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Education

Innovating Flexor Tendon Repair Training with a Three-dimensional Printed Model

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Background: Flexor tendon repair is a technically demanding procedure, with functional outcome directly proportional to skillful execution. A repair must be strong to manage early mobilization and precise to allow for gliding through the tendon sheath. As a result, junior residents face a steep learning curve that may be mitigated by exposure to surgical simulators.

Methods: To facilitate flexor tendon repair training, a surgical training device and accompanying instructional video were developed. Simulation workshops were held for junior orthopedic and plastic surgery residents (n = 11). To objectively assess validity of the curriculum, study participants performed cadaveric flexor tendon repairs before and after the workshop. Anonymous recordings of these repairs were graded by two certified hand surgeons. Additionally, a tensometer was used to measure strength of repair.

Results: Model realism, educational utility, and overall usefulness rated high: 4.6 ± 0.52 95% confidence interval (CI) for realism, 4.9 ± 0.42 95% CI for device, 4.7 ± 0.96 95% CI for video, and 4.9 ± 0.66 95% CI overall. Subjective confidence increased after the training session (73% ranked "moderately" or "extremely"). Likewise, scores given by the surgeons grading the repairs improved for overall quality and time of repair (pre: 2.77 ± 0.61, post: 4.22 ± 0.56, P= 0.0002). Strength of repair did not change (P = 0.87).

Conclusions: The proposed three-dimensional surgical simulator for flexor tendon repair is realistic and useful, with improved surgical technique and improved confidence demonstrated after use. This design can be three-dimensionally printed en masse and provide value to hand surgery training curriculum. *(Plast Reconstr Surg Glob Open 2024; 12:e6125; doi: 10.1097/GOX.0000000000006125; Published online 3 September 2024.)*

INTRODUCTION

Acute hand injuries are the most common occupational injuries evaluated in United States emergency departments, many involving a flexor tendon injury.[1,2] Flexor tendon lacerations, their repair, and their recovery result in variable acute and chronic disability, significant time out of work, and notable economic burden.[1,3] Greater than 80% of tendon transection generally necessitates surgical intervention.[4]

Flexor tendon repair is a technically demanding procedure. The repair must be strong enough to allow for early mobilization, but also precise for smooth gliding through the tendon sheath. Teaching this technique to junior residents in the operating room can be difficult, due to the time constraints, delicate nature, and decreased outcomes with multiple repair attempts. A patient's functional outcome is directly proportional to skillful execution.[5,6] To accelerate the initial learning curve of junior residents in flexor tendon repair, it is reasonable to investigate surgical simulation.[6–8] Simulated training has been shown to familiarize the trainee with the basic skills of instrument and tissue handling, and give constructive feedback. Ideally, simulators should help junior residents establish proper technique in a controlled, minimally stressful setting, before their first procedure on a patient.

The goal of this study, therefore, was to provide a training model that would allow for efficacious surgical

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training that would increase junior resident comfort with flexor tendon repair.

METHODS

Creation of Three-dimensional Printed Flexor Tendon Training Device

A three-dimensional (3D) printed surgical training device for zone 2 digital flexor tendon repair was designed using the plastic surgery department's 3D printing lab (Lifespan 3D Printing Lab, Providence, R.I.). The device includes a platform, upon which is mounted an anatomically representative and bendable digit (Fig. 1). Metacarpals and phalanges were generated from a patient computed tomography scan. Using open-source software (Blender, Amsterdam, The Netherlands), flexible connectors in the metacarpophalangeal and interphalangeal joint spaces were digitally incorporated to facilitate digit flexion. The digit was then embedded into a 25 × 6.5 × 0.2 cm platform, which has engraved schematics of multiple suture techniques (Modified Kessler, Robertson, Cruciate, Tang, and running epitendinous) for reference. The platform also delineates the position of the five annular (A1–5) and three cruciform (C1–3) pulleys, to provide a better visual understanding of relevant anatomy. A separate model was also designed to include a complete set of physical pulleys that are manufactured out of prosthetic skin and dental rubber bands (Fig. 2). These pulleys are secured via non-anatomic pegs. All simulators were printed on a Stratasys J750 Polyjet printer (Eden Prairie, Minn.).

The model's mock flexor tendons, measuring 10 cm in length, were produced by pouring Dragonskin FX-Pro silicone (Smooth-On, Inc., Penn., USA) into a tendon-shaped mold designed in Blender. The specific density and compliance were directed by advice from multiple established hand surgeons. Once the mock tendons are cured, they can be threaded through the model's pulleys and fastened at the base of the platform with a tethering device under desired tension. These tendons can be lacerated, repaired, and reloaded for repeat use. Due to their length, each mock tendon can accommodate roughly three to four repair attempts before replacement (Fig. 3).

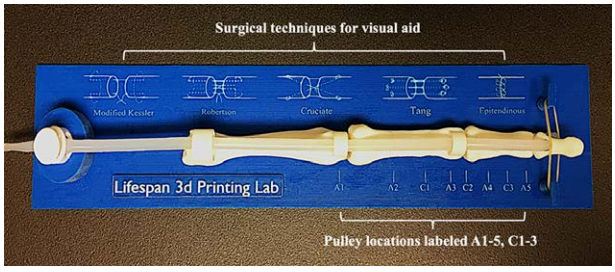

Fig. 1. 3D printed flexor tendon repair trainer loaded with a transparent silicone tendon. The metacarpophalangeal and interphalangeal joints are bendable, and the tethering device at the left side of the platform allows the user to adjust tendon tension to their preference. The top of the platform depicts four common core suture techniques and a running epitendinous suture technique as a visual guide for trainees. The bottom of the platform labels the anatomic locations of the five annular (A1-5) and three cruciform (C1-3) pulleys. The device can be printed en masse on a Stratasys J750 Polyjet printer.

Takeaways

Question: Can a simulator be effectively and affordably created that improves junior residents' operating skill and confidence for flexor tendon repair?

Finding: An objective improvement in flexor tendon repairs, as graded by hand surgeon attendings, was demonstrated in all tested domains (stitch placement, tendon handling, tendon alignment, and overall performance) aside from knot tying. Strength of repair did not demonstrate a difference under tensometer testing.

Meaning: Incorporation of surgical models can accelerate the learning curve and improve confidence in junior residents. Emphasis on providing affordable, accessible resources will help with eventual clinical performance.

A publicly available instructional video on flexor tendon repair was used to supplement the learning experience with the training device by providing proper placement of two core sutures (Modified Kessler and Cruciate) and an epitendinous suture (https://www.youtube.com/watch?v=wz67RPj6oNg). This video was created by one of the authors (M.B.). The intent of the video is to provide a step-by-step visual guide that learners can refer to and follow along with, while practicing flexor tendon repair techniques.

Cadaveric Tendon Assessment

Cadaveric digits were used to test the time and quality of a zone 2 tendon repair on each study participant; this testing occurred before and after training on the 3D model above. A 3D printed platform was used to secure the cadaveric digits. The built-in tethering mechanism on the platform provided adjustable tension on the tendons. Flexor tendons were exposed via Bruner incisions, and the A2 and A3 pulleys were released for exposure. Residents would perform a modified Kessler repair on these tendons. Cadaveric tendon repairs were recorded anonymously, using a cellphone and fiberboard recording station (Fig. 4). All participants wore the same-colored gloves for anonymity.

Training Simulations

First and second year residents in both orthopedic and plastic surgery were recruited to participate in a hands-on flexor tendon repair workshop. Before arriving, the participants filled out a de-identified 10-question survey to indicate years of training, current level of confidence in flexor tendon repair, and prior live operative experience. The training portion of the workshop consisted of a 10-minute instructional video, followed by 1 hour of unlimited practice on the flexor tendon simulator. The participants were given unlimited access to suture and mock tendons for practice of modified Kessler and epitendinous repairs. Pre- and posttests in which the participants performed cadaveric tendon repairs were recorded

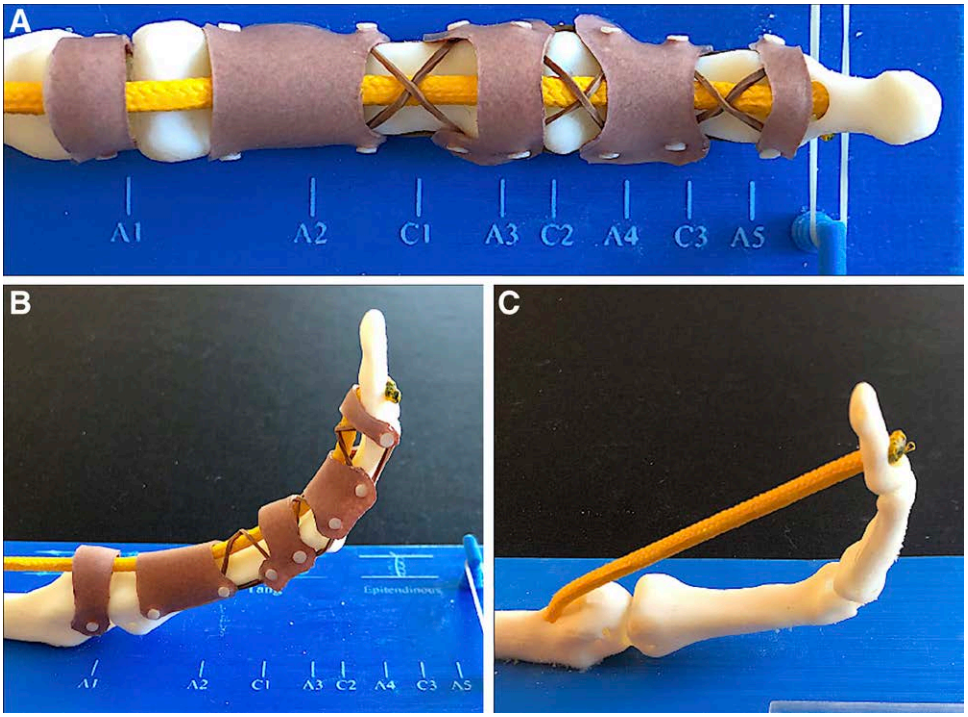

Fig. 2. A model with a complete set of physical pulleys. The annular pulleys (A) are made from prosthetic skin and the cruciform pulleys are made from dental rubber bands. These pulleys hold the tendon in place during flexion (B), and damage to the pulleys leads to bowstringing (C).

for each participant. Two established orthopedic hand surgeons served as control subjects, as a baseline measure of proficiency; they performed cadaveric tendon repairs without the workshop intervention, and their repairs were anonymously recorded.

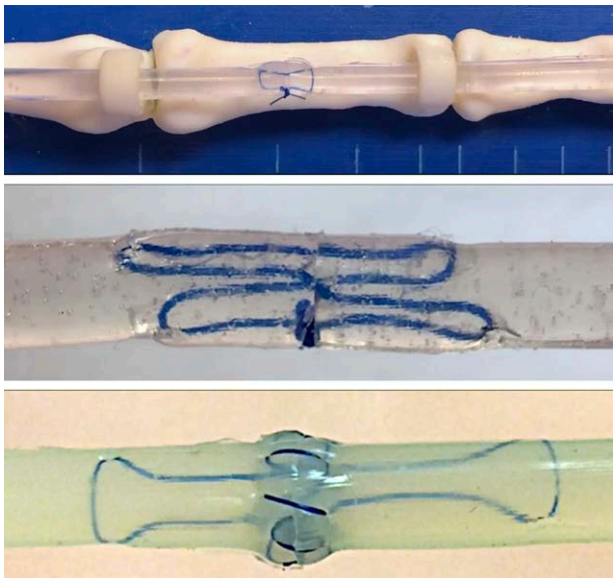

Fig. 3. Silicone tendon structure to allow for visualization of core suture. Modified Kessler in situ to display feedback facilitated repairs. Four-strand cruciate and modified Kessler core sutures shown in example core tendons in the lower panels.

Repair Scoring

The anonymous pre- and postworkshop videos as well as the control subject videos were graded in a random order by two certified hand surgeons. This was done in a blinded fashion. Using a five point scale, the participants were graded on stitch placement, tendon handling, knot tying, tendon alignment, and overall performance, in similar fashion to Ingraham et al[6] (Fig. 5).

Tendon Strength Measurements

The repaired cadaveric tendons were removed from digits and placed under progressive tensile force until failure. This was performed with a tensometer (Instron 4201 Tension and Compression Testing Machine). The resultant terminal force was recorded (Fig. 6).

Statistical Analyses

Rankings were used for pre- and postsurveys, with analysis by Wilcoxon rank sum. Continuous variables for scoring and strength of repair were assessed with Student *t* test and ANOVA, where appropriate. All relevant statistical tests were calculated through GraphPad Prism (version 9.5.1).

RESULTS

Subject Demographics and Baseline Confidence

Eleven surgical trainees (four orthopedic surgery residents and seven plastic surgery residents) participated in the study. Only one participant had previously

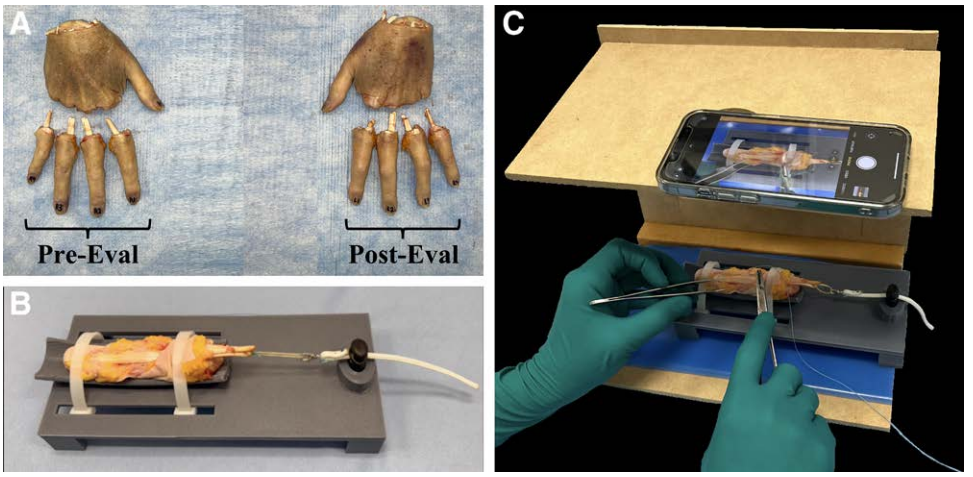

Fig. 4. Cadaveric fingers utilized for pre- and posttest workshops to demonstrate intraoperative conversion. A, Fingers were paired and labeled to allow for similarity between digits each participant used. B, Tendons were placed under tension in 3D printed platform. This was placed inside a stand that gives the participant an ability to record their repairs in an anonymous fashion. Similar gloves were used to allow for this anonymity.

1st Suture		2nd Suture		3rd Suture	
Correct Placement (Grasps approximately 1cm of tendon, away from center)		Correct Placement (Within 1mm previous exit, 5-10mm from tendon edge)		Correct Placement (Runs parallel to tendon and exits at cut end)	
Proper Handling		Proper Handling		Proper Handling	
4th Suture		**5th Suture**		**6th Suture**	
Correct Placement (Within 1mm previous exit, 5-10mm from tendon edge)		Correct Placement (Grasps approximately 1cm of tendon, runs parallel)		Correct Placement (Runs parallel to tendon and exits at cut end)	
Proper Handling		Proper Handling		Proper Handling	
Knot Tying		**Overall Tendon Placement**		**Overall Performance**	
Knot Tied Appropriately		Tendon Edges (Tendon edges abutting, not bunching or gapping)		Overall Surgical Movement, Planning, and Execution	

Fig. 5. Scoring rubric for flexor tendon repair broken down by each suture placement. Suture scoring was divided into correct placement and proper handling. Overall performance and final knot tying were separate and scored at the end of the video assessment.

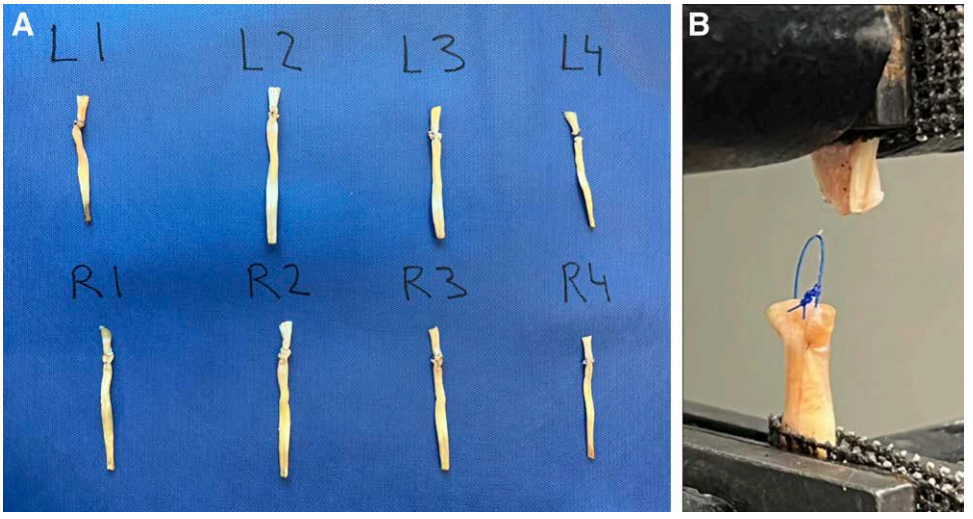

Fig. 6. Tendon removal and strength testing after repairs. Tendons were removed from each finger (A). Tendons were loaded into Instron 4201 Tension and Compression Testing Machine and placed under progressive tensile force until failure (B).

Table 1. Depicting the Demographics of Included Learners from Both the Orthopedic and Plastic Surgery Departments

Variable	% Participants
Participant specialty	
Orthopedic surgery residents	4/11 = 36%
Plastic surgery residents	7/11 = 63%
Year of training of participants	
PGY-1	9/11 = 82%
PGY-2	2/11 = 18%
Previous live flexor tendon repair	1/11 = 9%
Previous practice outside OR	0/11 = 0%
Would welcome practice outside OR	11/11 = 100%

PGY, post-grad year.

participated in a flexor tendon repair surgery, and 100% of the PGY1 and PGY2 study participants indicated that they were "not at all" confident in flexor tendon repair technique on their presurvey (n = 11). None of the participants had ever practiced outside of the operating room, although all participants (n = 11) indicated that they desired a means to practice flexor tendon repair in a controlled, nonoperative setting (Table 1). After the workshop, there was a significant increase in subjective confidence levels in both core and epitendinous suture placement ($P = 0.001$) (Fig. 7).

Using a five-point Likert scale, the participants were surveyed on the realism, educational utility, and usefulness for both the tendon model and the instructional video. The device and video received scores of 4+ across all categories (Fig. 8).

Repair Time and Skill as Reviewed by Hand Surgeons

Following the hands-on workshop, all participants improved their flexor tendon repair time. Average preworkshop repair time was 5.25 minutes, which decreased to 3.5 minutes after simulator exposure (Fig. 9).

Improvements were also noted in objective skill assessment by the surgeons who evaluated the participants' repairs. Stitch placement increased from a score of 3.09 ± 0.73 to 4.23 ± 0.343 ($P = 0.003$). Tendon manipulation increased from 3.47 ± 0.62 to 4.34 ± 0.37 ($P = 0.003$). Knot tying increased from 3.2 ± 1.47 to 4.7 ± 0.47 ($P = 0.005$). Tendon alignment improved from 2.45 ± 1.37 to 4.27 ± 0.90 ($P = 0.016$). Together, these improvements were reflected in a significant increase in overall performance ($P = 0.0003$; Fig. 10).

Tensile Strength Testing

There was no demonstrable difference in terminal breaking strength of repairs before and after the workshop (pre: 21.6N ± 8.39, post: 22.1N ± 7.11, $P = 0.87$).

DISCUSSION

A 3D printed surgical simulator was developed to enhance flexor tendon repair training for surgical trainees. Historically, residents have gained surgical experience with this procedure through a graduated training model, where they initially observe as an assistant before progressively assuming a more active role in the operating room over time.[9,10] Efforts are made to safely advance toward surgical competence, yet surveyed junior residents generally feel uncomfortable and underprepared for flexor tendon repairs. Not surprisingly, all resident participants desired a better way to practice outside of the operating room.

Various approaches to flexor tendon repair simulation have previously been described in the literature.[6,9,11–13] Some studies endorse using porcine tendons because they are cheap and feel similar to human tendons.[11,12] Although useful, such animal models come with known biohazard risks, require access to laboratory space, and may violate some cultural or religious practices.[10,11] Other articles describe practicing on lacerated rubber bait worms,[6] silicone tubes,[9,13] and urinary catheters[14] secured to a platform; however, these models do not incorporate anatomic structures aside from the mock tendon. One study built

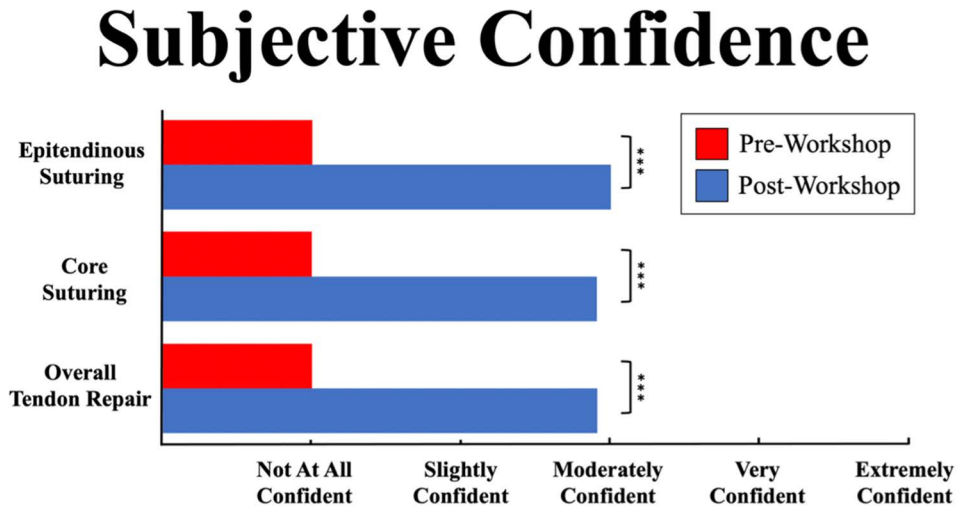

Fig. 7. Subjective confidence before (preworkshop, red) and after (postworkshop, blue) from participant. There was a significant increase in subjective confidence levels in epitendinous suturing, core suturing, and overall tendon repair ($P < 0.001$).

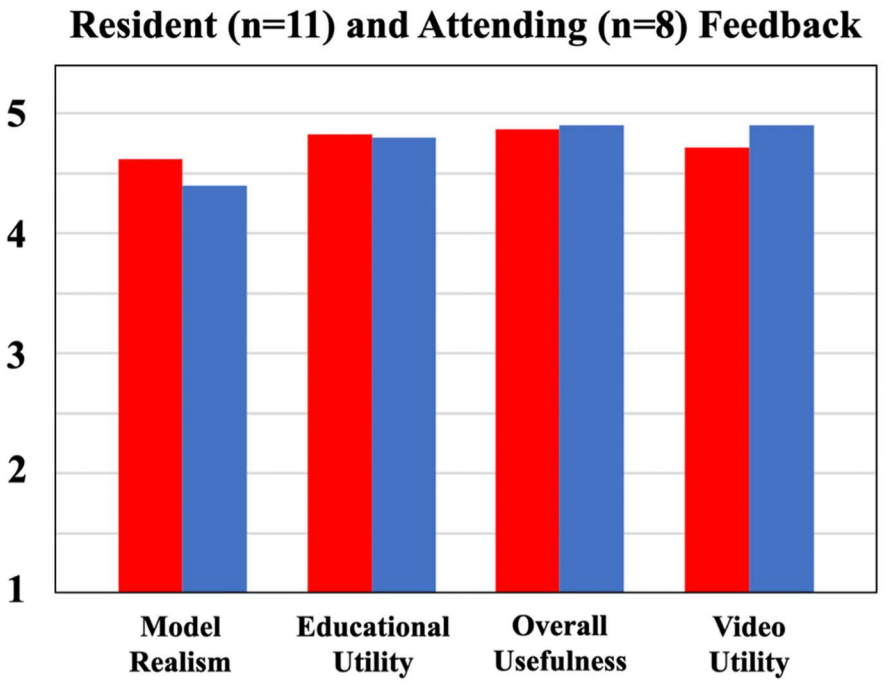

Fig. 8. Feedback on model realism, educational utility, overall usefulness, and video utility. These were highly rated in all categories by both resident and attending physicians.

a more complete training device with wooden phalanges connected by wire hinges and pulleys made of micropore tape; this requires significant manual assembly for each simulation.[11]

The novel device introduced in this study is an anatomically accurate model that is easily produced and requires minimal assembly. The model includes flexible, labeled joints and pulleys with schematics of core and epitendinous suturing techniques. The mock tendons themselves are transparent, which allows learners and instructors to visualize the path of suture as it travels through the cut tendon, giving real-time feedback.[13] Although there is an offset of tendon feel with this design, the benefits in terms of cost, availability, and transparency outweigh this drawback. This was corroborated by the survey responses of both residents and hand surgeons (Fig. 8). Furthermore, unlike cadaveric or animal training models, this 3D printed trainer is sterile and can be mass produced at a reasonable price. The reusable simulator costs approximately $40 to print; the mock tendons costs less than $0.25 each to make. Afterward, the simulator can be used infinitely, whereas the tendons can be used as much as there is room, which trended about five repairs each. Overall, this affordable model provides an opportunity for trainees to gain technical skill and for any surgeon to experiment with new techniques.

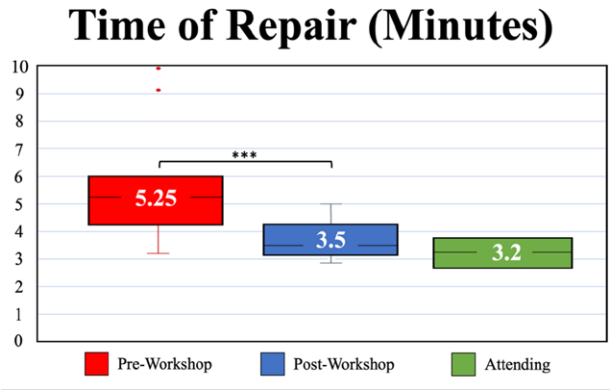

Fig. 9. Time of repair before (preworkshop, red) and after (postworkshop, blue) the workshop and device utilization. This significantly decreased ($P < 0.001$). Time approached average attending time.

The participants' objective improvement in cadaveric tendon repair skill, as seen in the scores by hand attendings, demonstrates the validity of this simulator and increased confidence of the resident participants.[15] In all domains, participants significantly improved their skill after only one training session. With more frequent and consistent use of these models, further improvement is anticipated. This is due, in part, to the repetition of this procedure that can be effectively reproduced in this simulator.

Strength of repair did not change between the pre- and postworkshop groups. Previous studies have shown that strength of repair is correlated most closely with number of core sutures and use of grasping versus locking knots.[16] Because tensile strength can also be influenced by suture material choice and knot tying ability, we do not expect this metric alone to be a significant indicator

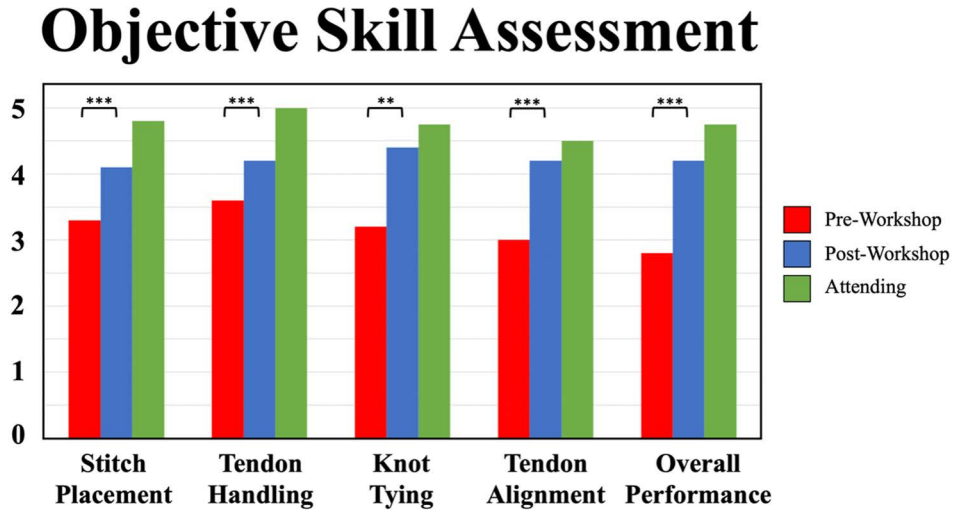

Fig. 10. Scoring results from each category as displayed in Figure 6. Stitch placement increased from a score of 3.09 ± 0.73 to 4.23 ± 0.343 ($P = 0.003$), tendon manipulation increased from 3.47 ± 0.62 to 4.34 ± 0.37 ($P = 0.003$), knot tying increased from 3.2 ± 1.47 to 4.7 ± 0.47 ($P = 0.005$), and tendon alignment improved from 2.45 ± 1.37 to 4.27 ± 0.90 ($P = 0.016$).

of improvement in skill. Other factors, including tendon gapping, knot exposure, external suture burden, tendon bunching, and early motion affect clinical outcome and should be considered as well.[16,17]

Finally, it should be noted that the participants' skill, time, and confidence improvements were achieved within a single 2-hour workshop. If instead residents were given longitudinal access to the device with opportunity for deliberate practice at staggered intervals throughout their training, it is likely that their improvement would be even more pronounced.[18,19] Incorporation of supervising surgeons into these simulated environments may facilitate trust and earlier resident participation in the operating room, along with improved clinical results at teaching facilities. Future developments for this project include longitudinal tracking of workshop scores, survey responses, and formal operative experience with tendon repair throughout the duration of these participants' multi-year training and the incorporation of more supervising surgeons into these workshops for direct feedback.

CONCLUSIONS

Using 3D printing technology, an anatomically representative surgical simulator was developed for zone 2 flexor tendon repair of the digit. A flexor tendon repair workshop for surgical trainees confirmed the utility of this device in surgical resident training. Scores for repair time and quality of repair significantly improved after use of this device in a single training workshop. Initial feedback from resident and supervising surgeons has been uniformly positive regarding model realism and educational utility. When 3D printed en masse, the device is affordable, easily assembled, and reusable—all factors that facilitate accessibility. The devise is a valuable tool with potential to improve resident training and clinical outcomes at teaching facilities.

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DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

REFERENCES

1. de Jong JP, Nguyen JT, Sonnema AJM, et al. The incidence of acute traumatic tendon injuries in the hand and wrist: a 10-year population-based study. *Clin Orthop Surg.* 2014;6:196–202.
2. Clark DP, Scott RN, Anderson IW. Hand problems in an accident and emergency department. *J Hand Surg Br.* 1985;10:297–299.
3. Chang MK, Tay SC. Flexor tendon injuries and repairs: a single centre experience. *J Hand Surg Asian Pac Vol.* 2018;23:487–495.
4. Tang JB, Lalonde D, Harhaus L, et al. Flexor tendon repair: recent changes and current methods. *J Hand Surg Eur Vol.* 2022;47:31–39.
5. Jo S, Calfee RP. General principles of flexor tendon repair. *Hand Clin.* 2023;39:131–139.
6. Ingraham JM, Weber RA, Weber RA. Utilizing a simulated tendon to teach tendon repair technique. *Hand (N Y).* 2009;4:150–155.
7. Noland SS, Fischer LH, Lee GK, et al. Essential hand surgery procedures for mastery by graduating plastic surgery residents: a survey of program directors. *Plast Reconstr Surg.* 2013;132:977e–984e.
8. Heskin L, Simms C, Holland J, et al. A systematic review of the educational effectiveness of simulation used in open surgery. *Simul Healthc.* 2019;14:51–58.
9. Abdulal S, Onyekwelu O. An alternative model for teaching tendon repair and surgical skills in plastic surgery. *JPRAS Open.* 2016;7:12–15.
10. Pabari A, Lim P, Lindford A, et al. A cost effective training tool for flexor tendon repair: pig's trotters. *J Plast Reconstr Aesthet Surg.* 2006;59:1248.

11. Brichacek M, Diaz-Abele J, Shiga S, et al. Three-dimensional printed surgical simulator for Kirschner wire placement in hand fractures. *Plast Reconstr Surg Glob Open*. 2018;6:e1706.
12. Sirisena R, Lahiri A, Chong AKS, et al. Surmounting the learning curve of core suture placement with tendon repair simulator. *J Hand Surg Asian Pac Vol*. 2018;23:217–220.
13. Holmes WJM, Tehrani H, Mishra A, et al. The use of a silicone flexor tendon as a teaching model for flexor tendon repair: a clear view. *J Plast Reconstr Aesthet Surg*. 2013;66:294–295.
14. Hoeyberghs JL, Flemming AFS. Flexor tendon repair in perfect safety. *Eur J Plast Surg*. 1994;17:215–217.
15. Klit A, Konge L, Nayahangan LJ, et al. A national needs assessment to identify technical procedures in plastic surgery for simulation-based training. *J Plast Surg Hand Surg*. 2023;57:137–144.
16. Strickland JW. Development of flexor tendon surgery: twenty-five years of progress. *J Hand Surg Am*. 2000;25:214–235.
17. Skirven TM, DeTullio LM. Therapy after flexor tendon repair. *Hand Clin*. 2023;39:181–192.
18. Mitchell SA, Boyer TJ. Deliberate practice in medical simulation. In: *StatPearls* [online]. StatPearls Publishing; 2023. Available at http://www.ncbi.nlm.nih.gov/books/NBK554558/. Accessed June 19, 2023.
19. Petrosoniak A, Sherbino J, Beardsley T, et al. Are we talking about practice? A randomized study comparing simulation-based deliberate practice and mastery learning to self-guided practice. *CJEM*. 2023;25:667–675.