A haptic model of a bone-cutting burr

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Abstract. We describe a strategy for collecting experimental data and validating a bone-burr haptic contact model developed in a virtual surgical training system for middle ear surgery. The validation strategy is based on the analysis of data acquired during virtual and real burring sessions. Our approach involves intensive testing of the surgical simulator by expert surgeons and trainees as well as experimental data acquisition in a controlled environment.

1 Introduction

The temporal bone is one of the most complicated anatomical areas in the human body [1]. Surgical accessibility of all of its structures has vastly increased the number of potential treatments for patients with hearing or balance disorders. Successful execution of temporal bone dissection requires a high level of dexterity, experience and knowledge of the patient anatomy. Human cadaver dissections are currently considered the primary teaching tool. However, the physical limitations and decreased availability of the material, as well as its high handling and disposal cost and the risks associated to transmission of diseases such as BSE, make this training method increasingly problematic. A VR simulator realistically mimicking a patient-specific operating environment would therefore significantly contribute to the improvement of surgical training.

Accurate and fast burr–bone interaction simulation is a key enabling technology in the development of such a simulator. It has to include burr–bone contact detection, bone erosion, generation of haptic response, and synthesis of secondary visual effects, such as bone debris accumulation, blooding, irrigation, and suction [2]. The human perceptual requirements of a simulator impose very stringent constraints on performance, making bone dissection simulation a technological challenging task.

In this paper, we describe the strategy we use to collect experimental data and to validate a bone-burr haptic contact model developed in a virtual surgical training system [3, 4]. The validation strategy is based on the analysis of data acquired during virtual and real burring sessions. Our approach involves intensive testing of the surgical simulator by expert surgeons and trainees as well as experimental data acquisition in a controlled environment. The rest of the paper is organized as follows. Section 2 summarizes the related work in surgical simulation and the current state-of-the-art haptic models available in literature. Section 3 describes the current setup for our surgical training system and the experimental setup that we currently use to record bone-burr physical contact forces. We then illustrate our preliminary results for the validation of the contact model and the testing of the surgical simulator prototype.

2 Related work

A number of groups are developing simulators for bone dissection.

Early systems (e.g. [5]) focused on increasing the understanding of the anatomy by providing specialized visualization tools of static models. The VrTool [6] and the VOXEL-MAN system [7, 8] mainly concentrate on accurate visual presentation of free-form volume-sculpting operations. The Ohio Virtual Temporal Bone Dissection simulator [9, 10, 11], similarly to our work, aims instead at realistically mimicking the visual and haptics effects of a real operation. Our work is characterized by a physically based contact model, the use of patient specific data, and the focus on validating the haptic model with experimental data. To our knowledge, such data is not currently available in the literature. References [12, 13] provide a general overview of the project, mostly covering pre-operative planning; reference [2] focuses on the human factor analysis; reference [3] presents an implementation of visual and haptic simulation of bone dissection based on a ”first principles” model.

3 Methods and tools

3.1 Surgical simulator setup

Our surgical simulator has been designed following the requirements identified in a human factor analysis[12, 13]. The analysis involved a review of existing documentation, training aids, and video recordings, interviews with experienced operators, as well as direct observation of the procedure being performed in theater. We harness the difference in complexity and frequency requirements of the visual and haptic simulations by modeling the system as a collection of loosely coupled concurrent components. The haptic component exploits a multi-resolution representation of the first two moments of the bone density to rapidly compute contact forces and determine bone erosion.

The visual component uses a time-critical particle system evolution method to simulate secondary visual effects, such as bone debris accumulation, blooding, irrigation, and suction. The system runs on two interconnected multiprocessor machines. The data is initially replicated on the two machines. The first is dedicated to the high-frequency tasks: haptic device handling and bone removal simulation, which run at 1 KHz. The second concurrently runs, at about 15–20 Hz, the low-frequency tasks: bone removal, fluid evolution and visual feedback. The two machines are synchronized using one-way message passing via the Stanford VRPN library[14]. The Virtual-Reality Peripheral Network (VRPN) system provides a device-independent and network-transparent interface to virtual-reality peripherals. This communication library provides also a suitable mean to record complete traces of the training sessions, which can then be processed off-line by data analysis tools.

3.2 Experimental setup

Our bone dissection simulation technique is based on the assumption that bone/burr contact forces are well approximated by functions of the first two moments of the bone characteristic function, restricted to the region contained in the burr [3, 4].

Figure 1: **Surgical simulator setup vs experimental setup**: on the left the virtual surgical training system user interface is composed by two phantom devices that provide force feedback for sucker and burr, as well as an N-vision binocular display that presents images to the user; on the right the experimental setup for measuring contact forces between the burr bit and the bone

In order to validate this assumption and tune the model internal parameters, an experimental setup has been built to measure contact forces between the burr bit and the bone (see figure 1 right). Our experimental setup is composed by the following items:

- a robotic arm in composite material with three degrees of freedom;
- a mini drill MINICRAFT, model MB150, commonly used for surgical training;
- a laser displacement sensor, MESSTECHNIK Opto ILD1400;
- a set of Kiowa strain-gauges, to measure deformations along principal directions.

The robotic arm is used to perform movements along principal directions at constant velocity, while keeping the burr bit applied to the bone. The displacement sensor records the position of the burr bit, while the strain-gauges, placed on the robot grip, measure the contact forces between bone and burr along the normal and tangential direction. The strain-gauges signals are acquired and processed by a Dataforth DAQ Board, extended with a number of additional input modules. The data is acquired, recorded, and visualized using National Instruments LabView.

4 Results

4.1 Simulator results

Our current training system is configured as follows: a single-processor PIV/1500 MHz with 256 MB PC133 RAM for the high-frequency tasks (haptics loop (1KHz) and interprocess communication loop); a dual-processor PIII/800 MHz with 512 MB PC800 RAM and a NVIDIA GeForce 4 Ti 4600 and running a 2.4 linux kernel, for the low frequency tasks(receiving loop, simulator evolution and visual rendering); a Phantom Desktop and a Phantom 1.0 haptic devices, that provide 6DOF tracking and 3DOF force feedback for the burr/irrigator and the sucker; a n-vision VB30 binocular display for presenting images to the user.

The performance of the prototype is sufficient to meet timing constraints for display and force-feedback, even though the computational and visualization platform is constructed from affordable and widely accessible components. We are currently using a volume of 256x256x128 cubical voxels (0.3 mm side) to represent the region where the operation takes place.

We are extensively testing the virtual surgical training system in collaboration with surgeons of the Department of NeuroScience of the University of Pisa. In particular, contact model parameters and erosion factors have been tuned according to their indications and there is consensus that they represent a good approximation of reality. The first training sessions were performed by an expert surgeon and two trainees; each of them was asked to make three times the same intervention.

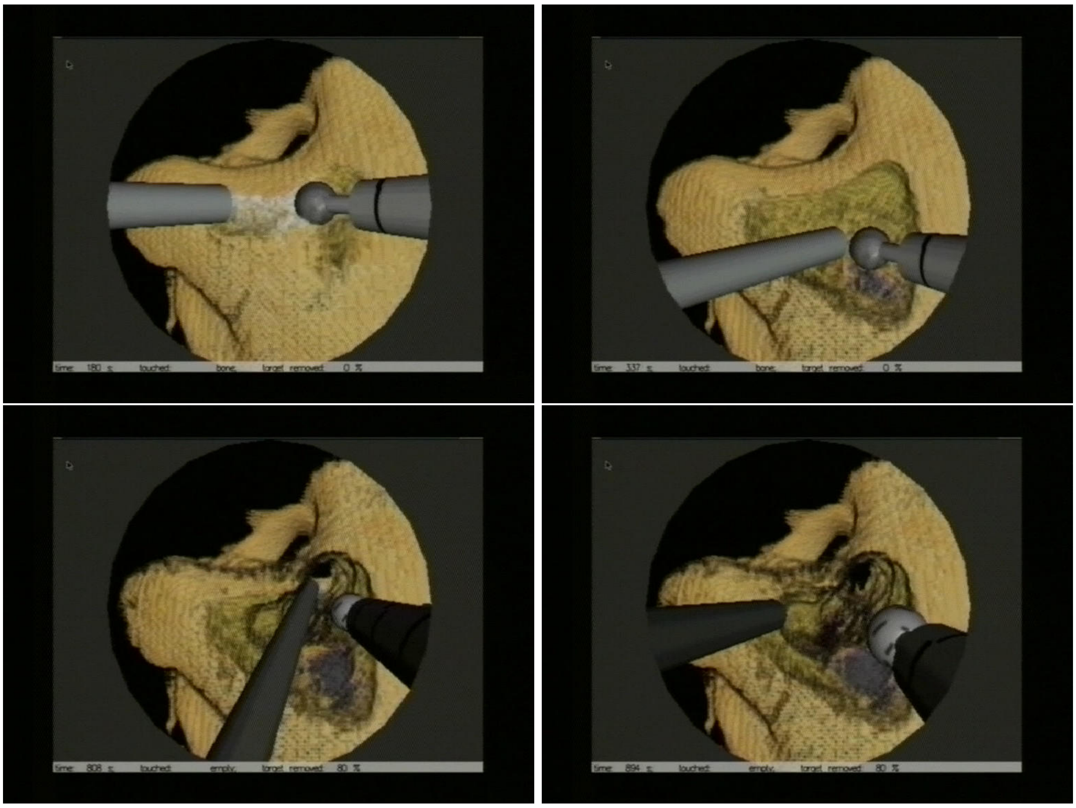

Figure 2: Sequence recorded from the simulator: the principal steps of a basic mastoidectomy are represented

Figure 2 shows a basic mastoidectomy sequence recorded from the simulator, with typical noble structures recognizable. Figure 2 top left shows the the cortex removal, figure 2 top right the cavity saucerization, figure 2 bottom left the lateral sinus, and figure 2 bottom right the mastoid antrum.

Measurement data are obtained by processing the VRPN logs.

Figure 3 shows on the left typical burr force plot, while on the right shows the associated burr tip speed. Force and velocity plots highlight that surgeon movements are periodic and characterized by repeated lateral strokes of 2-3 cms with variable durations [2].

Current available data show consistency between different training sessions of the same user. Average forces exerted by burr are between 0.7 and 1.3 N for the expert surgeon and between 0.8 and 1.1 N for trainees, while average tool velocities are between 8.0 and 12.0 m/sec for the expert surgeon and 10.0 and 17.0 m/sec for trainees.

4.2 First experimental results

At the time of this writing, we are carrying out a number of data acquisition runs, with burr moving at constant velocity towards the bone, and are measuring vertical contact forces as a function of displacement. Different burr tips, velocities, and materials are being tested. In

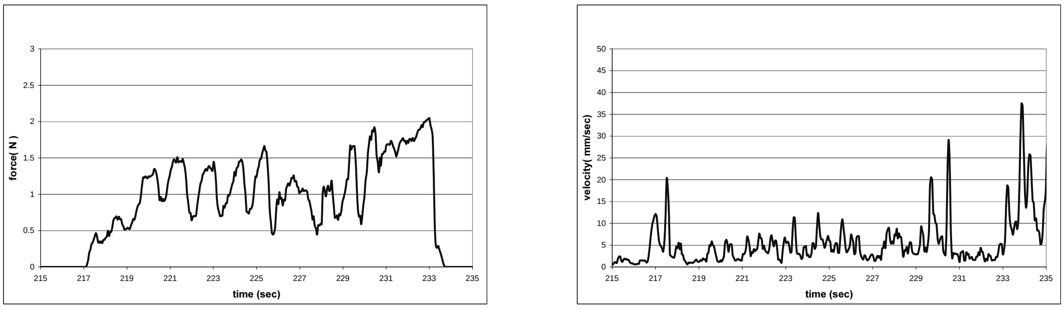

Figure 3: **Training session**. Example of a burr contact force and velocity recorded during a training session with the simulator.

particular, we plan to measure and compare the characteristics of human petrous bone with the characteristics of Pettigrew Plastic Temporal Bones [15].

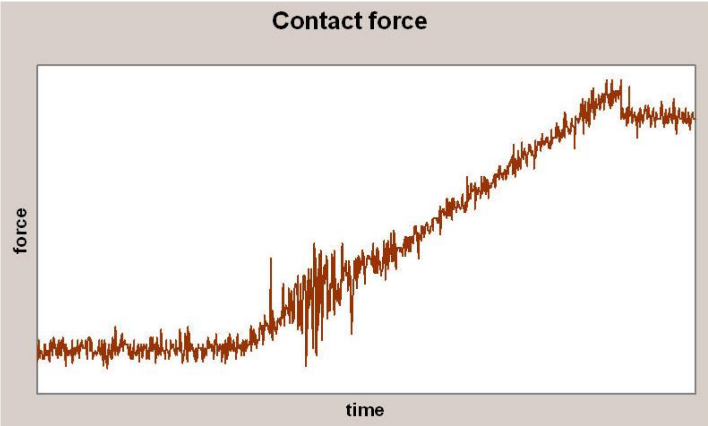

Figure 4: **Experimental measures**. Experimentally measured vertical contact force as a function of time. Constrained vertical motion at constant speed, with burr drilling a hole in a human temporal bone.

Our preliminary results indicate that the experimental setup is appropriate to measure vertical contact forces as a function of displacement (see figure 4). Successive sets of measures on the same material report consistent data. We are currently in the process of fitting the contact force model to the experimentally acquired data. The general behaviour of the acquired curves appears to be consistent with our force model.

5 Conclusions and Future Work

We presented a strategy for collecting experimental data and validating a bone-burr haptic contact model developed in a virtual surgical training system for middle ear surgery. Our approach is based on the analysis of data acquired during virtual and real burring sessions and it involves intensive testing of the surgical simulator by expert surgeons and trainees as well as experimental data acquisition in a controlled environment. We are currently in the process of acquiring experimental data for different materials, burr tips, and burring velocities. We are also working on defining metrics appropriate to the quantitative analysis of virtual training session traces.

Acknowledgments

These results were obtained within the framework of the European Union IERAPSI project (EU-IST-1999-12175). We would like to thank Pietro Ghironi for the precious technical support, the surgical residents Michele D'Anteo and Simone Valori for their performances during the training sessions, and Francesco Pia for his technical support during the experimental sessions. We also acknowledge the NIH National Research Resource in Molecular Graphics and Microscopy at the University of North Carolina at Chapel Hill for the VRPN library.

References

[1] R. A. Nelson. *Temporal Bone Surgical Dissection Manual*. House Ear Institute, Los Angeles, second edition, 1991.

[2] Marco Agus, Andrea Giachetti, Enrico Gobbetti, Gianluigi Zanetti, Nigel W. John, and Robert J. Stone. Mastoidectomy simulation with combined visual and haptic feedback. In J. D. Westwood, H. M. Hoffmann, G. T. Mogel, and D. Stredney, editors, *Medicine Meets Virtual Reality 2002*, pages 17–23. IOS Press, January 2002.

[3] Marco Agus, Andrea Giachetti, Enrico Gobbetti, Gianluigi Zanetti, and Antonio Zorcolo. Real–time haptic and visual simulation of bone dissection. In *Proc. of Ieee Virtual Reality 2002*, pages 209–216, Orlando, FL, USA, March 2002.

[4] Marco Agus, Andrea Giachetti, Enrico Gobbetti, Gianluigi Zanetti, and Antonio Zorcolo. Adaptive techniques for real–time haptic and visual simulation of bone dissection. submitted for publication.

[5] T. Harada, S. Ishii, and N. Tayama. Three-dimensional reconstruction of the temporal bone from histological sections. *Arch Otolaryngol Head Neck Surg*, 114:1139–1142, 1988.

[6] RB Kuppersmith, R Johnston, D Moreau, RB Loftin, and H Jenkins. Building a virtual reality temporal bone dissection simulator. In J. D. Westwood, editor, *Medicine Meets Virtual Reality 5*, pages 180–186, Amsterdam, The Netherlands, January 1997. IOS Press.

[7] Bernhard Pflesser, Andreas Petersik, Ulf Tiede, Karl Heinz Hohne, and Rudolf Leuwer. Volume based planning and rehearsal of surgical interventions. In Heinz U. Lemke et al., editor, *Computer Assisted Radiology and Surgery, Proc. CARS 2000, Excerpta Medica International Congress*, 1214, pages 607–612, Elsevier, Amsterdam, 2000.

[8] Bernhard Pflesser, Andreas Petersik, Ulf Tiede, Karl Heinz Hohne, and Rudolf Leuwer. Haptic volume interaction with anatomic models at sub-voxel resolution. In *10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,Proc. Haptics 2002*, pages 66–72, 2002.

[9] G. Wiet, J. Bryan, D. Sessanna, D. Streadney, P. Schmalbrock, and B. Welling. Virtual temporal bone dissection simulation. In J. D. Westwood, editor, *Medicine Meets Virtual Reality 2000*, pages 378–384, Amsterdam, The Netherlands, January 2000. IOS Press.

[10] Jason Bryan, Don Stredney, Greg Wiet, and Dennis Sessanna. Virtual temporal bone dissection: A case study. In *IEEE Visualization*, pages 497–500, 2001.

[11] D. Stredney, G. Wiet, J. Bryan, D. Sessanna, J. Murakami, O. Schamllbrock, K. Powell, and B. Welling. Temporal bone dissection simulation – an update. In J. D. Westwood, H. M. Hoffmann, G. T. Mogel, and D. Stredney, editors, *Medicine Meets Virtual Reality 2002*, pages 507–513. IOS Press, January 2002.

[12] N. W. John, N. Thacker, M. Pokric, A. Jackson, G. Zanetti, E. Gobbetti, A. Giachetti, R. J. Stone, J. Campos, A. Emmen, A. Schwerdtner, E. Neri, S. Sellari Franceschini, and F. Rubio. An integrated simulator for surgery of the petrous bone. In J. D. Westwood, editor, *Medicine Meets Virtual Reality 2001*, pages 218–224, Amsterdam, The Netherlands, January 2001. IOS Press.

[13] Marco Agus, Andrea Giachetti, Enrico Gobbetti, Gianluigi Zanetti, and Antonio Zorcolo. A multiprocessor decoupled system for the simulation of temporal bone surgery. *Computing and Visualization in Science*, 5(1), 2002.

[14] ll Russell M. Taylor, Thomas C. Hudson, Adam Seeger, Hans Weber, Jeffrey Juliano, and Aron T. Helser. Vrpn: a device-independent, network-transparent vr peripheral system. In *Proceedings*

of the ACM symposium on Virtual reality software and technology, pages 55–61. ACM Press, 2001.

[15] Alastair Pettigrew. Pettigrew plastic temporal bones. http://www.temporal-bone.com/.