Elements of Virtual Temporal Bone Surgery: Manipulandum Format may be More Important to Surgeons than Haptic Device Force Capabilities

Bertram Unger, MD, PhD; Nariman Sepehri, PhD; Vivek Rampersad, MSc; Justyn Pisa, AuD [ID];
Michael Gousseau, MD; Jordan B. Hochman, MD FRCSC

Background: Temporal bone simulations are critiqued for poor drill-bone interaction. This project appraises the import of increasing haptic device and manipulandum fidelity on the perceived realism of drilling a virtual temporal bone.

Virtual surgical contact forces rely on haptic device fidelity and are transmitted through a manipulandum. With identical software, both device hardware and manipulandum may each contribute to realism. We compare the three degrees of freedom (DOF), 3N Geomagic Touch (3D Systems, SC) to a 6DOF, 5.5N HD^2 (Quanser, ON) with the both standard ("HD^2–Standard") and in-house customized otic drill manipulandum ("HD^2–Modified").

Methods: Six otologic surgeons performed three virtual mastoidectomy surgeries on a temporal bone surgical simulator. The HD^2 manipulandum was modified for attached otic drill with gravity compensation and requisite mechanical modifications. Surgeons, in random order, performed the dissection with the different hardware platforms.

Results: Two-tailed t-tests demonstrate that for the *acoustic properties* of each simulation, the HD^2–Modified manipulandum was favored ($p \leq 0.0004$). For *overall similarity of bone*, both HD^2–Standard ($p \leq 0.05$) HD^2–Modified ($p \leq 0.03$)) were favored over the Geomagic; however they were not appreciably different when directly compared to each other. There was no preference for increasing haptic device fidelity in virtual drill bone interaction.

In forced rank, users favored the HD^2–Modified in osseus, vibrational and overall realism, as well as being preferred for education and preoperative rehearsal ($p \leq 0.0164$).

Conclusion: Increasing manipulandum realism was favored. However surprisingly, there was no preference for increased device fidelity, illustrating incremental stiffness had nominal impact. There may be a ceiling to drill bone interaction in virtual haptic simulation.

Key Words: temporal, bone, surgery, 3D, printed, model, haptic, virtual reality, simulation.

Level of Evidence: 2b.

INTRODUCTION

Globally, surgical residents are increasingly trained on virtual reality haptic simulators to maximize knowledge and skill prior to clinical exposure.[1–6] In order to allow users to interact with virtual tissues, these haptic simulations rely on two elements: a software component which provides visualization and force-feedback calculation as well as a hardware platform consisting of electronics, motors, and a physical manipulandum with which the user interacts with virtual tissues.

Surgery of the temporal bone requires knowledge of intricate three-dimensional (3D) anatomical structures and highly developed technical skills. While a variety of software solutions have been developed for temporal bone simulation, most systems employ similar off-the-shelf hardware platforms.[7,9–13] One of the more commonly used systems is the Geomagic Touch (3DS, Rock Hill, SC).[2–4,6,8] While the focus of most research has been on the software algorithms used to simulate the virtual environment, it is logical to assume that the hardware employed may also play a significant role in the user's learning experience. The range and resolution of forces available from the hardware may impact the feel of the bone at the drill tip, while the size of workspace, degrees of freedom of motion, and manipulandum shape and mass can affect user hand and arm motions.
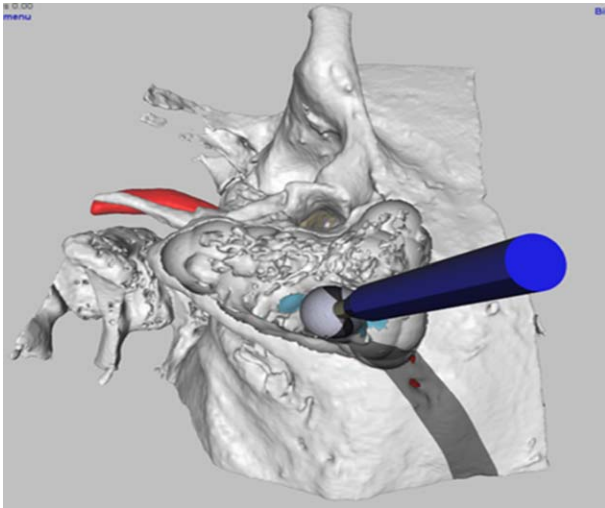
Fig. 1. Haptic Temporal Bone Simulation Graphical Representation Rendering software for graphic and hardware are the same across the three modalities under study.

By modifying the haptic hardware, it should be possible to achieve a more realistic temporal bone simulation with improved value. This would be significant as previous work has identified limitations in virtual temporal bone drill bone interaction as contrasted with both cadaveric and printed simulations.[13]

We have developed temporal bone surgical simulation software for use in either a stand-alone haptic simulation or a mixed-reality simulation which employs a virtual haptic system in combination with a 3D printed temporal bone.[6,14] The stand-alone system uses, as its haptic interface, a Geomagic Touch device with its standard manipulandum. The device permits three degrees of freedom (DOF) and can generate 3 N of force. The mixed-reality system uses a high definition (HD^2) high-fidelity haptic device (Quanser Inc., Markham, ON) modified to carry an otic drill as its haptic interface. This device has the capacity for six DOF activity and permits force generation up to 5.5 N. The HD^2 can be used with the standard mid-wand manipulandum (unmodified) or with an attached otic drill (modified).

Fig. 3. Custom surgical drill gripper mechanism for HD^2 haptic device and polystyrene ergonomic support system.
HD = high definition

As both hardware platforms (HD^2 & Geomagic Touch) (Fig. 1) use the same haptic rendering software, we can directly compare the effect of these platforms on expert users' perception of system realism This should be valuable in identifying priorities in simulator design for temporal bone surgical training.
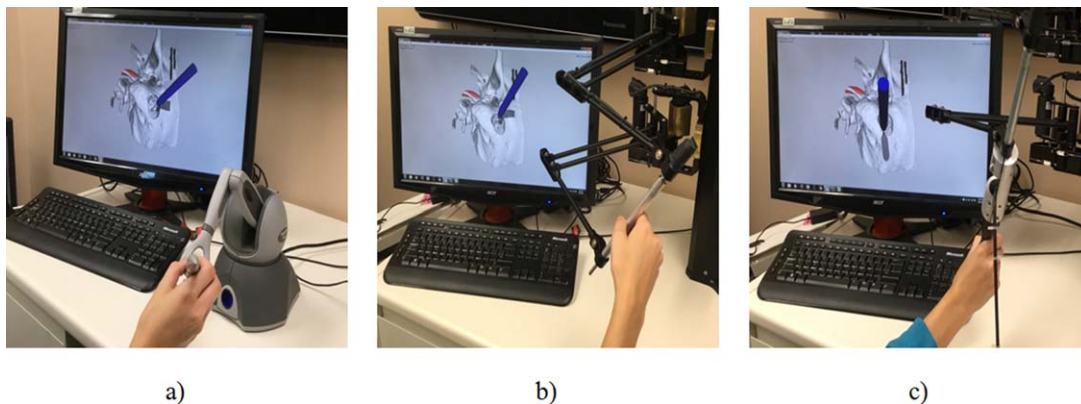

Fig. 2. Hardware platforms and manipulandi. a) Geomagic Touch with standard manipulandum (Geomagic); b) HD^2 with standard manipulandum (HD^2–Standard); c) HD^2 with otic drill manipulandum (HD^2–Modified).
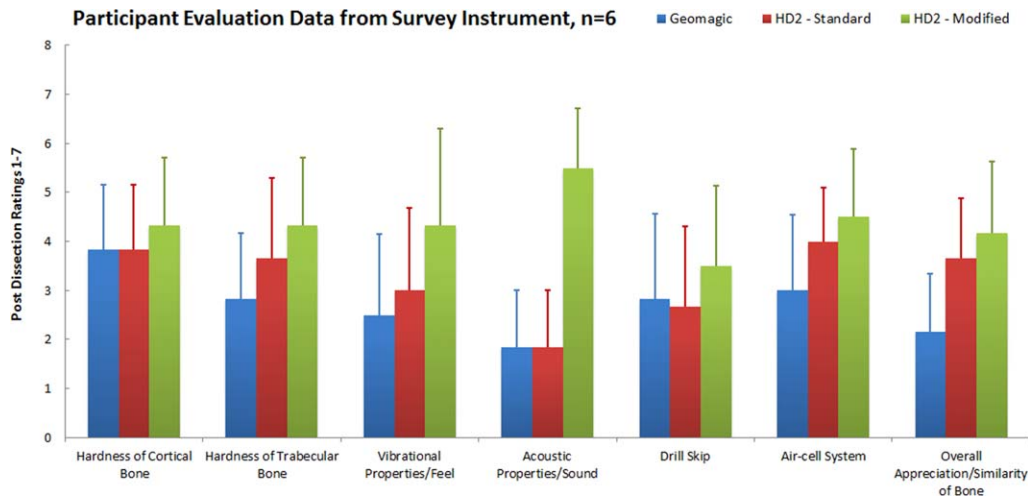HD = high definition

Fig. 4. Mean 7-Point Likert-scale values for perceived physical properties of "Geomagic" (Geomagic Touch with standard manipulandum), "HD²–Standard" (HD² with standard manipulandum), and "HD²–Modified" (HD² with attached otic drill manipulandum). Error bars indicate 1 SD.
HD = high definition

MATERIALS AND METHODS

In order to study the effect of haptic hardware and manipulandum on users' simulation experience we employed three different hardware platforms using identical software. The three platforms are: 1) Geomagic Touch with its standard manipulandum ("Geomagic", Fig. 2a); 2) HD² with its standard manipulandum ("HD²–Standard", Fig. 2b); and 3) HD² with otic drill modified manipulandum ("HD²–Modified", Fig. 2c).

All systems used the same in-house haptic rendering software.[6] The software uses a micro computerized tomography (CT) template created from cadaveric bone. The microCT data is manually segmented into polygon mesh models of separate anatomic features. The virtual haptic model is created by recombining individual polygon mesh models into a single voxellated model from which forces are calculated during haptic interaction. The forces are then passed on to hardware for presentation to the user via the device manipulandum. It should be noted that in order to port the software from the normative Geomagic Touch end effector to the HD², modifications (available from the authors as a supplement) were required to the interface portion of the code but the underlying force calculation algorithms remained unchanged.

We have previously published work on the mechanical merger of the HD² with an otic drill.[14] This required the development of a custom drill gripper (Fig. 3), and software for gripper gravity cancellation. We also adjusted appreciated forces from mid-wand to drill tip by modifying the haptic device software.

The experimental setup had participants seated in front of a computer display of the temporal bone, with the haptic manipulandum grasped in the dominant hand (Figs. 2a–c). Due to the larger workspace of the HD² device, ergonomics dictated the need for an arm-rest made of polystyrene foam (Fig. 3). No conditions were placed on the surgeon's choice of grip or orientation with respect to the device or the computer monitor.

Six otologic surgeons tested the three hardware platforms by performing simulated surgery on a virtual temporal bone. Each surgeon had 15 minutes to evaluate each of the three hardware platforms for a total experiment time of 45 minutes. Following the simulation experience, surgeons were asked to fill out a survey which included a 7-point Likert questionnaire on the perceived physical properties of each system and a forced ordered ranking of the systems for perceived realism and educational qualities.

Results were evaluated using a student's t-test and ANOVA analysis (SPSS 20).

RESULTS

Six otologic surgeons participated in the study with a total of 78 years of temporal bone surgical experience. There were five male participants and one female participant. Results of the seven-point Likert questionnaire can be seen in (Fig. 4), along with results of an analysis of variance (ANOVA) analysis of significance. The ANOVA analysis reveals that participants felt the three platforms differed significantly only for acoustic properties ($p = 0.00008$) and overall perception of the systems' similarity to cadaveric bone ($p = 0.043$).

Further analysis was performed using a student's two-tailed t-test. This illustrates that for acoustic properties, significant differences only exist for comparisons between the Geomagic/HD²–Modified ($p = 0.000345$) and HD²–Standard/HD²–Modified ($p = 0.000345$) platforms. For overall similarity to bone, the difference between the Geomagic platform and the HD²–Standard platform was not significant ($p = 0.054$), however significance was found between the Geomagic and HD²–Modified ($p = 0.02621$) conditions.

Ordered ranking of the three hardware platforms by the six participants can be seen in Table I. Each system was ranked with respect to realism and usability criteria. The "HD²–Modified" condition was favored in osseous, vibrational, and overall realism, as well as being preferred for education and preoperative rehearsal. Based on a combinatoric calculation, the results of Table I indicate that the probability of this pattern of ranking occurring by chance equals 0.0164.

Ranking of Three Hardware Platforms by Six Participants for Realism and Usability. HD^2–Modified Received the Highest Total, Followed By HD^2–Standard and Geomagic with a Total of 23 Points.

Table shows number of times ranked as either 1st, 2nd, or 3rd		Geomagic			HD^2–Standard			HD^2–Modified		
		1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Overall	Overall Realism	2	1	3	0	4	2	4	1	1
Manipulandum Comparison	Osseous Realism	1	1	4	0	5	1	5	0	1
	Drilling Realism	1	1	4	0	5	1	5	0	1
	Preferred for Education	1	2	3	0	4	2	5	0	1
	Preferred for Preoperative Planning	1	2	3	0	4	2	5	0	1
	Ease of Use	1	2	3	0	4	2	5	0	1
	Preferred Simulation	1	2	3	0	4	2	5	0	1

HD = high definition

DISCUSSION

This is a pilot study with a sample of convenience, necessitated by the need for highly-trained expert participants with requisite experience in temporal bone surgery.

Increasing manipulandum fidelity was generally preferred. This may be because the feel of the drill-based manipulandum is more familiar. There is also evidence that the tactile and proprioceptive systems may provide complementary information so it is possible that drill vibration may improve participants' ability to navigate within the 3D operative field.[15,16]

In order to accurately mimic the aural experience of drilling bone, the acoustic properties of each haptic device were also thought to be important components in a simulation.[4] While this was preferred in the HD^2-Modified condition, the significance is questionable. There may have been a bias owing to actual presence of a real oscillating drill as manipulandum. The virtual software produced a sound designed to serve as a drill analogue in the other two conditions. Device vibration was not appreciated as significantly different, likely owing to the intrinsic haptic software algorithm, which produces a linear vibration based on drill speed.

Previous work illustrated surgical residents strongly preferred a 3D printed simulation over virtual.[13] In large part, this preference was attributed to the realistic drilling experience. Hence, it was postulated that improving the fidelity of the virtual drill-bone interface by increasing haptic fidelity may address this concern. The HD^2 has better force resolution and maximum force capability than the Geomagic Touch system. While this study found the HD^2 with modified manipulandum was favored across categories, there was no statistical difference between the unmodified HD^2 and the Geomagic Touch, specifically of note in appraisal of osseus realism. It is notable that there is a considerable price difference between the Geomagic and Quanser systems. This would otherwise speak against the more expensive hardware, except the favored manipulandum can only be merged with the more costly robot.

There are several confounding software modifications that may have influenced this result. While the effects of gravity on the gripper mechanism are canceled, inertia continues to be present. This would, however, only affect the HD^2–Modified condition and does not clarify why there is no difference between the higher fidelity HD^2–Standard and Geomagic conditions. There was also requisite modification to the haptic driver software when ported to the HD^2. This may have degraded the quality of perceived osseus interaction. The HD^2 system has a larger movement arm with a need for increased stability at the end of the manipulandum. If the software had not been adapted, the user would experience a significant kick with generated contact forces. A low pass filter is therefore applied to dampen/slow force output and provide a gentler slope of contact. However, this seems an insufficient explanation as the HD^2–Modified condition was significantly preferred and HD^2–Standard was not, when compared to the Geomagic condition. Hence, the more suspect probability is an overarching limit to haptic device realism–a possible "haptic ceiling"–in replicating drill bone interaction.

The spatial orientation of both platforms is different, resulting in an inability for blinding in this study as well as a potential impact to end-user perception. However, due to the inherent differences between robots, it was not possible to overcome this limitation.

Simulation is and will continue to be an important adjunct in training. This article identifies what may be considered priorities in the generation of similar simulations. It further highlights that differing platforms can impact end user perception of utility.

CONCLUSION

Otologic surgeons preferred a more familiar manipulandum. There was no preference for increasing haptic fidelity in drill-bone interaction. This may prove a general concern for virtual haptic temporal bone simulation. Given the greater cost of the higher fidelity system, this question is important to resolve.

BIBLIOGRAPHY

1. Wiet GJ, Stredney D, Wan D. Training and simulation in otolaryngology. *Otolaryngol Clin North Am* 2011;44:1333–1350.
2. Trier P, Noe KØ, Sørensen MS, Mosegaard J. The visible ear surgery simulator. *Stud Health Technol Inform* 2008;132:523–525.
3. Agus M, Giachetti A, Gobbetti E, et al. Mastoidectomy simulation with combined visual and haptic feedback. *Stud Health Technol Inform* 2002;85:17–23.
4. Morris D, Sewell C, Barbagli F, Salisbury K, Blevins NH, Girod S. Visuo-haptic simulation of bone surgery for training and evaluation. *IEEE Comput Graph Appl* 2006;26:48–57.
5. O'Leary SJ, Hutchins MA, Stevenson DR, et al. Validation of a networked virtual reality simulation of temporal bone surgery. *Laryngoscope* 2008;118:1040–1046.
6. Kraut J, Hochman JB, Unger B. Temporal bone surgical simulation employing a multicore architecture. In: *Proceedings of 2013 26th Annual IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, Regina, Saskatchewan. 2013.
7. Agus M, Giachetti A, Gobbetti E, Zanetti G, Zorcolo A. A multiprocessor decoupled system for the simulation of temporal bone surgery. *Comput Vis Sci* 2002;5:35–43.
8. Wiet GJ, Rastatter JC, Bapna S, Packer M, Stredney D, Welling DB. Training otologic surgical skills through simulation-moving toward validation: a pilot study and lessons learned. *J Grad Med Educ* 2009;1:61–66.
9. Andersen SAW, Mikkelsen PT, Konge L, Cayé-Thomasen P, Sørensen, MS. Cognitive load in mastoidectomy skills training: virtual reality simulation and traditional dissection *Compared J Surg Educ* 2016;73:45–50.
10. Wiet GJ, Stredney D, Sessanna D, Bryan JA, Welling DB, Schmalbrock P. Virtual temporal bone dissection: an interactive surgical simulator. *Otolaryngol Head Neck Surg* 2002;127:79–83.
11. Zhao YC, Kennedy G, Yukawa K, Pyman B, O'Leary S. Improving temporal bone dissection using self-directed virtual reality simulation: results of a randomized blinded control trial. *Otolaryngol Head Neck Surg* 2011;144:357–364.
12. Sewell C, Morris D, Blevins NH, et al. Providing metrics and performance feedback in a surgical simulator. *J Int Soc Comput Aided Surg* 2008;13:63–81.
13. Hochman JB, Rhodes C, Kraut J, Pisa J, Unger B. End user comparison of anatomically matched 3-dimensional printed and virtual haptic temporal bone simulation: a pilot study. *Otolaryngol Head Neck Surg* 2015;153:263–268.
14. Hochman JB, Sepehri N, Rampersad V, et al. Mixed reality temporal bone surgical dissector: mechanical design. *J Otolaryngol Head Neck Surg* 2014;43:20–23.
15. Rincon-Gonzalez L, Naufel SN, Santos VJ, Helms Tillery S. Interactions between tactile and proprioceptive representations in haptics. *J Mot Behav* 2012;44:391–401.
16. Blanchard C, Roll R, Roll JP, Kavounoudias A. Combined contribution of tactile and proprioceptive feedback to hand movement perception. *Brain Res* 2011;1382:219–229.