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Endoscopic Third Ventriculostomy on a Microneurosurgery Simulator

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Abstract

Endoscopic third ventriculostomy is a procedure used to treat hydrocephalus by making a perforation in the floor of the third ventricle of the brain under endoscopic guidance. To provide a training tool to neurosurgery residents, an endoscopic simulator was developed and integrated on NeuroTouch, a simulator for microneurosurgery training. The simulator includes two exercises: 1) *burr hole selection*, where the trainee is asked to choose the location of the burr hole on a plastic head and the orientation of the trajectory to the foramen of Monro; and 2) *intraventricular navigation and perforation*, where the trainee is required to find the third ventricle with a neuro-endoscope and to perforate its floor, while avoiding damage to critical structures. The simulator provides feedback on trainee performance either graphically or using quantitative metrics. The simulator allows easily switching from endoscopic third ventriculostomy mode to microscopic craniotomy mode using a retractable stereoscope based on a single screen and mirrors, detachable plastic heads, and quick-connect tool handles to give more realistic haptic feedback.

Introduction/Background

Minimally invasive surgical procedures have reduced patient length of stay, but can be difficult to master. To help overcome this difficulty, surgical simulators have been developed for many minimally invasive surgeries over the last two decades. Technical skills training on simulators has been shown not only to speed up the learning curve and make operating room time more efficient [Aggarwal 2007], resulting in an estimated simulator payback period of 6 months [Frost & Sullivan 2004], but also to reduce the number of surgical errors [Seymour 2002][Gurusamy 2008]. Some insurers have even offered malpractice insurance premium incentives for following simulation training [Hanscom 2008].

Neurosurgery is one of the surgical specialties with the highest risk and the most expensive malpractice insurance premiums [Rodwin 2008]. It requires safe manipulation of instruments around very fragile tissues. In a prospective study on over 1000 neurosurgery cases, 78% of surgical errors were considered preventable. The most frequently reported errors are technical [Stone 2007].

Hydrocephalus, a condition affecting close to one in every 1000 live births [Persson 2007], is the accumulation of an abnormal amount of cerebrospinal fluid (CSF) in the ventricles of the brain. Obstructive hydrocephalus is usually caused by a blockage between the third and fourth ventricles. If left untreated, a child with hydrocephalus has less than 25% chance of reaching adult life [Laurence 1962].

Endoscopic third ventriculostomy (ETV) is a treatment modality of obstructive hydrocephalus whereby the floor of the third ventricle of the brain is perforated under endoscopic guidance to release cerebrospinal fluid pressure. In a meta-analysis including 2884 patients, ETV had an 8.5% overall complication rate, a 2.4% rate of permanent morbidity and a 0.2% mortality rate [Bouras 2011]. Care must be taken to avoid damaging critical structures such as the basilar arteries and the fornix. Perforation of the basilar arteries can cause massive bleeding which can be lethal. Damage to the fornix has been reported to cause amnesia and personality disorders [Ersahin 2008]. Using an endoscope increases the difficulty of the procedure, as damage can occur in the blind angle of the endoscope [Ersahin 2008] and venous bleeding in the cerebrospinal fluid can quickly burr the endoscopic view.

Recent papers have compared the potential benefits of using virtual reality simulation in neurosurgery training to its well recognized value in aviation [Quest 2007] and in nuclear submarine operation [Apuzzo 2009]. Virtual reality simulators developed for endoscopic sinus surgery [Edmond 1998][Parikh 2009][Tolsdorff 2010] can potentially be applied to neurosurgery training, such as for transsphenoidal pituitary surgery [Wolfsberger 2006]. Virtual simulators have also been developed for ventriculostomy [Larsen 2001][Lemole 2007] and endoscopic third ventriculostomy [Freudenstein 2001][Brown 2006][Çakmak 2009], some of which have passed several validation steps [Çakmak 2009]. Most of the available neurosurgery simulators only allow training for specific procedures.

In a survey of 99 United States neurosurgery programs, over 70% of respondents believed that simulation would improve patient outcome and could supplement conventional training, and said that they would make simulator practice mandatory, if available [Ganju 2012]. A bootcamp involving first postgraduate year neurosurgery residents took place at one location in the United States in 2009 [Selden 2011], and at 6 locations the following year [Selden 2012]. The bootcamp included hands-on training sessions on simulators. One advantage of the bootcamps is to allow residency programs to share the cost of providing access to a large breadth of simulation resources. In parallel with these initiatives, the Congress of Neurological Surgeons has set up a Simulation Committee to develop a national neurosurgery curriculum involving simulation [Lobel 2011].

Supported by a network of surgeons from 23 Canadian teaching hospitals, the National Research Council of Canada is developing NeuroTouch, a virtual reality simulator for microneurosurgery procedures [Delorme 2012], and has proposed a set of fundamental skills and associated simulation exercises that can help improve neurosurgery residents skills prior to receiving operating room training [Choudhury 2012].

The objective of this work is to develop an ETV simulation that can run on the same hardware and software platform as NeuroTouch. This paper will cover the simulation exercises definition, the hardware and the software developments of the ETV simulation.

Simulation exercises definition

In order to define the educational objectives, the ETV procedure was analysed and decomposed into steps, which were then prioritized in terms of their importance for training. As thoroughly explained in other works, e.g. [Cinalli 2005], the steps of the procedure generally include:

1. Selection of the appropriate entry point and trajectory;
2. Cannulation of the lateral ventricle;
3. Navigation within the lateral ventricle and entry into the third ventricle through the foramen of Monro;
4. Identification of the third ventricle's floor and selection of the ventriculostomy site;
5. Fenestration of the third ventricle's floor;
6. Confirmation of adequate ventriculostomy;
7. Inspection of the fornix and removal of the endoscope.

Based on a survey of 32 neurosurgeons, Haji *et al.* [Haji 2012] have ranked steps of the ETV procedure in order of importance to simulate, and have ranked typical errors based on both frequency and seriousness. Their results indicate that the top three procedural steps, in order of decreasing importance, are 4, 3 and 5. These steps account for the majority of the intraoperative errors that were identified. Based on feedback from our network of collaborating surgeons, and these results, we have chosen to start with simulating steps 1, 3, 4, and 5, and two exercises were defined for the simulation development.

The first exercise, referred to as *burr hole selection*, comprises step 1. In this exercise, the point of cortical entry and trajectory must be chosen. A successful cannulation is one that enters the ventricle at a point and orientation which allows navigating through the foramen of Monro into the third ventricle so that the floor may be fenestrated. To minimize tissue damage along the insertion path, the ideal trajectory is typically defined by an imaginary line, from the center of the ideal fenestration zone on the third ventricle floor through the center of the foramen. The ideal burr hole location is the point at which this line intercepts the skull (see Figure 1). Imaging studies [Kanner 2000][Knauss 2009][Duffner 2003] indicate that this point is located, on average, approximately 2-3 cm lateral to the midline and 1 cm anterior to the coronal suture. The learning objective of this exercise is to use visible physical anatomical landmarks to select the correct entry point and trajectory, as is commonly done in the clinical setting. A mixed-reality simulation was developed in which the user is presented with a mannequin head and required to use the available physical anatomic landmarks, such as the cranium midline, the intertragal line and the inner canthus, to select both the position and orientation that would be used to cannulate the right ventricle.

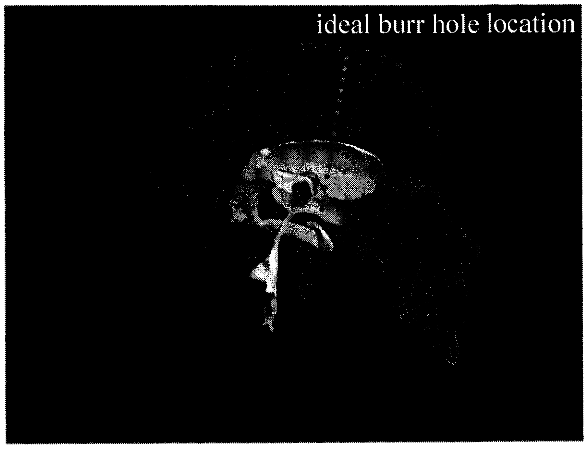

Figure 1. The ideal burr hole location and trajectory definition.

In the second exercise, denoted *intraventricular navigation and perforation*, the user performs steps 3-5 using a model in which an expert has already performed the cannulation and placed a peel-away tube. In this exercise, the learning objectives are: i) to navigate within the right ventricle and through the foramen of Monro using a neuro-endoscope, taking care not to damage any delicate structures, such as choroid plexus and fornix; ii) once inside the third ventricle, to use visual cues to locate the correct fenestration point; iii) to manipulate a second tool within a working channel of the neuro-endoscope to puncture the floor at the selected position. The exercise is performed with a neuro-endoscope model having a single working channel. In real procedures, a range of different tools is used for the initial fenestration of the floor and subsequent dilation of the stoma [Hellwig 2005]. As the main goal of this simulation is the initial fenestration, we chose a simple blunt tool. All steps of this exercise are done under endoscopic guidance.

Hardware development

The NeuroTouch microneurosurgery simulator hardware (see Figure 2) was adapted to accommodate the different needs of the proposed ETV exercises and the already existing microneurosurgery exercises. The base hardware includes a computer, a screen and a plastic mannequin head (see Figure 3). The stereoscope design described in [Delorme 2012] was modified from two mirrors and two screens, to four mirrors and one screen. Furthermore, the mirrors were mounted on a retractable frame allowing easy switching between mono-display for ETV and stereo display for microsurgery. A neuro-endoscope handle with a blunt probe instrument inserted in its working channel is mounted on a PHANTOM Omni (Sensable, Wilmington, MA) haptic device to provide force feedback. A magnetic connector was designed to easily switch between a plastic head with a craniotomy opening for microsurgery and a plastic head with a burr hole for ETV. Quick-exchange tool handle connectors with automatic tool recognition were designed to easily connect and disconnect tools to the haptic system. These components are shaped and organized spatially to mimic the real surgical environment.

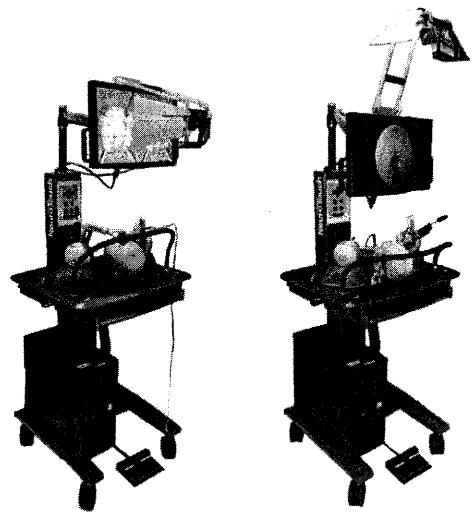

Figure 2. NeuroTouch simulator hardware settings: microneurosurgery vs endoscopic neurosurgery.

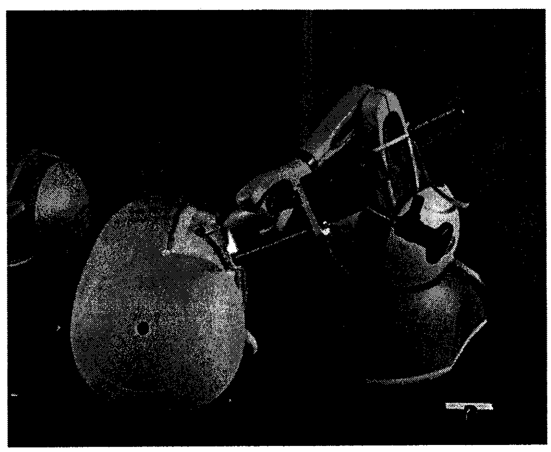

Figure 3. Base hardware setup for the ETV simulation.

Several technical challenges related to the hardware configuration were encountered during the development. The use of a physical head model requires a registration procedure, such that proper alignment of the physical head with the virtual model can be ensured. In this procedure, the user is asked to touch four pre-defined positions on the physical head. A rigid transformation, which matches the fiducial points on the real and virtual models in a least-squares sense is then calculated [Horn 1987]. The registration error is displayed, allowing the user to accept the result, or re-do the procedure to improve the accuracy (see Figure 4).

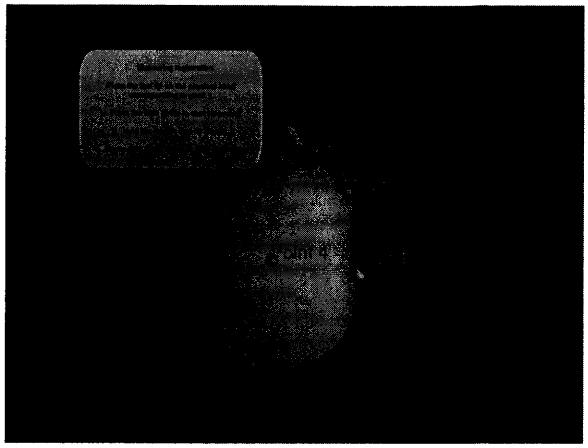

Figure 4. Registration procedure for proper alignment of the virtual and physical heads.

A second difficulty encountered during the development is that the PHANTOM Omni device used in the system senses the 6 degrees of freedom of the end effector (3 rotation and 3 translations), but only provides force feedback on the 3 translations. ETV simulation requires torque feedback in two rotations (azimuth and elevation) and force feedback in the axial direction. Since the neuro-endoscope shaft must pass through a small opening in the skull, it is convenient to place a ball joint at this point to constrain the motion of the neuro-endoscope and thus convert the 3 forces that the Omni device can generate into two torques and one force (see Figure 5). In such a case, the end-effector of the haptic system can either be located inside or outside the head. We chose to place the end-effector outside the head. The advantage to this configuration is that it allows easy removal of the neuro-endoscope from the head. However, the drawback is that it reduces the accuracy of the neuro-endoscope tip position. Noise in the haptic system's orientation sensors can make the position of the neuro-endoscopic camera, which is displaced from the end effector position along the tool handle, tremble, causing the on-screen image to shake. To minimize this effect, the azimuth and elevation of the neuro-endoscope are calculated from the position of the end-effector and the position of the ball-joint, rather than read from the Omni device encoders.

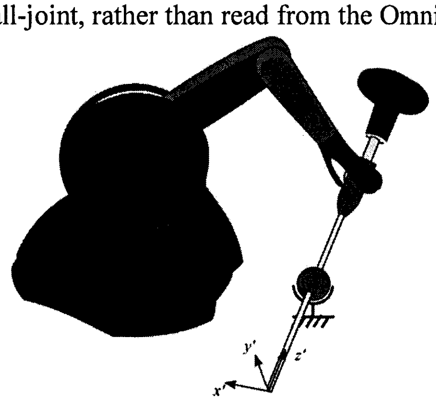

Figure 5. Design of the ball joint mechanism.

Software development

The burr hole selection exercise is done by placing the tip of the neuro-endoscope at the chosen entry point on the mannequin head, and orienting towards the foramen of Monro (see Figure 6). At the end of the exercise, the user-selected trajectory is displayed as a red arrow in a semi-transparent head model which also shows the position of the ventricles and an acceptable range of trajectories as a cone (see Figure 7). This interactive 3D display provides the trainee not only an idea about his performance relative to an expert's suggestion, but also an intuitive notion of the consequence of his selection, especially in the case of a bad selection.

Figure 6. Burr hole selection exercise in the ETV simulation.

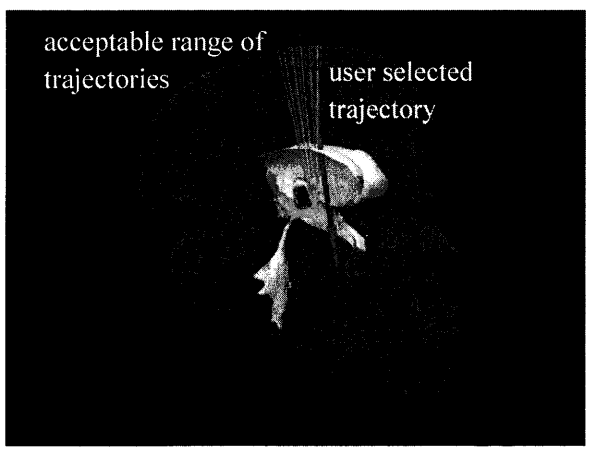

Figure 7. Performance evaluation of the burr hole selection exercise.

In the navigation and perforation exercise, the user is first asked to insert the neuro-endoscope into a pre-drilled burr-hole in the mannequin head and guide it down a peelaway tube placed in the virtual brain model. Then, as described previously, they must navigate the neuro-endoscope to the floor of the third ventricle and perforate the floor with a blunt tool inserted in the neuro-endoscope, exposing the subarachnoid space and some anatomical structures behind the floor. During this exercise, the haptic system attached to the neuro-endoscope provides tactile feedback when contact is made with the deformable ventricle walls, using a collision detection algorithm [Neubauer 2012].

Though most structures of interest may be resolved with preoperative imaging methods, the small size of many details makes creation of a virtual model which exactly matches a patient's anatomy difficult. Indeed, Rohde *et al.* compared intraoperatively identified anatomical pathologies and virtual MR endoscopic images and found the sensitivity of virtual MRI endoscopy for detection of anatomical variants of the ventricular system to be low [Rohde 2001]. For this ETV simulation module, we developed a synthetic deformable model of the ventricular system that captured the large-scale anatomy and was consistent with MRI-based measurements of a population of hydrocephalic patients [Duffner 2003].

Anatomical structures, such as the choroid plexus, the septal vein, the thalamostriate vein, the mammilary bodies, the pons, the basilar artery and the infundibulum are displayed as graphical textures on the visible surface of the ventricles or on additional surfaces inside the ventricles (see Figure 8). In addition, structures visible through the ventriculostoma, such as the basilar artery, pons and clivus, are modeled as solid objects.

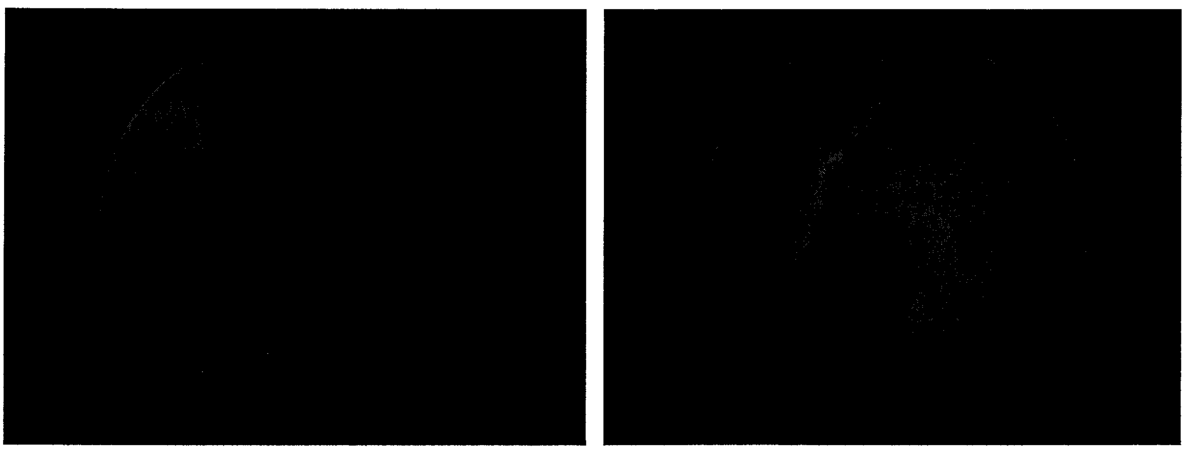

Figure 8. Anatomical structures present in the navigation and perforation exercise, left: inside the right lateral ventricle; right: inside the third ventricle.

To enhance realism, the floor of the third ventricle moves according to the combined effect of breathing and blood pulsation. Particles floating in the CSF are also displayed.

For trainee performance feedback, ideal, acceptable and unacceptable perforation zones on the floor of the third ventricle of the model were defined by neurosurgeons. Immediately after perforation, a message displays the name of the zone affected (Figure 9(left)). At the end of the simulation, the total time and the relationship of the perforation site to nearby structures is displayed (Figure 9(right)). Additional user performance data, such as tool trajectory and contact force with critical structures at each moment of the simulation, are saved in a file and can be used for further analysis of the trainee.

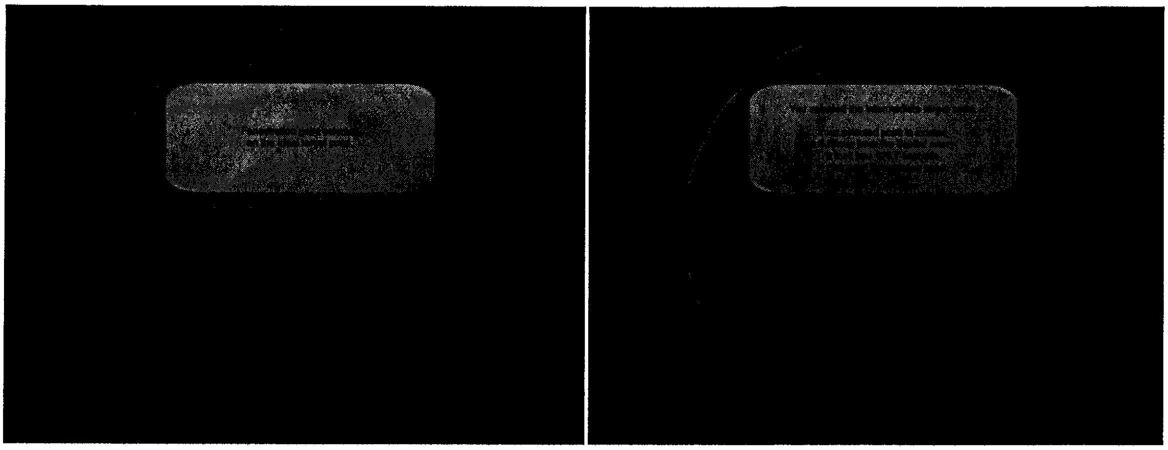

Figure 9. Performance feedback for the navigation and perforation exercise:
left: immediate message to the user; right: metrics display at the end of the exercise.

Discussion

To our knowledge, this is the first simulator permitting trainees to practice both craniotomy-based microsurgery and ETV on the same hardware platform. It was designed through close collaboration between developers and end-users. It contains two simulation exercises to practice, first, the burr-hole position and entry orientation selection, second, to navigate inside the ventricular system, reach the third ventricle and perforate the third ventricle floor.

Future developments include the ability for the user to perform the navigation and perforation exercise using the trajectory selected in the burr hole selection exercise and, either an expert-suggested entry point, or the entry point chosen by the user. This would help the trainee to understand the consequence of a suboptimal burr hole selection and trajectory on the rest of the procedure. Another improvement would be to simulate the enlargement of the perforation site using forceps or a fogarty balloon, and to allow the evaluation of proper CSF flow through cues such as flapping movement of the tissue surrounding the stoma. Performance metrics need to be further developed, in particular penalties for touching critical structures.

A training curriculum, based on the microneurosurgery exercises in NeuroTouch and focusing on reduction of common surgical errors, is currently being constructed by an expert panel of neurosurgeons. Studies are underway to evaluate the face and construct validity of the simulator through randomized, prospective, blinded studies utilizing novice, intermediate and expert participants.

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