Research Article

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A High-fidelity Tactile Hand Simulator as a Training Tool to Develop Competency in Percutaneous Pinning in Residents

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Abstract

Introduction: We developed an economical three-dimensional printed and casted simulator of the hand for the training of percutaneous pinning. This simulator augments the traditional "See one, do one, teach one" training model.

Methods: To evaluate the simulator, five expert orthopaedic surgeons were recruited to perform percutaneous pinning on the simulator and then to complete a questionnaire on its realism and expected usefulness. Evaluation was based on responses to multiple-choice questions and a Likert-type scale.

Results: All subjects expressed that the tactile hand simulator is useful for residency training. They would recommend the simulator to their colleagues and indicated interest in testing future iterations. Subjects rated highly the realism of the material, the purchase of the pin, and the cortical–cancellous bone interface.

Conclusion: The learning of tactile skills in addition to visual cues on a tactile simulator is expected to benefit residents. It provides a low-cost and low-risk environment outside the operating room for residents to hone their skills.

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The Halsted model of "See one, do one, teach one" forms the basis of most residency programs. Since the introduction of the Accreditation Council of Graduate Medical Education Outcome Project, many residency programs have looked into increasing the efficiency of residency training.[1] Although the cadaver laboratory highlights the variabilities in human anatomy, the high cost of acquiring and handling cadavers makes it prohibitive to use cadavers for repeated and deliberate practice for skills acquisition.[2,3] Thus, one common strategy is to use simulators in residency training outside of the operating room (OR) time.[4-6]

Current simulators range from simple polyvinyl chloride (PVC) pipes and rubber band constructs[7] to realistic mannequins[4,6] and highly accurate multimaterial three-dimensional (3D) printed simulators.[7,8] In 2015, Lopez et al[7] showed that the use of simulators improved the acquisition of surgical skills. With a simple PVC pipe and foam block setup, they found that medical students who trained on the simulator outperformed junior residents in many skill sets. Although a PVC-foam simulator may be able to aid the learning of tactile feedback, it does not present the actual anatomy. Thus, a learning gap still exists between working on the PVC pipes and performing surgery on a patient. On the other extreme, realistic mannequins are often too expensive to be used on a regular basis.[4] Recent multimaterial 3D printing technology can create anatomic simulators with matching material properties, but it is still prohibitively expensive. Thus, currently, no effective way of creating low-cost anatomic simulators with high tactile fidelity exists.

Our goal was to develop economic and standardized training simulators and assessment tools for surgical training in residency training programs. Although the availability of cadavers and patient cases limits the exposure of residents, 3D printing enables residency program directors to implement a "standard" set of cases that their residents should be trained in and subsequently assessed on at the end of each year of residency.[9] Developing an objective assessment of surgical competency is a challenging problem,[4] and standardized simulators will help to eliminate at least one source of bias. 3D printing technology can potentially enable tactical training time outside of high-cost and high-risk OR time.

In this article, we present an economic 3D printed tactile hand simulator that provides both tactile and visual cues to bridge the gap between simulation and surgery. This tactile hand simulator was designed for percutaneous bone pinning of any of the phalanges and metacarpal bones. For a percutaneous procedure to be successful, the surgeon has to (1) locate the center of the bone to start drilling, (2) palpate the bones to target the correct plane of drilling, and (3) feel for the bicortical structure while drilling to track the depth and location of the pin. Challenges include slippage of the pin on the bone surface and controlling the drill to stay in the target plane.

Our tactile hand simulator was designed to enable all three steps to be performed to varying levels of difficulty. It has a soft gel layer over the rigid 3D printed skeleton to enable palpation of the bones to locate the center of bones and plane of drilling. Its 3D printed skeleton incorporates a bicortical structure to provide the tactile feedback, and initial trials showed slippage of pins on the bone surface. In addition to the three steps, our simulator has a transparent gel layer to provide additional visual feedback for junior residents. The transparent gel is covered by a removable opaque skin layer, and removing this skin layer reveals the skeleton. For junior residents, this visualization of the underlying bone structure informs them of the expected tactile feedback.

In this article, we also present the responses of a questionnaire study that solicits feedback from expert surgeons on the realism and expected usefulness of this simulator for residency training. Expert surgeons were each given a simulator and a questionnaire on the realism and effectiveness of our tactile hand simulator in residency training.

Methods

Tactical Hand Simulator

A tactical hand simulator is made using a combination of 3D printing and casting process. Similar to the clubfoot simulator described by Wu et al,[10] the hand simulator is made of a 3D printed skeletal structure embedded in a ballistic gel matrix so that each bone piece is independently suspended in the gel.

First, the skeleton is refined from a computer-aided design (CAD) model of the hand to reflect a more realistic anatomy (alternatively, segmentations from CT images could be used) and exported as a surface shape model (ie, STL file format[11]). A fifth metacarpal bone fracture was included to provide context for the pinning exercise. The STL file is then postprocessed to insert links between bone pieces so that the skeleton can be printed as a single piece. 3D printing was done by our in-house 3D printing service. The skeleton was printed in white ABS plastic using a high-precision fused deposition modeling printer (Dimension 1200es; Stratasys) at a print resolution of 0.010″. A bicortical structure (cortical-cancellous-cortical) is incorporated in the 3D printed skeleton by specifying a 25% to 30% fill setting (sparse–low density). This setting generates an internal porosity that mimics cancellous bone.

The skeleton is then cast in the ballistic gel that mimics soft tissues. As suggested by Wu et al,[10] the mold for casting ballistic gel is designed in CAD software (Blender; Blender Foundation) and printed on a stereolithography printer (Form2; Formlabs) using standard resin. This mold is made in several small sections because of constraints in print volume and to facilitate demolding. The 3D printed skeleton is then inserted into a 3D printed mold, and the ballistic gel is cast over the skeleton.

After cooling and demolding, a removable skin layer is created by

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brushing silicone over the ballistic gel and rotating the simulator to achieve a uniform thickness. The silicone used is pigmented silicone (Dragon Skin 10 and Fleshtone Silc Pig; Smooth-On) according to the manufacturer's instructions.[12]

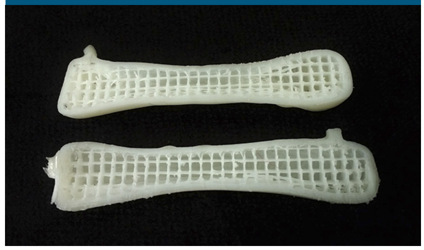
Finally, the links between the bone pieces are broken to create independent pieces held in place by the gel. The simulator is thus able to support bony operations such as bone pinning, while featuring overall flexibility that facilitates palpation of the underlying bones.

The material cost of creating a hand simulator was approximately $150. The cost of 3D printing is based on the rate in our institute's in-house 3D printing service, which offers similar rates as bureaus for consumer 3D printing. Approximately 4 hours of postprocessing work after 3D printing is necessary to complete the simulator. The entire production time (including 3D printing time and other waiting time) is about 2 days. The cost is expected to be reduced markedly in the future as the cost of 3D printing continues to decrease. Economies of scale at mass production will also lower the unit cost of each simulator.

Figure 1

Photograph demonstrating a tactile hand simulator without the skin layer to show the underlying three-dimensional printed skeleton. Subjects worked on the simulator, with the skin layer being intact.

Figure 2



Photograph demonstrating the sliced view of the metacarpal bone to show the internal trabecular structure.

Questionnaire Study

In a study to evaluate the hand simulator, five orthopedic surgeons were recruited as participants of the study. Inclusion criteria were age of at least 18 years, >5 years of experience in orthopaedics, and performance of percutaneous pinning of hand bones on a regular basis. Surgeons who were involved in the development of the phantom were excluded to eliminate bias.

All subjects were given a hand simulator and written instructions to perform transverse pinning of the second and third metacarpal bones, transverse pinning of the fifth and fourth metacarpal bones, and five additional transverse or intramedullary pinnings of the distal radius and at least one phalange. After the percutaneous pinning was performed, all subjects were requested to complete a questionnaire regarding the realism of the simulator and its expected usefulness in residency tactical training. This study was approved (expedited review) by the institutional review boards (RC-6301 and STUDY2016_00000519).

Results

A tactile hand simulator, as shown in Figure 1, with a fifth metacarpal bone fracture was developed with input from clinical collaborators. The bicortical structure in the 3D printed skeleton is shown in Figure 2. The 3D printed mold designed to cast this simulator is shown in Figure 3. This hand simulator was given to participants as part of the questionnaire study. Figure 4 shows a trial session of a bone pin inserted across the fourth and fifth metacarpal bones. The skin was partially removed to reveal the pin through the metacarpal bones. Figure 5 shows pin tracks between the fourth and fifth metacarpal bones on a simulator used in this study (the bone pin was removed). Subjects' responses to the questionnaire are shown in Tables 1 through 3. See Supplemental Digital Content 1 (Table 1, http://links.lww.com/JG9/A22) for the complete responses.

All subjects have worked or are working with the residents, and the following are the consolidated results of the questionnaire:

- All agree that the tactile hand simulator is useful for residency training.
- All would recommend the simulator to their colleagues, and three of five indicated that they would go out of their way to do so.
- Three of five would use the current simulator in residency training.
- All of them are interested in testing the next iteration of the simulator because they see potential in the simulator as an effective training tool.

Subjects rated the realism of the material, purchase of pin in bone, and cortical–cancellous bone interface to

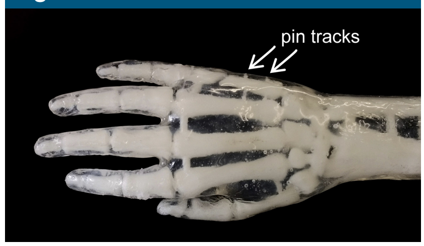
Figure 3

Photograph demonstrating a three-dimensional printed mold for casting the soft-tissue layer (ballistic gel) of the hand simulator.

Figure 4

Photograph demonstrating an example of percutaneous bone pinning (not part of the study session). The skin layer was partially removed to show the pin going across the fourth and fifth metacarpal bones.

Figure 5



Photograph demonstrating a tactile hand simulator, with the skin layer removed to show pin tracks through the fourth and fifth metacarpal bones after a study session. The bone pin was removed.

be four of five on average. Other features were rated at least three of five on average. The lowest rated features are the skin and the joints. Subjects most commonly listed the anatomic accuracy and cortical–cancellous bone interface as the most important features and removable opaque skin covering as the least important.

Although some improvements to the simulator were suggested in the open-ended questions, two subjects expressed great enthusiasm for the simulator. One subject described the simulator as an excellent adjunct to residency training; another described the simulator training as a great way to build skills away from the OR and cadaver laboratory.

Conclusion

The learning of tactile skills, in addition to visual cues, on a tactile simulator enables low-risk tactical training sessions outside the OR. In this article, we present a tactile hand simulator, which is printed using a 3D printer. Its features include a bicortical structure in all bone pieces, a soft transparent tissue layer, and flexible joints. Responses from the questionnaire study indicate that it is an effective tool and an excellent adjunct to residency training. Although the sample size is small, all subjects are experienced surgeons who have trained or are training residents in the orthopaedics department. All of them indicated that the tactile hand simulator is realistic and would contribute positively to residency training even in its current form. In particular, they highly rated the tactile feedback of bone pinning in terms of pin purchase and cortical-cancellous interface.

This concept of the tactile simulator was first presented as a flexible clubfoot model that can support external fixation.[10] Our hand simulator adds emphasis to the bicortical structure, which is an important training feature for percutaneous pinning. In this version of the simulator, the cancellous bone was created as a grid, which builds upward relative to the build plate. Thus, the cancellous structure is anisotropic and dependent on the print orientation, which may not be ideal if isotropy is required in a simulator. Additional studies are underway to create an isotropic cancellous structure. Since this study, we have reduced the cost of the simulator to below $100 by adapting the 3D printing procedure

Table 1

Survey Responses of Expert Surgeons on the Simulator as a Training Tool[a]

Question	Most Common Response(s)	No. of Participants Who Selected This Response (of Five)
Q1. Are you involved in the planning or execution of the residency program?	Yes, I am currently involved in training residents.	Four
Q2. How useful will this model be in augmenting residency training?	Very useful. It will enable residents to learn surgical procedures much more easily.	Three
Q3. In your opinion, which features of this training model are the MOST important? (Please pick three options.)	Anatomic accuracy (ie, size, shape, and geometrical features); cortical–cancellous bone interface (tactile feedback)	Four each
Q4. In your opinion, which features of this training model are the LEAST important? (Please pick three options.)	Removable opaque skin covering	Three
Q5. Would you be interested in testing the next iteration of the model?	Yes, I see potential in this model as a training tool.	Five
Q6. Would you recommend this to a colleague who is a resident in training?	Yes, I would go out of my way to recommend it.	Three
Q7. If you were leading the residency program, would you use it in resident training?	Yes, I would use it as it is.	Three

[a] Only the most common responses are shown.

Table 2

Scoring of Different Features of the Simulator by Expert Surgeons

Rate the Realism of the Following Features (Please Circle One Number for Each Statement) 1: Unrealistic; 2: Needs Improvement; 3: Neutral; 4: Meets Expectation; and 5: Exceeds Expectation	Average Score	Lowest Score	Highest Score
Bone materials (hardness and texture)[a]	**4.2**	**4**	**5**
Purchase of pin in bone	**4.0**	**4**	**4**
Cortical–cancellous bone interface	**4.0**	**3**	**5**
Soft-tissue layer	3.2	2	4
Skin covering	3.0	2	4
Joints of the hand	3.0	2	4
Anatomic accuracy	3.6	3	4

[a] Features that scored at least 4.0/5.0 (80%) on average are indicated in bold.

to a more economic desktop 3D printer while still preserving the bicortical structure. A removable skin layer was also included in this tactile hand simulator to stagger the learning curve for junior residents.

One of the major advantages of the 3D printed simulator is the ability to engineer custom conditions that cater to the mastery of the residents and reduce the stress of learning. Being just graduated from medical school and often not having used any surgical tools before, junior residents face a steep learning curve even while working on a cadaver. Our simulator provides the customization necessary to stagger the learning curve. For

Table 3

Responses to Open-ended Questions

Question	Responses
Any suggestions for improvement as a training model?	Joint mobility to allow different types of percutaneous pinning options Other fracture patterns, such as distal radius fracture and proximal phalange fracture (one of the most difficult to pin) Skin is unrealistic. The major issue is binding with the pin, which could alter the direction and feel (cortical purchase) The ulna is too long. Make the ulna neutral to the radius. The carpal bones could be improved, but we probably would not test carpal bone pinning. The phalangeal heads and metacarpal bone heads could be more round C-arm simulation if possible
Anything else you care to share?	Excellent adjunct to residency training Nice concept—important part of training! A great way to build skills away from the OR and cadaver laboratory. Incorporation with a computer may take pieces of radiograph without risks of radiation exposures. There was a "good" feel from bone/bone—cortical pinning feel of bone was reproducible. I had a difficult time feeling the cortices with the IM pinning.

IM = intramedullary, OR = operating room

example, in training for percutaneous bone pinning, a junior resident may first practice without the opaque skin covering. This practice provides additional and immediate visual feedback to augment his or her psychomotor training.[4] He or she can then add the opaque skin covering to increase the difficulty of the task. Although additional studies are necessary to conclude whether the visual cues had any notable effect on their mastery of percutaneous bone pinning, junior residents who trained in percutaneous bone pinning on our simulator performed better than did the control group in a blinded assessment in a separate ongoing study (data not yet published). We also observed greater slippage of the pin when the opaque skin was left on than when it was removed. This observation is in line with our expectation that the transparent gel provided visual cues to help them complete the task more efficiently. This mastery-based training makes learning more efficient and less daunting.[13]

Our simulator also facilitates the implementation of deliberate practice by providing a low-risk environment where residents can make mistakes and learn from them.[4] This theory is supported by a recent study[5] wherein medical students learned external cardiac anatomy better on 3D printed simulators than cadaver specimens because they were less apprehensive and anxious when working with the simulators. This strengthens our belief that 3D printed simulators may be able to fill the critical gaps between the literature, textbook images, cadaver training, and surgery.

Our simulator is also procedure based, incorporating only those features that are critical to the procedure to stagger the learning curve for new learners. This hand simulator was designed to not have details such as vasculatures that are not directly relevant to percutaneous pinning. Instead, it has features such as the bicortical structure that are specifically critical to the learning of percutaneous pinning. Besides reducing cost and waste, this approach to designing simulators also reduces distractions to the learning.

In conclusion, simulators focusing on tactile and visual feedback are perceived to be effective training tools to help residents achieve competency during residency training. However, Malik et al[14] determined that funding and support are two of the main barriers to implementing the competency-based learning introduced by the Accreditation Council of Graduate Medical Education in 2001. Although 3D printing is a cost-effective method to create simulators, there may still need to be more support and funding for residency programs to adopt simulators that augment the Halsted model of residency training.

References

1. Mattar SG, Alseidi AA, Jones DB, et al: General surgery residency inadequately prepares trainees for fellowship: Results of a survey of fellowship program directors. *Ann Surg* 2013;258:440-449.
2. Ericsson KA: Deliberate practice and acquisition of expert performance: A general overview. *Acad Emerg Med* 2008;15:988-994.
3. Causer J, Barach P, Williams AM: Expertise in medicine: Using the expert performance approach to improve simulation training. *Med Educ* 2014;48:115-123.
4. Kotsis SV, Chung KC: Application of the "see one, do one, teach one" concept in surgical training. *Plast Reconstr Surg* 2013;131:1194-1201.
5. Lim KH, Loo ZY, Goldie SJ, Adams JW, McMenamin PG: Use of 3D printed models in medical education: A randomized control trial comparing 3D prints versus cadaveric materials for learning external cardiac anatomy. *Anat Sci Educ* 2016;9:213-221.
6. Vozenilek J, Huff JS, Reznek M, Gordon JA: See one, do one, teach one: Advanced technology in medical

education. *Acad Emerg Med* 2004;11: 1149-1154.

7. Lopez G, Wright R, Martin D, Jung J, Bracey D, Gupta R: A cost-effective junior resident training and assessment simulator for orthopaedic surgical skills via fundamentals of orthopaedic surgery: AAOS exhibit selection. *J Bone Joint Surg Am* 2015;97:659-666.

8. Baskaran V, Strkalj G, Strkalj M, Di Ieva A: Current applications and future perspectives of the use of 3D printing in anatomical training and neurosurgery. *Front Neuroanat* 2016;10:69.

9. Hoang D, Perrault D, Stevanovic M, Ghiassi A: Surgical applications of three-dimensional printing: A review of the current literature & how to get started. *Ann Transl Med* 2016;4:456.

10. Wu YY, Rajaraman M, Lee B, Plakseychuk A, Shimada K: A patient-specific flexible 3D printed orthopedic model for training and teaching of clubfoot correction surgery. *3D Printing and Additive Manufacturing* 2016; 3:98-105.

11. 3D Systems, Inc: *Stereolithography Interface Specification*. Valencia, CA, 3D Systems, Inc., 1989.

12. Smooth-On Inc: Dragon skin series addition cure silicone rubber compounds, ed. https://www.smooth-on.com/tb/files/DRAGON_SKIN_SERIES_TB.pdf. Accessed July 1, 2018.

13. McGaghie WC, Issenberg SB, Barsuk JH, Wayne DB: A critical review of simulation-based mastery learning with translational outcomes. *Med Educ* 2014;48:375-385.

14. Malik MU, Diaz Voss Varela DA, Stewart CM, et al: Barriers to implementing the ACGME outcome project: A systematic review of program director surveys. *J Grad Med Educ* 2012;4:425-433.