrity was evaluated during each session by the same examiner (AR), who discarded "air knots" by visual assessment. An air knot was defined as a square knot in which, after tying the second throw, a visual gap was seen by the examiner between the hook and the knot. Videos were reviewed by examiners (AR, CM, AI) during analysis of the data to verify appropriate technique (Video 1, example video of post-training knot tying).

Statistical analysis

All data were analyzed using R software for statistical computing (R-Project, version 3.4.1, 2017). The performances during the pre- and post-training tests were compared with a Student's t-test, Mann Whitney or Bonferroni procedure. Statistical significance was set at $p < 0.05$.

Results

The average training time to reach proficiency (Fig. 3) during the training session was 11:26 min, with a mean of 15 consecutive knots. The mean total applied force (Fig. 4) decreased by 35% in the post-training period compared to the pre-training period (7.5 N vs. 11.54 N, respectively, $p = 0.039$), with no statistical difference in completion time (18.9 s vs. 20.7 s, respectively, $p = 0.22$).

The mean peak force exerted upward during knot placement ('pulling up' force) was significantly lower in the post-training period compared to the pre-training period (1.29 N vs. 2.12 N, respectively, $p = 0.004$). It was also consistent throughout the consecutive knots in each test (Fig. 5), with lower forces measured only after feedback training and not through repetition alone.

There was no significant difference in total up force before and after the training session (11.01 vs 7.06 N, respectively, $p = 0.278$). There was no statistically significant difference in the time spent on order to complete one knot before and after the simulator training (21 s vs. 19 sec, respectively, $p = 0.222$). Nor was there a significant difference between the pre- and post-test times of upward movement during one knot (11 s vs. 7 sec, respectively, $p = 0.222$) and downward movement during one knot (1 s vs. 0.5 s, respectively, $p = 0.221$). We did not see a statistically significant difference in the tested results when comparing the participants by residency type,

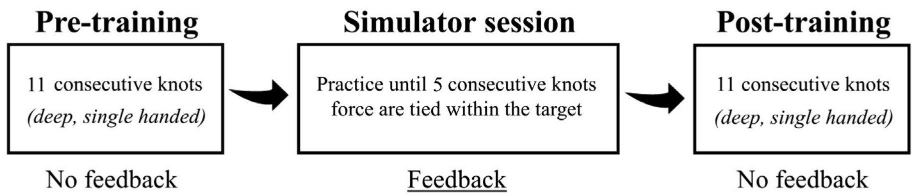

Fig. 2. Study design.

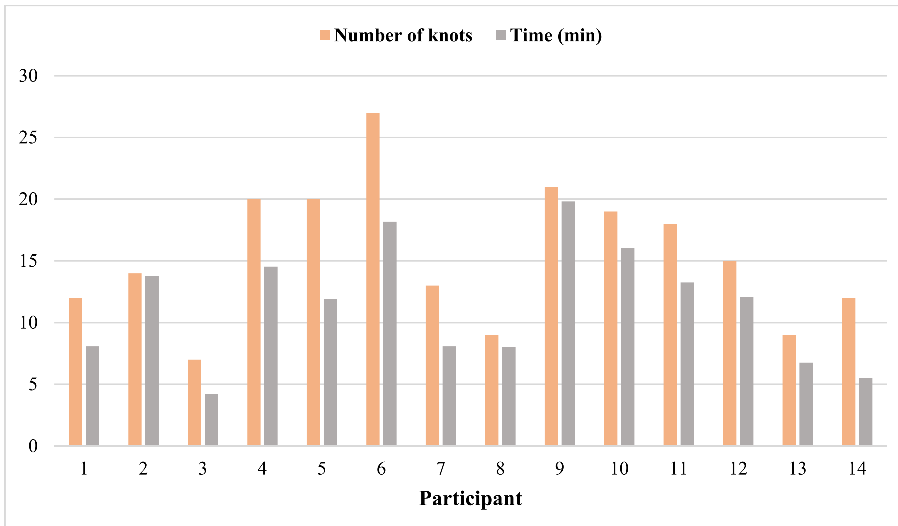

Fig. 3. Simulator training session for surgical residents. The session was over once the participant successfully tied 5 consecutive knots within the target force. The number of knots and time needed to achieve this goal is shown.

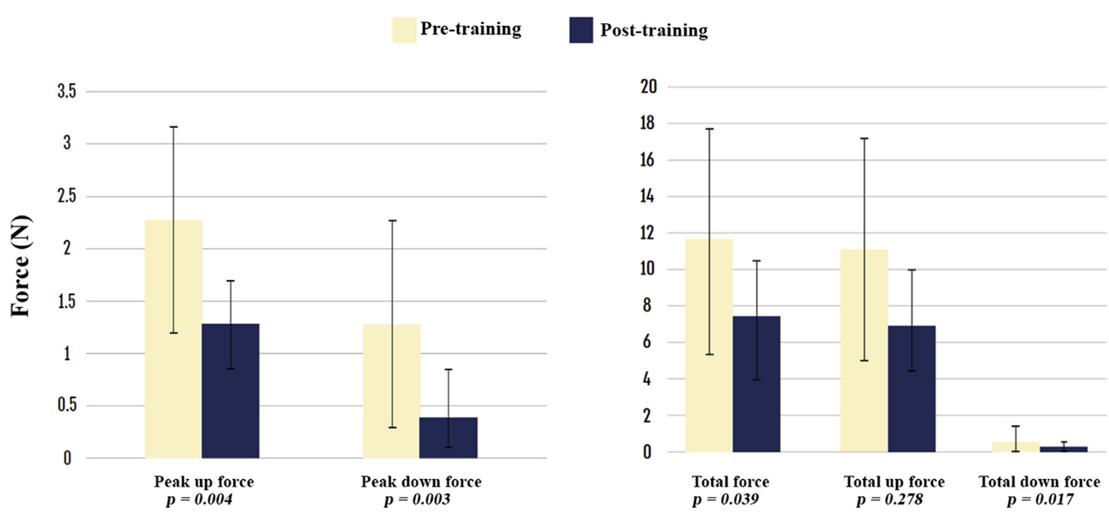

Fig. 4. Performance means, including confidence intervals, and p values before and after simulator feedback training.

age, months in residency, gender, dominant hand, prior knot tying experience and self-practice of knot tying.

Discussion

Our study shows that practice on a feedback based simulator reduced superfluous force by novice residents simulating knot tying for vessel ligation, as opposed to simple repetition training. After training with feedback, surgical residents achieved the same competence as experienced surgeons, as measured in our previous study.[10] The peak upward force is a critical contributor to tear of the thread or avulsion of tissue by inexperienced surgeons. Before training on the simulator, the participants had a mean peak upward force that was significantly higher than that of a cohort of experts (2.12 N vs 1.3 N, respectively), compared to a mean peak upward force of 1.29 N after training on the simulator.

Proficiency was established in a short time frame during the training session with minimal practice (an average of 11:26 min on 15 consecutive knots; Fig. 3). The importance of the visual and auditory feedback is demonstrated in the results after the practice

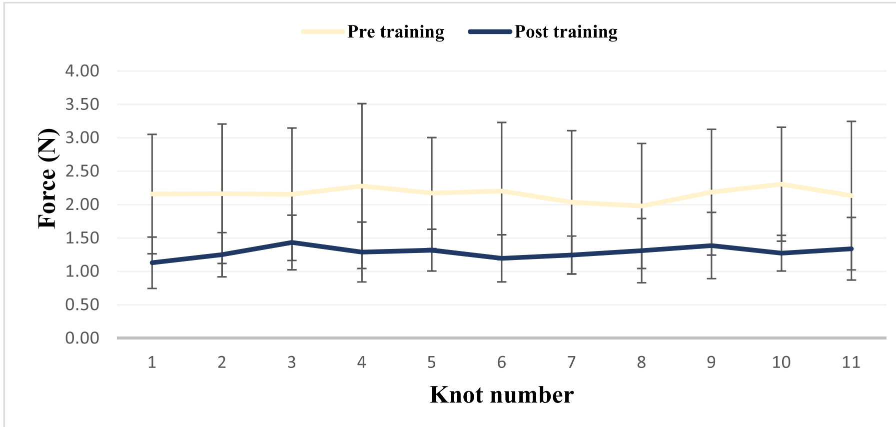

Fig. 5. Mean upward peak force measurement for each knot in the pre- and post-training tests with confidence interval.

period. As shown in Fig. 5, repetition by itself did not contribute to the reduction in the use of force. The force was consistent throughout the consecutive knots in each test, with lower forces measured only after feedback training. This is a crucial validation of the importance of immediate feedback when practicing basic surgical skills.

Our results are in line with those of Hsu et al.,[11,12] who developed a simulator for the same purpose. In their pilot study, with a similar design to ours, they reported that the training session was completed in an average of 19.4 ± 6.27 min and required an average of 11.7 ± 4.03 knots to reach proficiency.[12] There are two main differences between the simulators: their platform measures forces during successive vessel ligations on the same tubing, necessitating data manipulation, whereas ours assessed one knot at a time; they validated their simulator on a small cohort of 19 surgical residents, and tested it on 9 medical students, whereas we validated our simulator on 45 surgeons (15 board certified experts and 30 residents) and tested it on 14 residents.

Nevertheless, both studies reached the same conclusions: more experienced participants exerted less force compared to the less experienced ones; and practice on the simulator resulted in a reduction of the implemented force. These findings were also seen in laparoscopic simulators.[3–6]

Our experimental platform has its limitations. First, knot integrity was evaluated visually by an examiner. Furthermore, the measured force recorded by our sensor was only in the vertical axis. Finally, the correct amount of force was based on expert's performance, and not on tissue models assessing tear forces on tissue. However, given the available research models, we felt the data was valid for the current investigation. We recognize the need for improvements in our simulator and additional studies to assess how effectively knot-tying skills transfer to the operating room.

The results showed that the KNOTI simulator can be used as an objective tool for evaluating task performance, assessing competence and augmenting the learning process. Being an affordable and easy to handle and store instrument, such platforms can be readily accessible to residency programs around the world, especially in developing countries where interest in such teaching modalities is high; in addition, they facilitate international standardization while overcoming financial disparities.[8]

In future studies, we will compare our feedback simulator training with the gold standard training method for surgical residents – simple knot tying boards with immediate observer oral feedback.

Conclusions

Visual and auditory force feedback improves precise knot-tying skills for vessel ligation, indicating the effectiveness of the simulator for training and objective competency measurements of this basic surgical skill.

Declaration of competing interest

The authors have no conflicts of interests or financial ties to disclose.

Acknowledgments

The authors would like to thank all the surgeons and residents who participated in the study. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.amjsurg.2019.11.027.

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