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Three dimensional printing of a low-cost middle-ear training model for surgical management of otosclerosis

Christopher Razavi MD[1] | Deepa Galaiya MD[1] | Seena Vafaee[2] | Rui Yin BS[2] | John P. Carey MD[1] | Russell H. Taylor PhD[2] | Francis X. Creighton MD[1]

[1]Department of Otolaryngology – Head and Neck Surgery, Johns Hopkins University School of Medicine, Baltimore, Maryland, USA

[2]Laboratory for Computational Sensing and Robotics, Johns Hopkins University, Baltimore, Maryland, USA

Correspondence
Francis X. Creighton, MD, Johns Hopkins Medical Institute, Department of Otolaryngology-Head and Neck Surgery, 601 N. Caroline Street, 6 Floor, Baltimore, MD 21287, USA.
Email: francis.creighton@jhmi.edu

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Abstract

Background: Surgical management of otosclerosis is technically challenging with studies demonstrating that outcomes are commensurate with surgical experience. Moreover, experts apply less force on the ossicular chain during prosthesis placement than their novice counterparts. Given the predicted decreasing patient pool and the rising cost of human temporal bone specimens it has become more challenging for trainees to receive adequate intraoperative or laboratory-based experience in this procedure. As such, there is a need for a low-cost training model for the procedure. Here we describe such a model.

Methods: A surgical model of the middle ear was designed using computer aided design (CAD) software. The model consists of four components, the superior three dimensional (3D)-printed component representing the external auditory canal, a 90° torsion spring representing the incus, a 3D-printed base with a stapedotomy underlying the torsion spring, and a 3D-printed phone holder to facilitate video-recording of trials and subsequent calculation of the force applied on the modeled incus. Force applied on the incus is calculated based on Hooke's Law from post-trial computer-vision analysis of recorded video following experimental determination of the spring constant of the modeled incus.

Results: The described model was manufactured with a total cost of $56.50. The spring constant was experimentally determined to be 97.0 mN mm/deg, resulting in an ability to detect force applied to the modeled incus across a range of 1.2 to 5200 mN.

Conclusions: We have created a low-cost middle-ear training model with measurable objective performance outcomes. The range of detectable force exceeds expected values for the task.

Level of Evidence: IV.

KEYWORDS
3D printing, otosclerosis, resident education, stapedectomy, training model

1 | INTRODUCTION

Surgical management of otosclerosis is a technically challenging procedure which can yield excellent outcomes in expert hands. However, complications can also result irreversible sensorineural hearing and vestibular loss. Studies have demonstrated that outcomes are commensurate with surgical experience, with experienced otologists achieving a postoperative air-bone gap of <10 dB in up to 95% of cases, while trainees achieve this same benchmark in only 62% to 87% of their respective cases.[1-6] In fact, the learning curve for the procedure has been estimated to be between 60 and 80 cases, a stark contrast to the minimum number of 10 ossicular chain reconstructions (OCRs) required to graduate Otolaryngology—Head & Neck Surgery (OHNS) and the additional 20 OCRs required for Neurotology residencies as per the Accreditation Council for Graduate Medical Education (ACGME).[7] To complicate matters, the predicted decreasing patient pool, as well as the rising cost of human temporal bone specimens, have made it more challenging for trainees to receive adequate intraoperative or laboratory-based experience for this procedure.[8-10]

As such, many middle ear simulators have been proposed over the last 20 years. However, all are limited in their ability to provide objective measurable outcomes, anatomic fidelity, cost, or a combination of these factors.[10-13] Here, we describe a low-cost three-dimensionally printed middle ear model, which provides objective data regarding force exerted on the modeled incus during stapes prosthesis placement and crimping.

2 | METHODS

A surgical phantom was designed using computer aided design (CAD) software SolidWorks (Dassault Systèmes, Vélizy-Villacoublay, France) for the purposes of 3D printing. The phantom consists of four components, the external auditory canal (EAC)/middle ear (anatomic) component, the torsion spring modeling the incus, the aluminum base, and the phone holder. The anatomic components, specifically the size and location of the stapedotomy, was designed in such a way that would facilitate placement of a 0.5 to 0.6 mm diameter piston prosthesis with length between 4.25 and 4.75 mm. Three channels are designed within the anatomic component for placement of a backdrop and marker plate to aid computer vision analysis of spring deflection and ultimately, determination of force exerted on the modeled incus. The presence of the third channel facilitates reflection of the marker and backdrop location allowing the phantom to simulate both right and left sided procedures. The phone holder was designed to accommodate stabilization of a smart phone with video recording capabilities at a fixed distance from the stapedotomy site. These two components were then 3D printed with a stereolithographic printer (Stratasys uPrint SE, Eden Prairie, Minnesota; Figure 1).
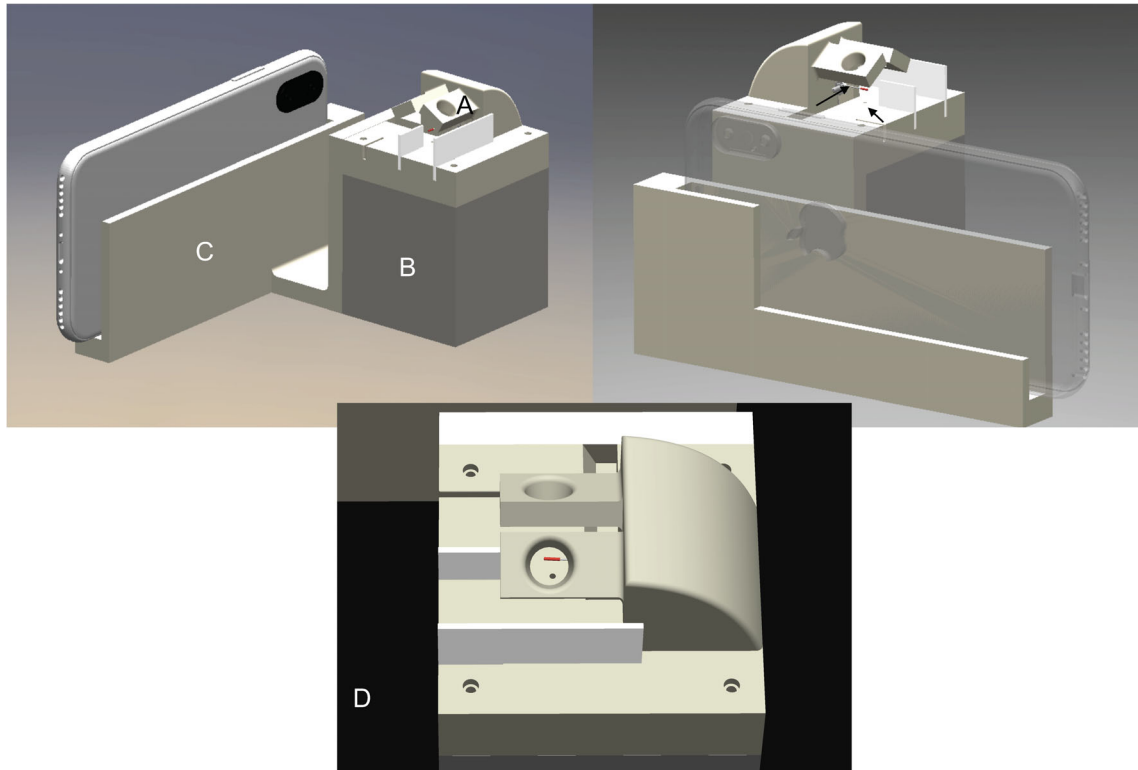

FIGURE 1 Computer aided design drawings of the middle-ear training model. (A) The EAC/middle ear anatomic component. (B) The aluminum base. (C) The smart phone holder. The short arrow depicts the stapedotomy, while the long arrow highlights the torsion spring modeling the incus. Panel D demonstrates the operative view for placement of a piston prosthesis, where the modeled incus and stapedotomy can be visualized

The anatomic component and phone holder were then attached to the aluminum base with a combination of through holes/screws and adhesive. Adhesive was chosen for fixation of the phone holder to allow for rotation of this component in a facile manner when alternating between right and left sided procedures. A 90° left-hand wound torsion spring (https://www.mcmaster.com/9271K576/) with a wire diameter of 305 um was then integrated into the system by threading it onto the 3D printed rod within the anatomic component to form the incus of the phantom. This particular spring was chosen due to its high sensitivity; however, the outer diameter was too small and finish too smooth to allow for manual crimping of the prosthesis. As such, two layers of heat shrink tubing were added to the horizontally oriented component of the torsion spring to increase its diameter and provide friction, more closely mimicking operative conditions. The heat-shrink tubing chosen had a 610 μm inner diameter, which approximates the size of the human incus.[14]

The spring constant (k) of the system was then experimentally determined, based on Hooke's Law. For a torsional spring, this states that k is equivalent to the force applied multiplied by the moment arm divided by angular displacement. To do this, the phantom and phone-stand were placed together on a high precision scale. Next to the scale, a separate stand with adjustable height carried a tool that was used to depress the spring. (Figure 2) The difference in apparent mass before and after depressing the spring was recorded by the scale and used later to determine the force applied onto the spring. Meanwhile, the phone recorded a video of the spring being depressed. A computer vision script was then used to determine the angular displacement of the spring and the length of the moment arm. This process was repeated a total of 20 times with different displacements. Multiplying the length of the moment arm and the applied force to the spring yielded the torque applied to the spring for each trial. The torsional spring constant was calculated by analyzing the directly proportional relationship between the applied torques and angular displacements.

After experimental determination of the force constant of the system, a computer vision script was developed that would output force on the modeled incus based on degree of torsional spring deflection. As such, force applied on the modeled incus could be determined for both prosthesis placement and crimping from analysis of recorded phone video and application of this computer vision script. Johns Hopkins Homewood institutional review board approval was obtained for the study and informed consent was obtained from all participants.

3 | RESULTS

The experimentally determined force constant for the system was 97.0 mN mm/deg based on the average calculated constant from 20 repeated spring displacements described above. The range of detectable forces on the modeled incus was calculated using the experimentally determined force constant, the maximum degree of spring deflection of 23°, and the minimum spring displacement that could be detected via computer analysis. This yielded a dynamic range of force detection of 1.2 to 5200 mN for the model. The entire system was fabricated for a cost of $56.50. (Figure 3).

4 | DISCUSSIONS

As operative volume for otosclerosis decreases, models such as the one described will be invaluable to trainees and ultimately to patients, as we aim to maintain excellent outcomes with stapedectomy in a new generation of surgeons. Furthermore, as the COVID-19 pandemic has demonstrated, there is a growing need for surgical training opportunities outside the operating theatre. Although many OHNS programs have provided extracurricular educational opportunities to trainees via didactic virtual lectures during the pandemic, these fall short in facilitating technical skill development. This is of concern for technically demanding procedures, such as stapedectomy, particularly when noting that a poor hearing outcome after stapes surgery is the most litigated case within
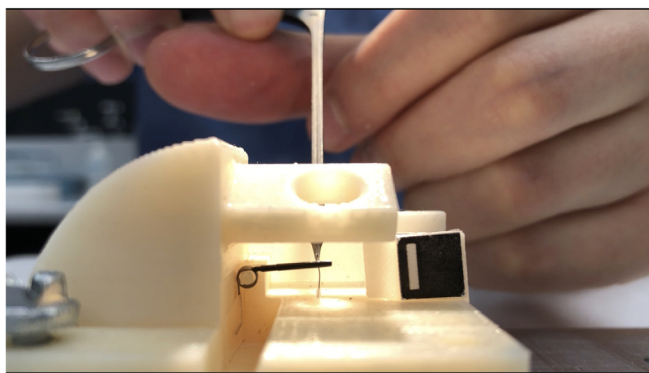

FIGURE 2 Experimental calculation of torsional spring force constant. The spring was displaced by a known magnitude. A computer vision script was then used to determine angular displacement of the spring and the length of the moment arm. This process was repeated 20 times with different displacement magnitudes to determine the torsional spring constant
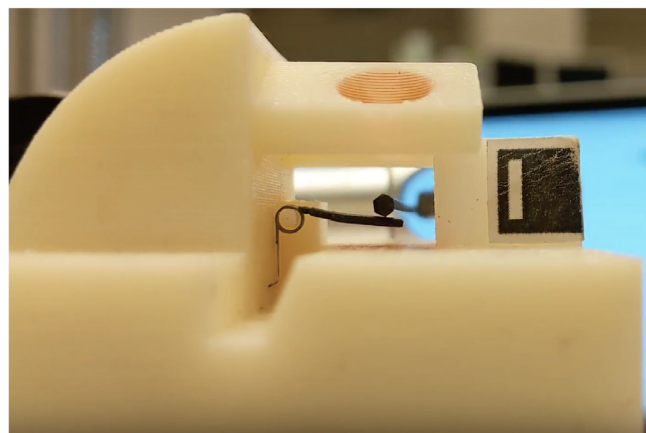

FIGURE 3 Demonstration of training model in use. The user can be seen placing a piston prosthesis on the modeled incus. The calibration marker (in black) can be seen on the right side of the image

otologic surgery.[15] High fidelity surgical simulators may help minimize the threats to trainee education that decreasing case volumes and operative independence will have on the future of our specialty.

With the advent of laser-assisted stapedectomy and footplate fenestration techniques, many Otologist suggest that the most technically challenging aspect of the case is the placement and crimping of the stapes prosthesis.[5,11] As such, some argue that the inferior outcomes seen in trainees with the procedure is therefore due to their less practiced hands with manipulation of the prosthesis itself.[4] Thus, a middle-ear model placing emphasis on prosthesis manipulation with an objective measurable outcome would be of great value to trainees. The model we describe provides these capabilities while also being low-cost. Prior studies have demonstrated that novices apply on average 139 and 522 mN of force, while their expert counterparts apply 42 and 204 mN of force in prosthesis placement and crimping, respectively.[16] The range of force that can be detected with this model is therefore more than adequate for those generally applied to the incus during middle ear prosthesis manipulation for both novices and experts.

Several studies have demonstrated that expert surgeons exert less force during procedural tasks than novice/junior surgeons.[16-18] Moreover, the force transmitted to the inner ear during middle ear surgery is often cited as a potential cause of sensorineural hearing loss during stapedectomy.[16-18] As such, improved performance in our model, which provides objective outcome measures that can be tracked, may directly translate to improved intraoperative performance, though this will need to be studied further.

Future studies will be needed to further validate our computer vision script and test its ability to be disseminated among training programs. These studies will need to examine placement and crimping forces, measured from our computer vision script, between surgeons of varying skill level, to ensure they are consistent with our previously studies.[15]

5 | CONCLUSIONS

We have developed a low-cost high-fidelity training model for the surgical management of otosclerosis. This model provides users with objective, and relevant, outcome measures that can be trended and improved upon. Models such as this are invaluable tools to supplement trainee operative education given the growing threats to resident operative opportunities.

CONFLICT OF INTEREST
The authors declare no potential conflict of interest.

ORCID
Christopher Razavi https://orcid.org/0000-0002-1616-0135
Francis X. Creighton https://orcid.org/0000-0003-3131-1162

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