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Translating the Simulation of Procedural Drilling Techniques for Interactive Neurosurgical Training

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Abstract

Background—Through previous and concurrent efforts, we have developed a fully virtual environment to provide procedural training of otologic surgical technique. The virtual environment is based on high-resolution volumetric data of the regional anatomy. This volumetric data helps drive an interactive multi-sensory, i.e., visual (stereo), aural (stereo), and tactile simulation environment. Subsequently, we have extended our efforts to support the training of neurosurgical procedural technique as part of the CNS simulation initiative.

Objective—The goal of this multi-level development is to deliberately study the integration of simulation technologies into the neurosurgical curriculum and to determine their efficacy in teaching minimally invasive cranial and skull base approaches.

Methods—We discuss issues of biofidelity as well as our methods to provide objective, quantitative automated assessment for the residents.

Results—We conclude with a discussion of our experiences by reporting on preliminary formative pilot studies and proposed approaches to take the simulation to the next level through additional validation studies.

Conclusion—We have presented our efforts to translate an otologic simulation environment for use in the neurosurgical curriculum. We have demonstrated the initial proof of principles and define the steps to integrate and validate the system as an adjuvant to the neurosurgical curriculum.

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Keywords

skull base; simulation; virtual reality; neurosurgery; training

Introduction/Problem Statement

Whether defining safe and minimally invasive trajectories to access neoplasms, or training for techniques used in debulking a lesion, a consummate understanding of the regional anatomy is essential. To gain such understanding, a safe and effective environment is critical to provide an accurate emulation of the anatomy and deliberate practice for learning and maintenance of psychomotor skills.

To provide this environment, we explored various approaches, including physical modeling with material tissue correlates, virtual representation, and a hybrid approach. Obviously there are advantages and disadvantages to either a physical or virtual approach. Both approaches have issues with biofidelity, especially in the sense of visual accuracy and tissue interactions. Physical models can be elegantly constructed, especially with the advent of 3-D printing. Physical models do allow the trainee to use actual instruments to execute performance. However, cost and repetitive use can be limiting. Physical models often provide no anatomical or pathological variance. Virtual models permit relatively low-cost simulations. Computational technology and interface equipment have stabilized in utility and seen a reduction in cost. With the use of Open-source software, and GPU video board developments being pursued and led by the gaming industry, these costs also continue to decline. Because the model is digital, repetition is not an issue. Anatomical and pathological variance can be captured in the acquisition, i.e., using a specimen with variance, or often the digital model can be modified to emulate a variance. However, the field is relatively new and there are limited interfaces that can accurately emulate hand-instrument and instrument-tissue interaction.

Nevertheless, we assert that there are distinct advantages in a virtual approach. Below, we present our methods and results in our initial deployment of a fully virtual, interactive environment for learning neurosurgical techniques as well as user assessment. The context of this deployment was within CNS simulation courses and was based specifically on procedures involving drilling, i.e., (pterional burr hole, pre-sigmoid, and retro-sigmoid craniotomy).

Background

Simulation's application to neurosurgery has evolved over the span of several decades. Kelly introduced the use of 3-D reconstructions for use in the pre-operative assessment and planning of volumetric stereotactic procedures.¹ In 2006, Wang *et al* introduced realistic deformable models depicting prodding, pulling and cutting of simulated soft tissues.² In 2007, Lemole *et al* demonstrated a system for ventriculostomy training that employed haptic feedback.³ Concomitantly, Acosta *et al* presented a haptic approach for a burr hole simulation.⁴ Both of these approaches combine natural viewing of the hands and synthesized visuals in an augmented reality approach, a hybrid of real and virtual components. Hofer

presented using Navigated Control for avoiding critical structures during surgical intervention.⁵ These approaches rely on a virtual model for accurate and precise planning and execution. More recently, Delorme and others presented NeuroTouch®, an integrated system including stereo graphics and haptic manual interfaces for microneurosurgical training.⁶ Through funding from the National Research Council Canada, the effort includes 20 sites participating in beta testing and validation.

Our early studies related to this effort correlated structural information from volumetric magnetic resonance data with functional data from electroencephalograms into integrated displays used for investigating drug and alcohol addictions, and sleep disorders.^{7, 8} Subsequent work involved the development and evaluation of three-dimensional volumetric displays of patient-specific data as compared to traditional methods in the study of brain and cranial base tumors.^{9–15} Concurrent work involved simulations for training anesthesia residents in the delivery of an epidural.^{16, 17} The epidural anesthesia simulations were our first investigations into integrating volume graphics with haptics (force reflecting technology). Using volumetric techniques, we also simulated pelvic compression neuropathies associated with birthing.¹⁸ Subsequently, we were part of a multi-institutional effort to develop and evaluate a Functional Endoscopic Sinus Surgery simulator that integrated visual and haptic interfaces. This involved two parallel developments, one focusing on surface-based representations^{19, 20}, the second focusing on volumetric representations.^{21–26} These studies showed that although surface-based representations were expedient and could provide interactive rates, they lacked the complexity and realism found in volumetric displays.²⁷ The ENT Surgical Trainer, as it has come to be known, has been identified as the first true procedural surgical simulation environment to undergo vigorous validation.²⁸

We have developed a virtual simulation for use in the training of temporal bone dissection for the laboratory that combines multimodal representations, stereoscopic volume rendering, and haptic and aural (stereo) feedback.²⁹ We have disseminated our temporal bone dissection simulator to ten additional institutions to obtain formative and preliminary summative evaluations.³⁰ The study demonstrated that virtual representations were capable of providing introductory training equal to cadaveric models.^{31, 32} The simulator is currently being employed to conduct a multiple institution randomized controlled trial to evaluate its efficacy for use in training, specifically in the integration of standardized metrics and automated assessment of performance.

Recently, we demonstrated translation of the otological technique simulator for the emulation of skull base techniques used in neurosurgery.³³ This simulation is completely virtual, providing visual, aural, and haptic (tactile) forces in an interactive, multisensory interface.

Methods

The course of our methods can be categorized into the following steps: Data Acquisition, Pre-Processing, Segmentation, Systems Integration, and Rendering and Use (Figure 1).

Data Acquisition

To obtain digital models, specimens were imaged using a Siemens 64-detector Somatom™ computed tomography scanner with a modified inner ear protocol with a FOV of 119 mm, an in-plane resolution of 0.232, and a slice thickness of .6mm.³⁴ Imaging was conducted at the Ross Heart Hospital at The Ohio State University Wexner Medical Center (OSUWMC). Digital data were then transferred to the Ohio Supercomputer Center for preprocessing.

Pre-Processing and Segmentation

Pre-processing includes rescaling and filtering to clean and prepare the data for segmenting. Segmentation involves interactive user-mediated demarcation of critical structures, surfaces, and regions based on surgical significance. The segments are used to localize instruments, determine violation of key and critical structures, and the contextual use of force, metrics that will be employed in quantitative automated assessment. In the neurosurgical application of our system, we have processed the data sets to provide for emulation of pterional, and pre- and retro-sigmoid approaches (Figure 2) to the lateral skull base.

Systems Integration, Rendering and Use

The system comprises a desk-side computer (Intel quad-core 3.6GHz processor with 16GB RAM running Windows 7) with an NVIDIA (Quadro 5000) Graphics Processing Unit (GPU). Processed and segmented data are loaded into the GPU for interactive stereo (20–30 frames per second) visuals. We employ a mix of custom rendering software using open-source (i.e., OpenGL) methods of direct volume rendering to achieve these results, including interactive drilling and removal of bone. A Geomagic Sensable® Omni® is used as a dexterous device to provide direct emulation of the user's manipulation of instruments, specifically the drill burr used to remove bone and gain access to underlying structures. Forces are calculated based on regional voxel intensities. Resistance to the applied force is used to modulate stored sounds of drilling. Stereo glasses and a stereo-ready monitor and headphones complete the interface (Figure 3), providing a rich, multisensory environment based completely on the user's interaction with a virtual model.

Table 1 demonstrates the directive and methods of scoring used in the study.

Quantitative Automated Assessment

Our current approach is based on a set of rules defined by expert surgeons. These rules rely on the volume data comprising defined structures and regions (e.g., sutures, sinuses, semicircular canals). Based on (virtual) procedures performed on the simulator by experts, we determine logical cutoff points for the amount of bone removal required for a certain level of expertise. For example, in the retro-sigmoid craniotomy task, between 1% and 50% of the Posterior Fossa Dural Plate must be removed during the procedure to get credit (Figure 4). Refer to Table 1 for our complete rule-based grading system. Penalties can be given if excessive or insufficient amounts of a specified structure are removed. A breakdown of one's score is provided to the residents upon completion of the procedure and results are saved for further analysis. In a deployment of this system in a classroom setting, residents (and their attendings) will be able to see their progress in procedures over time.

Faculty time investment is optimized in that both formative and summative feedback is provided to the trainee independent of the faculty's physical presence.

For the peritonal, pre and post-sigmoid approach, we provide quantitative automated scores to the final products of virtual models representing the application of procedural techniques.^{35, 36} We asked each of three experts to perform the 3 techniques as many times as possible. This information is employed to construct a composite score for determining expert variance of technique. Through the comparison of matching regions of voxels between high-quality expert products, i.e., drilled virtual bones, and those of residents using various distance metrics, we obtain a feature vector that is used in a range of clustering and classification algorithms. Given a set of final products previously graded by an expert, we then can extract features from the volumes and construct a decision tree.³⁷ Preliminary results using this method have resolved information for assessment more powerful than hand motion analysis in some metrics, obtaining kappa scores above 0.6 when comparing expert and automated grading scores for such metrics as "Complete Saucerization" and "Antrum Entered". This approach provides scoring for metrics that are not easily defined in terms of strict structural boundaries and can be straightforwardly extended to different procedures.

Results

We have presented our methods for constructing a virtual environment for procedural drilling techniques and their application to neurosurgery. We have conducted a small pilot study to gather feasibility data in practical courses that were held at the annual meetings CNS 2011 in Washington, DC, and CNS 2012, in Chicago, Illinois. A short didactic review was provided prior to the simulation study. Pre-assessment of skill was limited to the participants providing their rank. All participants were asked to perform the 3 techniques the best they could.

At this time, our data are not generalizable. We have seen a wide variance in user performance. In our initial data, we had (N=) 17 participants, not all of who finished every task listed above. A summary of the results is available in Table 2. The total possible score is 90 and the subjects were early-year residents. The low scores in general may indicate that the tasks are too difficult for early-year residents.

These preliminary pilot studies have, however, provided us valuable formative evaluation that will be integrated into the simulation to pursue the next level of controlled randomized validation studies required to further evaluate the efficacy of our designs in the neurosurgical curriculum. These studies will include pre and post test assessments, with a two-arm approach of simulation versus traditional training techniques.

The automated assessment provides a means of learning procedural techniques with feedback that does not require supervision by an attending surgeon. The breakdown with immediate scores gives a more concrete indication for improvement than hand motion analysis, i.e., economy of movement. Most important, all cases used for assessment are exactly equal in difficulty. This approach provides for a more quantified and objective assessment of procedural skills.

Discussion

We have presented the adaptation of virtual simulation techniques developed for otologic surgery to neurological techniques. Essential to this adaptation is the development of automated assessment techniques and their use in analysis of resident performance. These assessments are congruent with the CNS simulation initiative to provide bold and innovative methods for training and assessments. More specifically, it addresses the call for the formal integration of simulation as a training modality in the curriculum.³⁸ This effort seeks to address the “technological gaps and limitations” of current simulators, and to help to balance “the cost and time needed for development of new simulations.”

Through the adoption and adaptation of virtual techniques we present the advantages of cost efficiency, cleanliness, standardization and repeatability, and provision of anatomical and, eventually, pathological variance. The current limitations of a virtual approach include lack of soft tissue emulation and representation of the management of fluids such as bleeding and irrigation, although we are actively pursuing these capabilities.³⁹ In summary, we contend that a virtual approach can not only more rapidly capitalize on new technological advances, but that the virtual representation can itself iteratively drive innovation in other technological domains, such as imaging and robotics, as well as tool design and testing.

Conclusion

We have presented our efforts to translate an otologic simulation environment for use in neurosurgical training. We have demonstrated the initial proof of principles and now consider the steps to integrate and validate the system as an adjuvant to the neurosurgical curriculum as part of the CNS simulation initiative.

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Figure 1.
Diagram of data workflow.

Figure 2.
Use of the simulation at CNS Chicago 2012. Left, Resident providing summative feedback.
Right, Experts providing formative feedback.

Figure 3.

Left, Pre-sigmoid approach in simulator. Right, Retro-sigmoid approach. Note: View is arbitrarily established and modified interactively by the user.

Figure 4.

Left, View during mastoidectomy. Right, End result scored against expert composite score: Green=ALL experts removed bone. Cyan= SOME experts removed this region. Red (arrow) NO experts removed this bone.

Table 1

The following table lists the directive and methods of scoring used.

Directive	Negative points	Positive points	Total points possible
Drill a single burrhole on the pterional point.		10: If parts of each of the Sphenosquamosal suture, the Squamosal suture and Sphenoparietal suture are removed	10
Drill a single burrhole near the pterion that exposes only anterior fossa.	<ul style="list-style-type: none"> 5: If the middle fossa is entered 5: If the orbit is entered 	10: If the anterior cranial fossa is entered	10
Drill a single burrhole near the pterion that exposes the orbit and the anterior cranial fossa simultaneously.	<ul style="list-style-type: none"> 5: If the middle fossa is entered 	5: If the orbit is entered 5: If the anterior cranial fossa is entered	10
Perform a pterional approach and reduce the greater sphenoid wing to the superior orbital fissure without entering the orbit.	<ul style="list-style-type: none"> 3: If less than 5% or greater than 40% of the greater sphenoid wing removed: 3: If less than 5% or greater than 40% of the lesser sphenoid wing removed 5: Entered the orbit. 	10 points by default	10
Identify the digastric sulcus by drilling part of it away while minimizing removal of nearby structures.		10: if more than 30% of the digastric sulcus is removed.	10
Drill a retro-sigmoid craniotomy at the edges of the transverse and sigmoid sinuses. The goal is to expose a slight amount of sinus (in blue).	<ul style="list-style-type: none"> 5: None or over 20% of the sigmoid sulcus removed 5: None or over 20% of the transverse sinus removed 10: None or over 50% of the Posterior Fossa Dural Plate removed 5: Less than 20% of the digastric ridge removed 	10 points by default.	10
Drill the mastoid anterior to the edge of the sigmoid sinus, exposing the superior petrosal sinus and the IAC, while avoiding the facial nerve and middle and inner ear.	<ul style="list-style-type: none"> 10: Over 10% of the sigmoid sulcus removed 20: Drilled part of the facial nerve 10: Drilled part of a semicircular canal 20: Drilled cochlea 20: Drilled bone of middle ear 	10: Exposed sigmoid sulcus 20: Exposed IAC 10: Exposed the superior petrosal sinus	40

Table 2

Results from pilot study: N=17

	Time (minutes)	Total Score
Mean	12.8	24.1
Std. Dv	7.4	12.6
Median	11.2	22.0