

Innovating Medical Education: Development of an Affordable, 3-D Printed Knot-Tying Simulator

Background

Three-dimensional (3-D) printing offers an innovative option to produce clinical simulators due to its low production costs and widespread availability. We aimed to develop a low-cost, 3-D printed knot-tying simulator that overcomes the barriers students face in self-directed skills development.

Approach

Medical students completing a procedural residency preparation course (PRPC) completed a pre-survey with Likert scales and multiple choice questions to assess their perceptions of and barriers to self-directed knot-tying practice. Subsequently, a 3-D printed knot-tying simulator, which contains a progression of knot-tying challenges and a designated video curriculum, was designed. After utilizing the simulator in a one-hour, faculty-guided knot tying session, PRPC students assessed the educational utility and usability of the simulator via a post-survey.

Evaluation

The primary barriers students faced in engaging in self-directed knot-tying practice included limited accessibility to simulators and insufficient knowledge of knot-tying techniques. Many students (91.3%, n = 21) agreed that practicing with the simulator improved their knot-tying motor skills and was easy to use (100%, n = 23). Twenty-two (95.7%) students agreed they would continue to use the simulator beyond the knot-tying session and PRPC.

Implications

We demonstrate the educational utility and usability of a novel 3-D printed knot-tying simulator for medical education. Enabling students to engage in self-directed technical skills development is critical in developing surgical skills that can translate to clinical environments. Our simulator highlights the benefits of 3-D printers as an innovative, inexpensive option to improve the availability and accessibility to medical education tools.

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1. Background

Simulation-based training has rapidly grown to provide engaged medical students with modules to practice and develop core technical skills, such as surgical knot-tying, within safe environments (1). As simulators continue to grow in popularity with medical students, it is critical that they are readily available and accurately teach designated skills to a broad cohort of learners.

However, simulators are often associated with high costs, low accessibility, and limited portability (2,3). Traditional knot-tying simulators often range in cost between USA\$10 to USA\$100 and may be limited in their ability to be distributed globally. These barriers have limited the widespread implementation of simulation-based training and prevented students from partaking in skills practice necessary to improve their knot-tying abilities (4). To overcome these challenges, students often repurpose everyday items or independently purchase resources to improve their knot-tying skills. Yet, these methods may not accurately replicate knot-tying in the clinical setting or incorrectly teach students critical skills.

Potentially, three-dimensional (3-D) printing offers an innovative option to overcome the barriers associated with the development and widespread implementation of a knot-tying simulator. The benefits of 3-D printing include its low costs of production, widespread availability, and high printing fidelity (5). Furthermore, 3-D printed simulators have been shown to accurately replicate clinical environments and improve users' technical skills (6,7). We sought to understand medical students' perceptions of knot-tying and to develop and validate a cost-effective, 3-D printed knot-tying simulator for medical students.

2. Approach and Evaluation

2.1 Phase 1: Evaluating Medical Students' Perceptions of Knot Tying

In January 2023, we recruited medical students ($n = 50$) completing a procedural residency preparation course (PRPC) to complete an electronic survey generated on Qualtrics (Qualtrics, Provo, UT) gauging perceptions of, barriers to, and readiness for knot-tying during residency

training (Supplemental File 1). Students completed the survey using their mobile devices or computers during a dedicated five-minute period at their PRPC orientation session. Likert-type scaling was used to score materials, ranging from '1 – Strongly Disagree' to '5 – Strongly Agree'. The survey incorporated established methods of medical education survey development, including the option for participants to decline to respond to any question (8). This study was deemed exempt by the Institutional Review Board.

Thirty students completed the survey (60.0% response rate). One hundred percent (n = 30) agreed that learning to tie surgical knots was an important skill to learn at their level of training. Amongst the cohort, the overall preparedness to tie surgical knots during residency training was scored 3.8 ± 1.0 . The most common barriers to self-directed knot-tying practice were limited accessibility to knot-tying materials (86.7%, n = 26), insufficient knowledge of knot-tying instructional materials (56.7%, n = 17), and insufficient knowledge of knot-tying techniques (63.3%, n = 19) (Figure 1). One hundred percent (n = 30) of students agreed that they would benefit from a durable, portable tool with a designated knot-tying curriculum to practice their knot-tying skills.

2.2 Phase 2: Designing and Developing a 3-D Printed Knot-Tying Simulator

2.2.1 Simulator Goals, Components, and Cost

A knot-tying simulator was designed under the guidance of faculty surgeons. To address the concerns expressed by our students, we identified three objectives a knot-tying simulator must accomplish. These objectives were that a simulator must: 1) incorporate components that are cost-effective, 2) contain knot-tying challenges of increasing complexity, and 3) integrate a curriculum to teach students various knot-tying techniques.

Prototyping of the simulator was completed using Rhinoceros (Robert McNeel & Associates, Seattle, WA), a computer-aided design software able to create 3-D models. Stereolithography files were created and exported to PrusaSlicer software and printed on a Prusa

Mini+ Printer (Prusa, Prague, Czech Republic). The final design was a 45mm x 60mm x 20.5mm knot-tying simulator that weighed 13.0 grams (Figure 2). For final assembly, each knot-tying simulator required a suction cup, a 25mm x 25mm quick-response (QR) code printed onto vinyl sticker paper, and a 15mm diameter rubber band. The total cost of materials per device was less than USA\$1, which is significantly lower than those simulators found in online marketplaces.

2.2.2 Knot-Tying Skills Progression

Through an iterative prototyping process, we designed a graduated progression of skills challenges into the simulator. These knot-tying challenges included: 1) a tunneled port for basic knot-tying, 2) a tension mechanism for tying under tension, and 3) a shallow groove for delicate knot-tying. The design and objectives of each component are further outlined in Table 1. These design features were ultimately designed with the intention of equipping our learners with the ability to tie surgical knots under various circumstances that may be encountered during their residency training, such as approximating tissue edges or tying delicate tissue like blood vessels (9,10).

2.2.3 Knot-Tying Curriculum

Our final objective was to create a curriculum to teach users how to use the simulator and core knot-tying skills. Therefore, instructional videos teaching two-handed knots, one-handed knots, and instrument tying were developed and uploaded to YouTube (Google, San Bruno, CA). Furthermore, lessons on the function of each design feature of the simulator were developed to equip students to appropriately use the simulator's various skills challenges. The videos were kept under five minutes each to encourage student engagement (11). For users to easily access this video curriculum, a QR code linked to the video series was integrated into the model (Figure 3). A QR code was used due to its reliable, high-speed scanning and immediate access to information with the use of personal devices (12). Of note, we welcome both individuals and institutions who may or may not be utilizing this innovation to utilize these videos for educational purposes.

2.3 Phase 3: Evaluating Medical Students' Perceptions of the 3-D Printed Simulator

In March 2023, students in the PRPC participated in an hour-long knot-tying session guided by three faculty surgeons (Table 2). Students were taught how to use the simulator and how to tie various surgical knots with the assistance of the video curriculum. After observing the video curriculum, students were allotted time to ask questions. Furthermore, faculty surgeons were available during the self-directed practice to assist students and guide them through knot-tying techniques. Similar to the initial evaluation, students completed an electronic post-survey gauging the simulator's usability and educational utility (Supplemental File 2).

Twenty-three students completed the post-survey (46.0% response rate) (Figure 4). One hundred percent ($n = 23$) of respondents agreed that the simulator was a useful tool for practicing knot-tying skills. Among the respondents, 91.3% ($n = 21$) and 87.0% ($n = 20$) agreed that practicing with the simulator improved their motor skills and confidence in knot-tying, respectively. One hundred percent ($n = 23$) of students agreed that the simulator was easy-to-use and 82.6% ($n = 19$) stated the simulator provided a durable surface to practice their knot-tying skills. The mean $\pm$ standard deviation for the satisfaction score for the knot-tying simulator was 4.2 ± 0.7 . Importantly, 95.7% ($n = 22$) of people stated that they would continue to use the simulator beyond both the knot-tying session and PRPC. The effectiveness of the video curriculum in teaching how to tie two-handed knots and one-handed knots both scored 4.1 ± 0.9 . The video teaching students how to instrument tie was rated 4.0 ± 1.0 .

3. Implications

Our innovation demonstrates the ability to design a cost-effective tool for motivated learners to reliably engage in self-directed practice of their surgical knot-tying skills. Features such as the graduated progression of knot-tying challenges and an integrated video curriculum provide a dynamic learning experience for students. This structured approach to technical skills development

encourages continuous improvement and ensures students may build a strong foundation before tackling more advanced techniques.

Importantly, this innovation highlights the benefits of 3-D printing as a valuable tool that can increase the accessibility and availability of medical simulators. In addition to the PRPC knot-tying session, the high fidelity and efficiency of 3-D printing have allowed us to integrate the simulator into our institution's core surgical clerkship. With this, we are routinely distributing nearly 40 simulators to students every three months. Preparation of the simulators for a cohort of this size takes approximately three to five days. Therefore, we believe it is feasible for other institutions with 3-D printing capabilities to replicate our innovation.

Furthermore, the low cost of production has enabled us to allow students in the PRPC to keep the simulators after their course. This furthers the opportunities for students to engage in longitudinal skills practice that is essential for mastering knot-tying. In reflecting on this ability, an area of improvement for the implementation of the simulator includes creating a longitudinal curriculum for students. By creating a step-wise, structured approach to learning, we could create uniformity in training and assessing specific learning competencies that could allow students to track their progress and competency levels over time.

There are multiple limitations that exist in the design and implementation of our innovation. Implementation of our simulator required access to 3-D printers, which can range in cost from USA\$150 to USA\$3000. Moreover, the evaluation of our innovation relied on survey-based data and student perceptions of the simulator rather than objective measures and direct performance evaluations, which could provide standardized insight into the simulator's utility. Furthermore, the limited sample size, coupled with a low survey response rate, introduced a selection bias towards a subset of learners who are inherently motivated to engage in self-directed skills training. Therefore, our innovation may be limited in its ability to provide similar benefits to knot-tying skills development in a broader cohort of learners.

4. Conclusion

Guided by the barriers our students experience, our team designed a novel, low-cost 3-D printed knot-tying simulator that students agreed was simple to use and had high educational utility. To further achieve our goal of increasing the accessibility and availability of simulators, we have included both the simulator's design file (Supplemental File 3) and sources for the simulator's materials (Supplemental File 4) with this manuscript. Ultimately, these additions enable institutions and individuals with access to 3-D printers to reproduce the simulator and implement the innovation on both a small and large scale.

Pullout quotes:

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- One hundred percent ($n = 30$) agreed that learning to tie surgical knots was an important skill to learn at their level of training.
- Through an iterative prototyping process, we designed a graduated progression of skills challenges into the simulator.
- Therefore, instructional videos teaching two-handed knots, one-handed knots, and instrument tying were developed and uploaded to YouTube (Google, San Bruno, CA).
- Among the respondents, 91.3% ($n = 21$) and 87.0% ($n = 20$) agreed that practicing with the simulator improved their motor skills and confidence in knot-tying, respectively.
- Importantly, this innovation highlights the benefits of 3-D printing as a valuable tool that can increase the accessibility and availability of medical simulators.

- Furthermore, the low cost of production has enabled us to allow students in the PRPC to keep the simulators after their course.

References

1. Sadideen H, Plonczak A, Saadeddin M, Kneebone R. How Educational Theory Can Inform the Training and Practice of Plastic Surgeons. *Plast Reconstr Surg Glob Open*. 2018 Dec 12;6(12):e2042.
2. Milburn JA, Khera G, Hornby ST, Malone PSC, Fitzgerald JEF. Introduction, availability and role of simulation in surgical education and training: Review of current evidence and recommendations from the Association of Surgeons in Training. *Int J Surg*. 2012 Jan 1;10(8):393–8.
3. Danzer E, Dumon K, Kolb G, Pray L, Selvan B, Resnick AS, et al. What Is the Cost Associated with the Implementation and Maintenance of an ACS/APDS-Based Surgical Skills Curriculum? *J Surg Educ*. 2011 Nov 1;68(6):519–25.
4. Hosny SG, Johnston MJ, Pucher PH, Erridge S, Darzi A. Barriers to the implementation and uptake of simulation-based training programs in general surgery: a multinational qualitative study. *J Surg Res*. 2017 Dec 1;220:419–426.e2.
5. Brans K. 3D Printing, a Maturing Technology. *IFAC Proc Vol*. 2013 May 1;46(7):468–72.
6. Palmon I, Michaels R, Claflin J, Behrend M, Zopf DA, Waits S. Design, development and multi-institutional validation of a low-cost 3D-printed liver transplant simulator. *J 3D Print Med*. 2022 Dec;6(4):187–93.
7. Boyajian MK, Lubner RJ, Roussel LO, Crozier JW, Ryder BA, Woo AS. A 3D printed suturing trainer for medical students. *Clin Teach*. 2020 Dec;17(6):650–4.
8. Artino AR, La Rochelle JS, Dezee KJ, Gehlbach H. Developing questionnaires for educational research: AMEE Guide No. 87. *Med Teach*. 2014 Jun;36(6):463–74.
9. Kudur MH, Pai SB, Sripathi H, Prabhu S. Sutures and suturing techniques in skin closure. *Indian J Dermatol Venereol Leprol*. 2009;75(4):425–34.
10. Hsu JL, Korndorffer JR, Brown KM. Force feedback vessel ligation simulator in knot-tying proficiency training. *Am J Surg*. 2016 Feb 1;211(2):411–5.
11. Guo PJ, Kim J, Rubin R. How video production affects student engagement: an empirical study of MOOC videos. In: *Proceedings of the first ACM conference on Learning @ scale conference* [Internet]. New York, NY, USA: Association for Computing Machinery; 2014 [cited 2024 Mar 6]. p. 41–50. (L@S '14). Available from: <https://dl.acm.org/doi/10.1145/2556325.2566239>
12. Sharara S, Radia S. Quick Response (QR) codes for patient information delivery: A digital innovation during the coronavirus pandemic. *J Orthod*. 2022 Mar 1;49(1):89–97.

Supplemental Files

1. Pre-Survey Questions.docx
2. Post-Survey Questions.docx
3. Nodo-Tie.stl
4. Supply List.docx
5. Nodo-Tie QR Code.png

Figure/Table legends

Figure 1. Barriers to self-directed knot-tying practice. Knot-tying materials include sutures and simulators. Instructional materials refer to any physical or online references aimed at teaching knot-tying techniques. Knot-tying techniques refer to types of surgical knots, such as one-handed knots, two-handed knots, and instrument tying.

Figure 2. Printed and assembled knot-tying simulator. A. Overview of the knot-tying simulator with rubber band attached. The three knot-tying challenges from left to right are depicted: basic knot-tying, knot-tying under tension, and delicate knot-tying. B. Close-up view of the simulator depicting the attachment points of the tension bands for knot-tying under tension and the suction cup. C. Isometric view of the simulator with a pen in the shallow groove for delicate knot-tying.

Figure 3. Quick-response (QR) code linked to the knot-tying video curriculum (<https://www.youtube.com/@nodo-tie>).

Figure 4. Survey results depicting medical students’ perceptions to the 3-D printed knot-tying simulator’s educational utility and usability.

Table 1. Design features of the graduated knot-tying challenges of the simulator and benefits for self-directed practice and clinical applications.

Table 2. Structure and timing of the one-hour, faculty-guided knot-tying session.

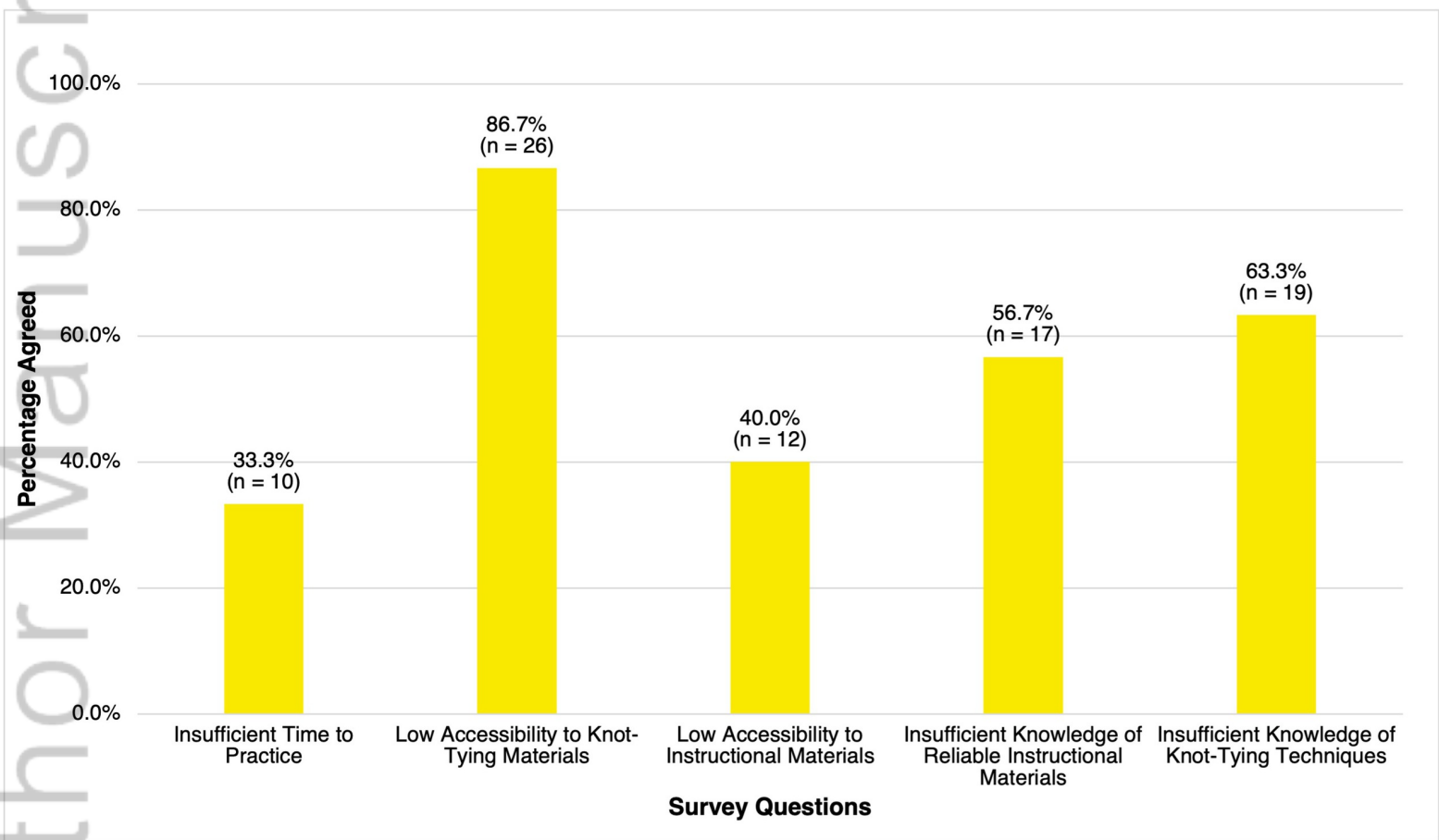


Figure 1.jpg



Figure 2.jpg



Figure 3.jpg

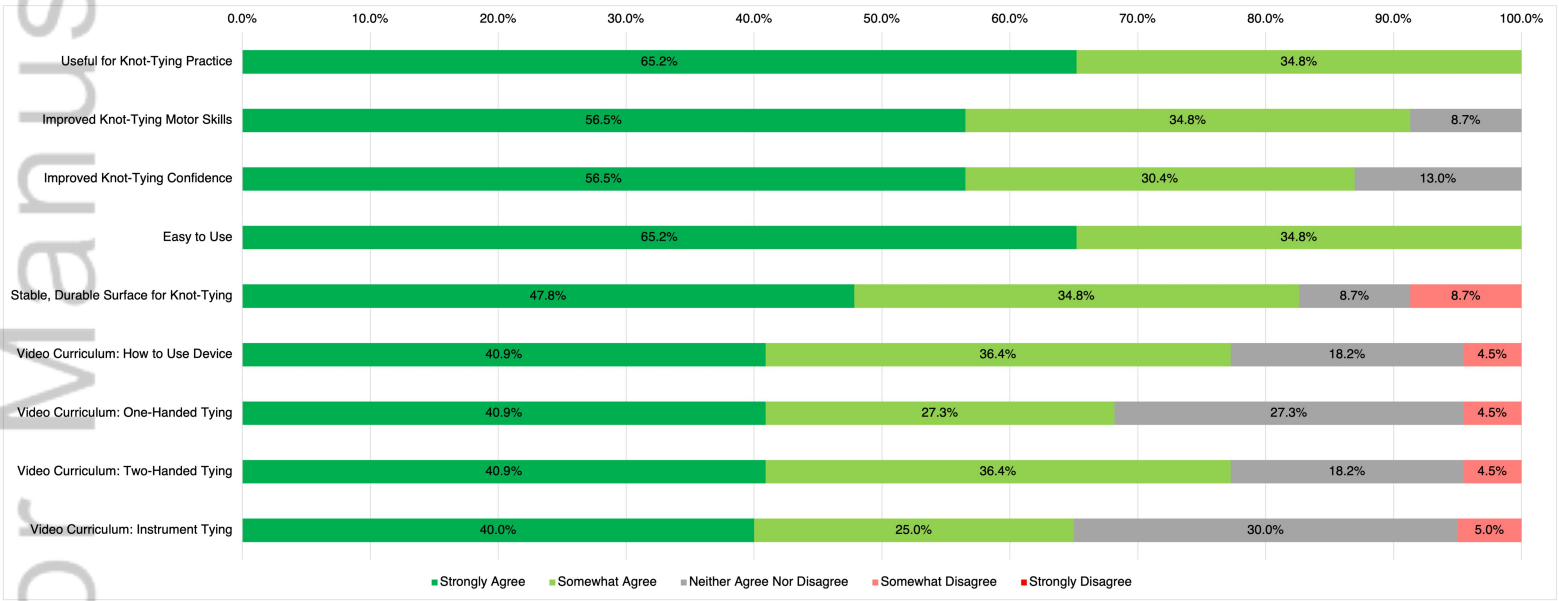


Figure 4.jpg