Published in final edited form as:

Int J Comput Assist Radiol Surg. 2017 December ; 12(12): 2039–2045. doi:10.1007/s11548-017-1541-5.

Expert Subjective Comparison of Haptic Models for Bone-Drill Interaction

Thomas Kerwin,

Ohio Supercomputer Center: 1224 Kinnear Road, Columbus, OH 43212, US

Brad Hittle,

Ohio Supercomputer Center: 1224 Kinnear Road, Columbus, OH 43212, US

Sonny Chan,

University of Calgary: 2500 University Dr. NW, Calgary, AB T2N 1N4, Canada

Don Stredney, and

Ohio Supercomputer Center: 1224 Kinnear Road, Columbus, OH 43212, US

Gregory Wiet

The Ohio State University Department of Otolaryngology: 4000 Eye and Ear Institute, 915 Olentangy River Road, Columbus, OH 43212, US

Nationwide Children's Hospital: 700 Children's Drive Columbus, Ohio 43205, US

Abstract

Purpose—A haptic algorithm to simulate the interaction between a surgical drill and bone using a constraint-based algorithm has been previously demonstrated. However, there has been no blinded study to determine if this algorithm is preferred by professionals who commonly use this type of system

Methods—Fourteen otologic surgeons were presented with a spring-damper model and a constraint-based model of drill-bone interaction rendered on a low-cost haptic device with only linear feedback. The participants were blinded as to what algorithm they were using. They then answered survey questions about their opinions of the models.

Results—The surgeons overwhelmingly preferred the constraint-based model. They generally preferred the constraint-based model in the individual questions as well.

Corresponding Author: Thomas Kerwin (kerwin@osc.edu).

Compliance with Ethical Standards

Conflict of Interest

T. Kerwin, B. Hittle, S. Chan, D. Stredney, and G. Wiet declare there is no conflict of interest.

Informed Consent

Informed consent was obtained from all individual participants included in the study.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Ohio State University institutional review board and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conclusions—Follow-up work can be done to fine-tune the parameters in the model, but this study shows that a sophisticated algorithm can make a significant difference even on a low-fidelity haptic device.

Keywords

Haptics; Surgical simulation; User study

Introduction

The mastoidectomy surgical procedure is frequently used to treat disease of the temporal bone. The temporal bone houses critical sensory structures such as the cochlea (hearing) and the semicircular canals (balance), as well as the carotid artery, jugular vein and facial nerve. Also in close proximity to the surgical site is the temporal lobe and cerebellum of the brain. The surgeon uses a hand drill to remove bone surrounding the above structures so they can be identified and preserved while the pathology is addressed. A high level of skill is required to become proficient in the drilling. The essential skill of removing and thinning bone surrounding the embedded structures is paramount to safe and effective surgery.

Currently, technical skills training of otologic surgeons includes observation in the operating room, review of text and multimedia material, practice in a cadaveric laboratory on human temporal bones and gradual increase in operative experience on live patients under the supervision of an established/expert otologic surgeon. Achieving proficiency requires hours of deliberate practice and considerable clinical experience. Surgical training requires at least 5 years under current methods at a cost of approximately \$80,000 per year per resident [1]. Conventional temporal bone laboratories with its related equipment cost over a million dollars to construct and are expensive to maintain [2]. Factors impacting the educational environment such as less time for training (pressure for patient throughput, work hour limitations for trainees), limitations of instructional resources (cadaveric material, access to expert faculty, exposure to hazardous material) and lack of standardized objective assessment tools have created barriers to traditional training paradigms in otologic surgery. There is no universally accepted methodology to objectively assess a surgeon's technical skill for certification. This has resulted in a wide variation in technical skill. Lastly, a simulation system to support innovation in surgical technique and pre-surgical rehearsal does not exist therefore limiting the potential to cultivate and evaluate new surgical strategies. The overall goal of our research program is to provide a computer based virtual reality system by which otologic surgeons can be trained and assessed with respect to their technical skills and can potentially be used for pre-surgical rehearsal.

Despite the fact that there are several systems described in the literature, none have reached universal acceptance or have been regularly integrated into training programs especially in the United States [3]. There are several reasons why this has not occurred but the two main reasons are the need to improve the fidelity of the systems (visual and haptic) and the lack of a uniform, valid and reliable method to assess performance. This work seeks to address the aspect of fidelity and more specifically that of the haptic display (drill/bone interaction) of the system.

The goal of the work presented here is to conduct a rigorous qualitative comparison of two different methods for rendering force feedback in our virtual temporal bone surgery simulator. The first is an ad-hoc, but effective force model used previously in our simulator, and similar to that used in other temporal bone surgery simulators [4], [5] and dental drilling simulators [6]. The second is a sophisticated, but more computationally costly constraint-based force model [7], also employed in another temporal bone surgery simulator [8].

Previous work

The virtual temporal bone system presented by Wiet et al. and developed at The Ohio State University and Nationwide Children's Hospital under NIH/NIDCD funding provides a virtual environment similar to that provided in a cadaveric temporal bone laboratory [1]. The temporal bone is represented within the system based on CT image data; 40 different bones are available for training. The interface consists of a stereo computer monitor and two haptic (sense of touch) feedback devices. The bone is displayed on the computer screen and the haptic device and mouse provide a means to make menu selections and rotate the bone in any plane as well as drill emulation. A modulated drill sound is provided for aural feedback. Using the haptic device(s), the user selects a bone, chooses burr type (cutting vs. diamond), burr size, magnification and orients the bone. Depressing a button on the dominant hand haptic device activates burr rotation. The drilling is non-deterministic in the sense that the user may drill anywhere on the bone. A second tool, the suction irrigator used simultaneously in the non dominant hand, is provided to the user and functions as it does in real surgery to clear debris and provide fluid irrigation to cool the burr. The system runs on a Windows-based desktop platform. Figures 1 and 2 show the user interface for the surgical simulation software and the test program used for our current study, respectively. In Figure 3, the typical setup for a user of the system is shown. We use the above-mentioned hardware and software system for the present study.

Haptic algorithms

A previously released version of our simulator system used a spring-ball force model [9]. In this model, rays are traced from the center to the perimeter of the drill burr. If part of the drill intersects the volume of the bone, the ray tracing will detect the position of intersection along its length. The distance of the intersection from the center of the burr is treated as the length of compression of a simple spring. Each individual spring applies a force on the burr along the direction of that spring. By summing all the forces from the individual springs, the total force on the burr is determined.

Although simple and computationally inexpensive, this algorithm has several drawbacks. Since the total force is a sum of linear forces, no torque is computed on the burr. Therefore, this is inherently a three degree-of-freedom algorithm. In addition, the ray tracing can miss voxels in the bone volume. If a voxel is positioned in a way that none of the rays intersect it but it is still inside the burr volume, no repelling force is generated. This can also happen in situations where equal forces are generated from opposite sides of the burr. Since forces are only computed instantaneously, with no information from previous timesteps, it is possible

for a user to move the device fast enough to “push” through a thin layer of solid voxels. This leads, in some cases, to the burr getting stuck inside the bone.

A more-recent haptic rendering algorithm evaluated in this study is a constraint-based, six degree-of-freedom haptic interaction model [7]. It is capable of simulating the virtual instruments’ motion under multiple contact constraints along the body of the instruments. Both feedback forces and torques are computed, though only lateral forces are displayed through the haptic devices used in this study, since the hardware used lacks the capability for torque display. An extension to that work describes methods to model the physical process of bone excision using both for cutting and diamond burrs, based on theories of orthogonal cutting and abrasive wear studied in machining mechanics [8]. The work presented here evaluates a reimplementation of those algorithms into an existing temporal bone surgery simulation system.

In our present work, We extended the haptic rendering algorithm to support bi-manual interaction, for a total of twelve degrees of freedom. This allows the surgeon to control a surgical drill in one hand and a suction-irrigator in the other, and appreciate contact forces between either instrument and the bone tissue, or between the instruments themselves.

A unique advantage of this and other constraint-based force computation models is that it is able to enforce non-penetration constraints between simulated objects. Using this method, the virtual representations of the surgical instruments remain free from intersection with the bone tissue, thus making it impossible to “push through” any of the solid virtual anatomy (though the amount of repelling force is limited by the capabilities of the haptic device). Because this behavior more closely resembles that of the physical processes we are attempting to simulate, we hypothesized that use of this constraint-based force feedback model would address many of the problems described previously.

Fidelity studies

Increased fidelity of various modes in a virtual simulation has been shown previously to improve the simulation. In driving simulation, Gracio et al. showed that the addition of appropriate motion feedback can increase the performance and acceptance of the user of the simulation system [10]. Harrington et al. [11] showed that increasing visual fidelity had a significant impact on knowledge gained from the use of a virtual environment. Work by Kobayashi et al. [12], where non-spatialized audio was compared with higher fidelity spatialized audio, determined that the spatialized audio increased both subjective reported feelings of presence in the virtual environment and physiological indicators associated with presence.

In a perception study, Agus et al. [13] showed that their haptic system had sufficient fidelity such that users could distinguish between removal of simulated plastic and simulated bone materials. However, they did not do any evaluation of the fitness of the haptic model for teaching purposes.

Forsslund et al. [14] investigated the differences between 3-DOF and 6-DOF haptic rendering in a more recent and similar study. The 6-DOF haptic rendering algorithm they

studied is the same as the one we evaluate in our present work [8]. In their study, medical students, some with clinical experience, performed tasks to touch a number of points in a simulator-like environment without excessive force placed on other objects in the scene. The test was performed using a 3-DOF haptic model, a 6-DOF model with torque output and a 6-DOF model without torque output. Subjects performed the task better and made fewer errors with the 6-DOF algorithm and performance measures had no significant difference between the system with torque output and the system with no torque output. Their findings suggest that use of high-degree-of-freedom haptic rendering in a virtual environment would yield tangible benefit, even when rendering through an under-actuated haptic devices, which encourages our employment of such techniques in our own temporal bone surgery simulator.

Our present study aims to expand of the findings of Forsslund et al. Specifically, we sought to investigate the perceived quality of haptic feedback, as rendered using two very different algorithms previously described, and implicitly compared against the real-world sensations, when performing a real surgical task of bone drilling, rather than tasks similar to a box trainer. Consequently, the participants enrolled in our study were, and needed to be, practicing otologists with experience performing temporal bone surgery.

Methods

A study was designed to compare qualitative perceptions of realism and suitability for training by expert otologic surgeons on two different force feedback rendering algorithms (Bryan et al. [9] and Chan et al. [7]) within the temporal bone virtual surgical environment. Software infrastructure that allows study participants to perform the same virtual temporal bone dissection task using each of the haptic algorithms, then answer a comparison survey, was developed specifically for this evaluation.

Survey

A custom survey program was written to gather opinions of the two haptic algorithms. This program uses the simulator system described above. Participants were presented with a temporal bone, blindly assigned one of the two haptic algorithms and asked to perform a basic mastoidectomy. They were then asked to perform a basic mastoidectomy again on the same temporal bone using the other haptic algorithm. The order of presentation of the haptic algorithms was randomized. Questions were asked afterwards. For each algorithm (identified in the survey by “A” or “B”), the users were asked the following questions on a five-point ordinal scale with endpoint labeling (1 is labeled “Not at all” and 5 is labeled “Very”):

- How similar was the feeling of bone removal in model X to that of an actual drill?
- How suitable is the drilling of model X for teaching surgical techniques?
- How well did model X let you feel small bone details?

A binary preference question was also asked: “Which force feedback model do you prefer, A or B?”. In addition, we had four fields for freeform comments:

- What do you like about Model A?
- What do you dislike about Model A?
- What do you like about Model B?
- What do you dislike about Model B?

A sample of convenience was utilized for this study due to the specialized skills required. Recruitment for the study was performed through our consortium of thirteen training institutions across the United States using email. These institutions were previously equipped with the appropriate computer hardware to run our present study. All of the subjects are fellowship-trained otologic surgeons actively involved in training resident surgeons in otologic skills and treating patients with a variety of otologic pathology. All of the subjects had experience using an earlier version of our simulator that used the ad-hoc force rendering model. The study was approved by The Ohio State University Institutional Review Board for human subjects research.

The simulation platform used consisted of a PC running Microsoft Windows 7, a Nvidia Quadro 5000 graphics card, and two Sensable (now Geomagic) Phantom Omni haptic devices. The Omni device supports lateral forces only and no torques, thus it is a three degree-of-freedom force output device and a six degree-of-freedom input device.

Results and discussion

We had a total of $N=14$ respondents to the survey. Substantially more respondents preferred the constraint-based haptic model (new) to the previous ad-hoc force rendering (old) (26 to 2).

Quantitative results

A paired Wilcoxon Signed-Ranks test was performed on the responses to the survey for the three different preference questions. For the question regarding how similar the bone removal felt to the actual drill, the differences between the new and old haptic model were statistically significant, $Z=2.16$, $p=0.0308$. The differences were significant for the question regarding the suitability of the models for teaching, $Z=4.59$, $p<0.001$. However, the differences in responses for the question regarding feeling small bone details were not significant, $Z=0.36$, $p=0.719$.

A view of the distribution of the responses is shown in Figure 4. Larger bars to the left represent more negative responses to the questions, while larger bars to the right represent more positive responses. Percentages of responses in the (1,2), (3), and (4, 5) ranges are also displayed. In general, the results support the superiority of the new haptic model. The results are the most decisive on the question of suitability for teaching surgical techniques. For the application of creating a surgical simulation system that trains residents, this is the most important metric to judge a haptic model. Results were not as strong regarding the similarity of the drilling to the actual device. Comparing these results to the previous question leads to a conclusion that there are aspects of the drilling that neither model represents well but that these aspects are not necessarily vitally important for learning surgical techniques.

Similarly, the lack of difference between the two models on the question of small bone details could show that these details are not vitally important to the surgery. We asked the participants to perform a basic mastoidectomy – it is possible that with a more advanced technique, such as a facial recess approach, the lack of ability to feel small details would impact the model's suitability for training residents.

For the question regarding the similarity of bone removal to the actual surgery, results tend to support the superiority of the new haptic model. Although the results are not significant, a trend in that direction can be seen. On the question of how suitable the different haptic models are for teaching surgical techniques, the new haptic model is preferred by a large margin for this purpose. The opinions on the ability for the models to feel small bone details were more mixed, with no clear difference between the two.

Qualitative comments

The recorded answers to the freeform comment fields were brief. Two topics that were mentioned by multiple participants are “chatter” and the speed of removal of the drilling. Two participants offered no comments. One person commented only that the two models seemed very similar.

Three participants commented negatively on “skitter” or “chatter” for the spring-ball haptic model. This is an artifact from the way the model interacts with the volume, but some surgeons said it replicated some vibrations felt during real drilling. The constraint-based model is more stable and does not have this artifact. A source of both praise and complaint was the relative ease of bone removal with the constraint-based haptic model. This ease, combined with the lack of “jumpy” behavior when drilling rapidly, may contribute to the overall preference for the constraint-based model.

Conclusion

The overall general preference of the users for the constraint-based drill model show that the experience of users aligns with our intuition about the superiority of that algorithm to the spring-ball model. The increased ability to compute accurate responses to the interaction between tool and bone results in a better user experience, even when the hardware output device used does not support torque feedback. Our work is consistent with those of Forsslund et al. [14] and additionally shows the applicability of those results to a specific, realistic simulation environment.

There are multiple drills available for surgical use, and informal discussion with surgeons reveal that different drills are perceived to have different tactile responses. We did not investigate the individual preferences of the surgeons polled about what types of drills they are most experienced with and what types they prefer when performing surgery. These preferences could possibly be a confounding factor in our analysis.

A future study could be used to tune the bone removal parameters to match the expected behavior of drills and burrs from different manufacturers. By asking each surgeon what drill they are most familiar with and having them adjust the removal aggressiveness to reflect

their experience with that drill, we can find a consensus value for each tool. By taking multiple measures from each surgeon, we reduce the overall error and find parameter values that will be realistic for simulating a particular drill, and hopefully increase the amount of skill transfer between the simulator to the use of those drills in a real surgical environment.

This experiment altered only the haptic algorithm: the physical devices were the same in both cases. An important implication of this research is that improving the force-feedback rendering algorithm of a surgical simulator can deliver real benefits, even on relatively low cost haptic devices.

Acknowledgments

Funding

This work was supported by the National Institute for Deafness and other Communication Disorders, National Institutes of Health, USA, R01DC011321.

Bibliography

1. Wiet GJ, Stredney D, Kerwin T, Hittle B, Fernandez SA, Abdel-Rasoul M, Welling DB. Virtual temporal bone dissection system: OSU virtual temporal bone system: Development and testing. *Laryngoscope*. 2012; 122(Suppl 1):S1–12. DOI: 10.1002/lary.22499 [PubMed: 22294268]
2. Arora A, Hall A, Kotecha J, Burgess C, Khemani S, Darzi A, Singh A, Tolley N. Virtual reality simulation training in temporal bone surgery. *Clin Otolaryngol*. 2015; 40:153–9. DOI: 10.1111/coa.12352 [PubMed: 25403097]
3. Musbahi O, Aydin A, Al Omran Y, Skilbeck CJ, Ahmed K. Current Status of Simulation in Otolaryngology: A Systematic Review. *Journal of Surgical Education*. 2016; doi: 10.1016/j.jsurg.2016.09.007
4. Petersik, A., Pflesser, B., Tiede, U., Höhne, K.-H., Leuwer, R. Surgery Simulation and Soft Tissue Modeling. Springer Berlin Heidelberg; Berlin, Heidelberg: 2003. Realistic Haptic Interaction in Volume Sculpting for Surgery Simulation; p. 194-202.
5. Acosta, E., Liu, A. Proceedings of IEEE Virtual Reality Conference. IEEE; 2007. Real-time Volumetric Haptic and Visual Burrhole Simulation; p. 247-250.
6. Kim L, Park SH. Haptic interaction and volume modeling techniques for realistic dental simulation. *The Visual Computer*. 2006; 22:90–98. DOI: 10.1007/s00371-006-0369-8
7. Chan, S., Conti, F., Blevins, NH., Salisbury, K. 2011 IEEE World Haptics Conference (WHC). IEEE; 2011. Constraint-based six degree-of-freedom haptic rendering of volume-embedded isosurfaces; p. 89-94.
8. Chan S, Li P, Lockett G, Salisbury K, Blevins NH. High-fidelity haptic and visual rendering for patient-specific simulation of temporal bone surgery. *Computer Assisted Surgery*. 2016; 21:85–101. DOI: 10.1080/24699322.2016.1189966 [PubMed: 27973948]
9. Bryan J, Stredney D, Wiet G, Sessanna D. Virtual temporal bone dissection: A case study. *IEEE Visualization*. 2001:497–500.
10. Grácio BJC, Wentink M, Valente Pais AR. Driver Behavior Comparison Between Static and Dynamic Simulation for Advanced Driving Maneuvers. *Presence: Teleoperators and Virtual Environments*. 2011; 20:143–161. DOI: 10.1162/pres_a_00040
11. Harrington MCR. The Virtual Trillium Trail and the empirical effects of Freedom and Fidelity on discovery-based learning. *Virtual Reality*. 2012; 16:105–120. DOI: 10.1007/s10055-011-0189-7
12. Kobayashi M, Ueno K, Ise S. The Effects of Spatialized Sounds on the Sense of Presence in Auditory Virtual Environments: A Psychological and Physiological Study. *Presence: Teleoperators and Virtual Environments*. 2015; 24:163–174. DOI: 10.1162/PRES_a_00226
13. Agus M, Brelstaff G, Giachetti A, Gobbetti E, Zanetti G, Zorcolo A, Picasso B, Franceschini S. Physics-based burr haptic simulation: tuning and evaluation. *Proceedings of the 12th international*

symposium on haptic interfaces for virtual environment and teleoperator systems. 2004; doi: 10.1109/HAPTIC.2004.1287187

14. Forsslund J, Chan S, Selesnick J, Salisbury K, Silva RG, Blevins NH. The effect of haptic degrees of freedom on task performance in virtual surgical environments. *Studies in Health Technology and Informatics*. 2013; 184:129–135. [PubMed: 23400144]

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Figure 1.

Screenshot of otologic surgery simulation software. A basic mastoidectomy is being performed. The external auditory canal (1) and the mastoid tip (2) are labeled. Objects nearer the top of the screen are more anterior (closer to the nose).

Figure 2.
Screenshot of haptic test software. The external auditory canal (1) and the mastoid tip (2) are labeled. Objects nearer the top of the screen are more anterior (closer to the nose).

Figure 3.
Simulator hardware setup. This is a typical setup with two haptic devices held by the user during the virtual surgery session.

Figure 4. Overview of the survey results for each model. Values below 3 are marked in tan, while values above 3 are marked in teal. Responses of 3 are marked in gray. Percentages for positive, middle and negative responses are given.