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Research Paper

# Nodo-Tie: an innovative, 3-D printed simulator for surgical knot-tying skills development

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A R T I C L E   I N F O

*Keywords:*
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A B S T R A C T

*Introduction:* Clinical simulators are an important resource for medical students seeking to improve their fundamental surgical skills. Three-dimensional (3-D) printing offers an innovative method to create simulators due to its low production costs and reliable printing fidelity. We aimed to validate a 3-D printed knot-tying simulator named Nodo-Tie.
*Methods:* We designed a 3-D printed knot-tying simulator integrated with a series of knot-tying challenges and a designated video curriculum made accessible via a quick-response (QR) code. The Nodo-Tie, which costs less than $1 to print and assemble, was distributed to second-year medical students starting their surgical clerkship. Participants were asked to complete a survey gauging the simulator's usability and educational utility. The time between simulator distribution and survey completion was eight weeks.
*Results:* Students perceived the Nodo-Tie as easy-to-use (4.6 ± 0.8) and agreed it increased both their motor skills (4.5 ± 0.9) and confidence (4.5 ± 0.8) for tying surgical knots in the clinical setting. Many students agreed the Nodo-Tie provided a stable, durable surface for knot-tying practice (83.7%, $n = 41$) and that they would continue to use it beyond their participation in the study period (91.7%, $n = 44$).
*Discussion:* Medical students found this interactive, 3-D printed knot-tying simulator to be an effective tool to use for self-directed development of their knot-tying skills. Given the Nodo-Tie's low cost, students were able to keep the Nodo-Tie for use beyond the study period. This increases the opportunity for students to engage in the longitudinal practice necessary to master knot-tying as they progress through their medical education.
*Key messages:* Clinical simulators provide proactive learners with reliable, stress-free environments to engage in self-directed surgical skills development. The Nodo-Tie, a 3-D printed simulator, serves as a cost-effective, interactive tool for medical students to develop their knot-tying abilities beyond the clinical setting.

## Introduction

Knot-tying is a fundamental skill in surgical practice that requires extensive training to ensure proficiency. In recent years, simulation-based training has become increasingly popular as a safe and effective method for medical students to develop technical skills [1]. These simulations have incorporated innovative technologies such as virtual reality and formalized curriculums to improve the realism of the training experience, allowing for improved learning outcomes [2]. As a result, medical students have been able to develop their knot-tying skills with reliability and consistency [3,4].

However, while surgical simulators have gained popularity, significant barriers remain. Cost, accessibility, and portability limit the widespread adoption of simulation as a training method [5,6]. These barriers may be even more pronounced in under-resourced and rural training programs, resulting in an inequitable distribution of clinical simulators and a lack of opportunities for medical students to engage in the necessary longitudinal practice required to master knot-tying [7,8]. Consequently, students often resort to using everyday items or purchasing resources independently, but these methods may not accurately

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replicate the complexity of knot-tying in a clinical setting or provide adequate instruction [9].

Therefore, three-dimensional (3-D) printing presents a promising solution to address the challenges associated with the development and widespread implementation of knot-tying simulators. The benefits of 3-D printing include low production costs, widespread availability, and high printing fidelity, making it an attractive option for medical educators [10]. 3-D printed simulators have also shown utility in replicating clinical environments in order to improve core technical skills in trainees [11,12]. The aim of this study was to validate a 3-D printed, cost-effective knot-tying simulator, henceforth referred to as the Nodo-Tie, for medical students, addressing the need for a more accessible and effective training tool.

## Materials and methods

### *Simulator design*

The Nodo-Tie was developed collaboratively with faculty surgeons using computer-aided design software (Rhinoceros, WA, USA). Stereolithography files were created and exported to PrusaSlicer software and printed on Prusa Printers (Prusa, Prague, Czech Republic). The final design had dimensions of 45 mm × 60 mm × 20.5 mm, weighed 13 grams, and took approximately 1 hour to print (Fig. 1A). The final assembly involved the placement of a suction cup, a quick-response (QR) code printed on vinyl stickers, and a 15 mm diameter rubber band (Fig. 1B). The total cost for each Nodo-Tie was $0.78 (Table 1).

### *Simulator design features*

In order to teach students a variety of technical skills, a graduated progression of knot-tying challenges was integrated into Nodo-Tie. The knot-tying challenges included a tunneled port for basic knot-tying, a tension mechanism for tying under tension, and a shallow groove for delicate knot-tying. The tunneled port accommodates a variety of suture types and sizes to allow for user-guided progression to finer sutures (Fig. 2A). The tension mechanism consists of a two-peg system with a rubber band that is brought together when knots are securely fastened (Fig. 2B). This skill is critical in the clinical setting as a means of bringing tissue edges together and preventing postprocedural wound dehiscence [13]. The third and most complex challenge in the simulator was a shallow groove to teach students to gently tie knots (Fig. 2C). By tying around an object, such as a pencil or pen, placed in the groove, students must fasten their knots without causing movement of the object. By replicating a knot-tying skill that uses minimal force, students can be prepared to tie knots that will not avulse or damage delicate tissue like blood vessels [14].

**Table 1**
Cost breakdown for each component of the Nodo-Tie.

| Component | Cost |
|---|---|
| 3-D Printing Materials | $0.33 |
| Suction Cup | $0.40 |
| Rubber Band (5) | $0.02 |
| QR Code | $0.03 |
| Total | $0.78 |

### *Video curriculum development*

To equip students for self-directed knot-tying practice, we developed a video curriculum to teach students how to use the Nodo-Tie and appropriately practice core knot-tying skills. Videos were kept under 5 minutes to encourage student engagement and uploaded to YouTube (Google, San Bruno, CA) [15]. The core knot-tying skills included in the video curriculum were two-handed knots, one-handed knots, and instrument tying. To improve access to the video curriculum, a QR code linked to the video series was integrated into the model due to its reliable, high-speed scanning with the use of personal devices (Fig. 3) [16]. The QR code was generated using Adobe Express (CA, USA) and printed onto a 25 mm × 25 mm vinyl sticker, which was placed onto a clearly visible aspect of each Nodo-Tie.

### *Simulator validation*

From January to July 2023, second-year medical students completing their core surgical clerkship were recruited to use the Nodo-Tie over an eight-week period. Students were given the Nodo-Tie and able to freely practice knot-tying with it during this time.

At the end of the study period, participants were asked to complete an 18-question electronic survey generated on Qualtrics (WA, USA) gauging their perceptions of the Nodo-Tie's educational utility, usability, and feasibility. The survey consisted primarily of Likert-type scaling to score the questions, ranging from "1, strongly disagree" to "5, strongly agree." The survey also included "Yes/No" and free text questions. The survey incorporated established methods of high-fidelity medical surveys, such as the option to decline to respond to any question [17]. Data was collected in a fully anonymized fashion.

## Results

49 medical students completed the survey (60.4% response rate) (Fig. 4). The overall mean ± standard deviation for the usefulness of the

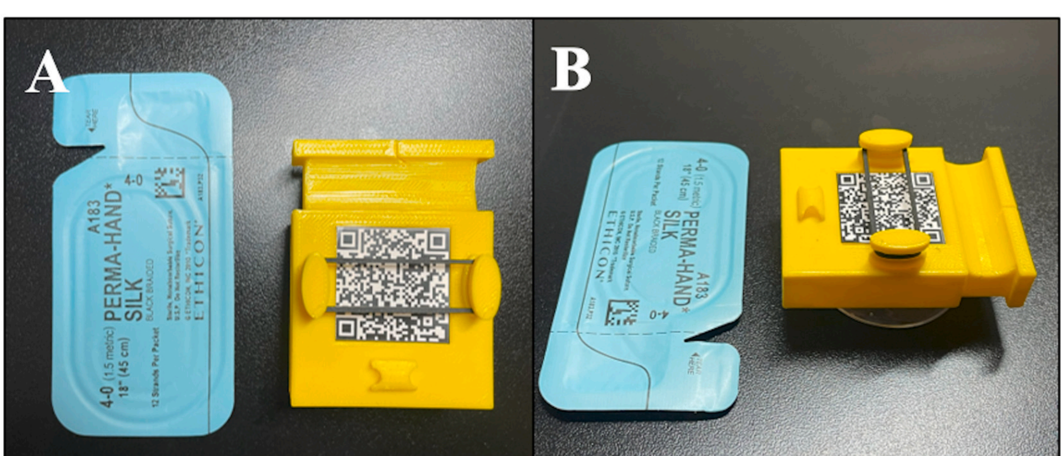


**Fig. 1.** Overview (A) and close-up view (B) of the Nodo-Tie.

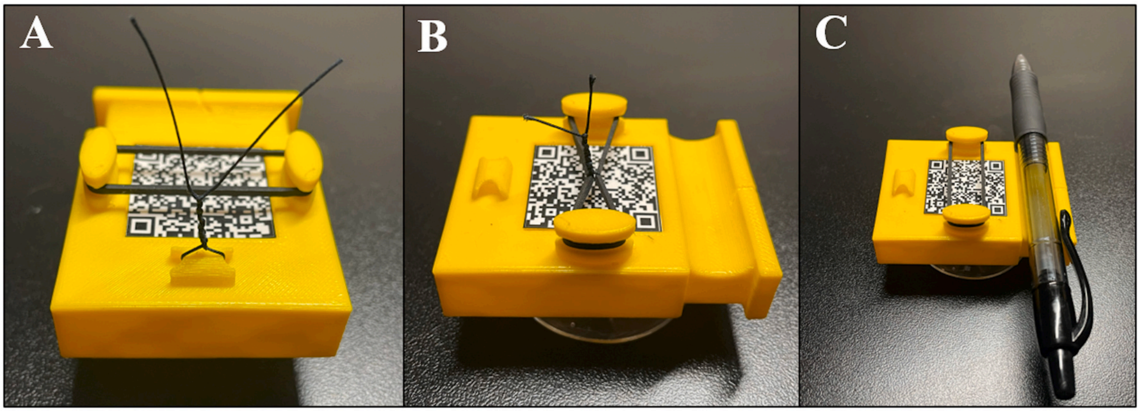


**Fig. 2.** Tunneled port (A) and tension mechanism (B) of the Nodo-Tie with tied surgical suture. The Nodo-Tie with a pen in the shallow groove (C).

**Fig. 3.** Quick-response (QR) code linked to the knot-tying video curriculum.

Nodo-Tie for practicing knot-tying skills was rated 4.5 ± 0.9. Respondents agreed that practicing with the Nodo-Tie improved their motor skills (89.8%, $n = 44$) and confidence (87.8%, $n = 43$) for knot-tying in the clinical setting. Of a maximum score of 4, the tension mechanism (3.6 ± 0.7) was rated the most useful component of the simulator as compared to the tunneled port (3.5 ± 0.9) and shallow groove (3.4 ± 0.9) (Fig. 5).

Regarding usability, 91.8% ($n = 45$) of medical students stated the knot-tying simulator was easy to use. The Nodo-Tie was also perceived to provide students with a stable, durable surface for knot-tying practice (4.3 ± 1.0). Furthermore, 85.7% ($n = 42$) agreed that the design features and compactness of the Nodo-Tie enabled them to use the simulator in various locations, such as at home, the library, or in a clinical setting. The overall satisfaction rating for the Nodo-Tie was scored at 4.3 ± 1.0. Importantly, 91.7% ($n = 44$) agreed that they would continue to use the Nodo-Tie for technical skills development beyond the study period.

Students were also queried to evaluate the feasibility of using the Nodo-Tie. During the study period, 85.7% (n = 42) of students stated that they were practicing knot-tying at least weekly. When practicing their technical skills, 31.3% ($n = 15$) stated they were using the Nodo-Tie "sometimes", 39.6% ($n = 19$) stated they were using it "most of the time", and 18.8% ($n = 9$) stated they were using it "all of the time." 73.3% ($n = 33$) of students stated that the Nodo-Tie was better than other resources they had previously used for knot-tying. Examples of secondary resources students had used to practice their technical skills were foam suture pads or strings on scrub pants.

In terms of the video curriculum, the effectiveness of the videos to teach participants how to use the Nodo-Tie was scored 3.9 ± 0.8. The effectiveness of the video curriculum to teach how to tie two-handed knots and one-handed knots was 3.9 ± 0.8 and 3.8 ± 0.9, respectively. The ability of the videos to teach students how to instrument tie was scored similarly at 3.8 ± 0.9.

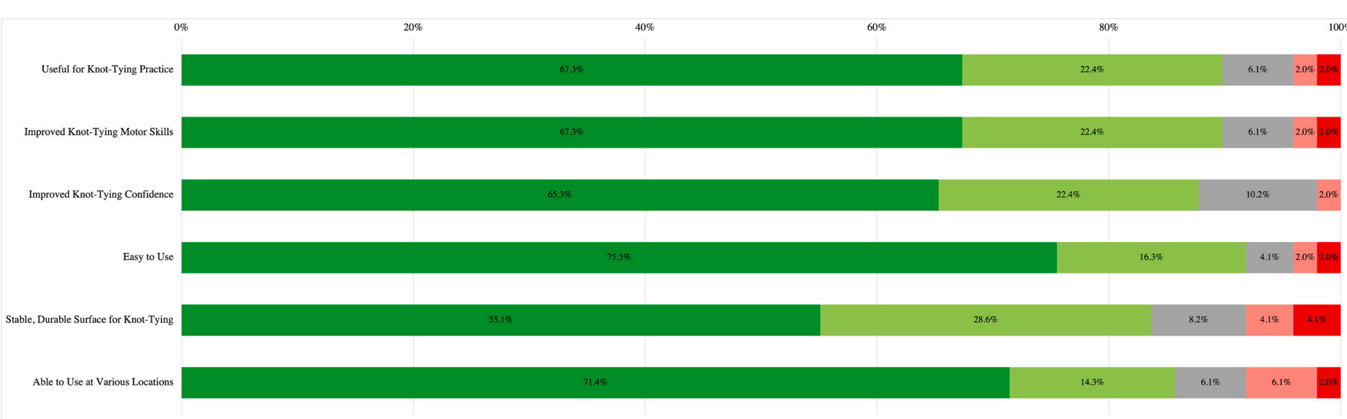


**Fig. 4.** Survey results depicting student's perceptions to the Nodo-Tie's educational utility, feasibility, and usefulness.

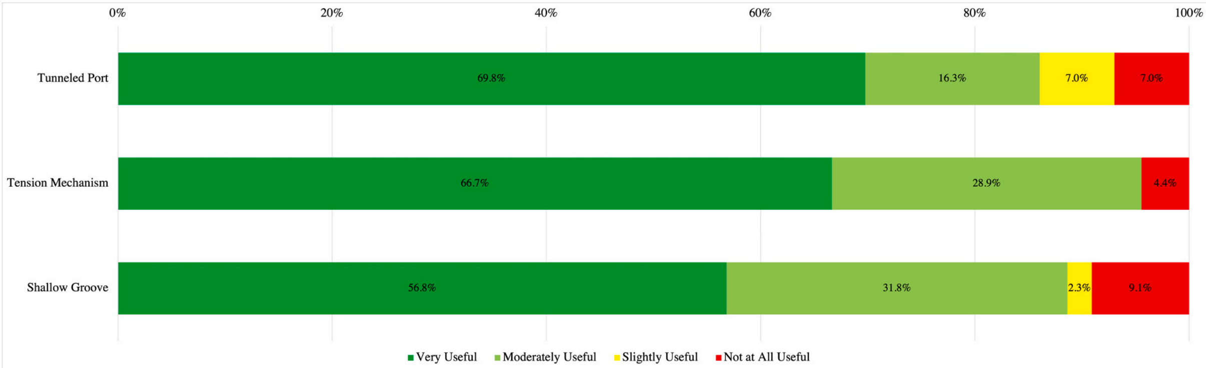


**Fig. 5.** Medical students' perceptions of the usefulness of each skills challenge in the Nodo-Tie.

## Discussion

As clinical simulators grow in popularity, it is critical that they are readily available for medical students seeking to participate in self-directed technical skills development. However, high costs and limited accessibility continue to restrict the widespread implementation of clinical simulators [5,6]. We proposed using 3-D printing to overcome these barriers and sought to develop a low-cost, 3-D printed knot-tying simulator.

By maintaining the relationship between high-fidelity manufacturing and core design features needed for reliable clinical simulation, our team was able to design the Nodo-Tie to function as a device students agreed was both easy to use and able to improve their technical knot-tying skills. Novel design features, such as the progression of knot-tying challenges and knot-tying video curriculum, further increase the Nodo-Tie's educational utility. As both components were validated by experienced surgeons, they ensure students are engaging in self-directed learning of appropriate skills. Therefore, students will be able to enter the clinical space without knowledge gaps or technical errors in their knot-tying abilities. Given the Nodo-Tie's cost, students were able to keep the knot-tying simulators after the study period. Not only does this support the Nodo-Tie's role in the short-term development of knot-tying skills, but it may also allow students to engage in the longitudinal practice necessary to master knot-tying during the remainder of their medical education.

Limitations of this study include a lack of comparison between the Nodo-Tie and other clinical skills simulators. However, there does not appear to be a simulator with similar design considerations to which to compare our simulator. Additionally, the duration of Nodo-Tie use during the study period was dependent on each individual's desire to use the simulator. Therefore, a student may have had minimal experience with the Nodo-Tie prior to completing the survey. To minimize this, participants also attended designated knot-tying sessions during the study period where they were able to use the Nodo-Tie in place of our institution's standard knot-tying board. Furthermore, our study did not evaluate a difference in medical students' knot-tying abilities before and after the study period. However, given students attended these designated knot-tying sessions and likely practiced their technical abilities in the clinical setting during the study period, it would be expected that the students' knot-tying abilities would improve regardless of their amount of practice with the Nodo-Tie.

## Conclusion

Given the positive feedback from students in this pilot study, our institution has elected to integrate our novel knot-tying simulator into the core surgical clerkship and procedural residency preparation course for future cohorts. The Nodo-Tie has also been incorporated into use for a variety of designated knot-tying sessions beyond these courses as well. Future directions include continuing to study the benefits of the Nodo-Tie amongst a larger cohort of medical students. Additionally, we are seeking to expand the Nodo-Tie's design features to include more technical knot-tying challenges as a means of broadening its usability amongst a larger range of trainees.

Furthermore, we are currently engaging in initiatives to increase awareness for the Nodo-Tie and distribute it beyond our institution. With this manuscript, we have included the design files for the Nodo-Tie and links to purchase the components needed to assemble the simulator. The design file has been formatted to be compatible with a variety of slicing software without the need for edits prior to printing. Additionally, we are currently creating a dedicated website and social media page to raise awareness about the Nodo-Tie's benefits and applications within medical education. Similarly, these outlets will contain the necessary resources so that individuals, including students, institutions, and medical professionals, can easily access, download, and acquire the simulator. Lastly, we hope to collaborate with institutions who may be interested in integrating the Nodo-Tie into their curriculum and encourage those interested in reaching out to the authors. Through these steps, we hope to highlight the Nodo-Tie as a reliable tool for medical education that can have positive outcomes on a wide range of learner's technical abilities.

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The authors have no relevant affiliations or financial involvement with any organization or entity with a financial interest or financial conflict with the subject matter or materials discussed in the manuscript.

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## Ethics approval

This study was deemed exempt by the University of Michigan Institutional Review Board (HUM00228883). A consent agreement for participants was included on the first page of the survey.

## CRediT authorship contribution statement

**Kian Pourak:** Conceptualization, Writing – original draft, Methodology, Validation, Data curation, Formal analysis. **Nicholas Zugris:**

Investigation, Writing – original draft, Methodology, Validation, Data curation. **Itai Palmon:** Investigation, Writing – original draft, Validation, Data curation. **Demetri Monovoukas:** Investigation, Writing – original draft, Validation, Data curation. **Seth Waits:** Conceptualization, Writing – review & editing, Validation, Methodology, Supervision, Data curation.

## Declaration of competing interest

Kian Pourak reports independently preparing a provisional patent submission for the Nodo-Tie. All other authors report no related conflicts of interest to declare.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.sopen.2023.11.007.

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