NeuroTouch: A Physics-Based Virtual Simulator for Cranial Microneurosurgery Training

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BACKGROUND: A virtual reality neurosurgery simulator with haptic feedback may help in the training and assessment of technical skills requiring the use of tactile and visual cues.

OBJECTIVE: To develop a simulator for craniotomy-based procedures with haptic and graphics feedback for implementation by universities and hospitals in the neurosurgery training curriculum.

METHODS: NeuroTouch was developed by a team of more than 50 experts from the National Research Council Canada in collaboration with surgeons from more than 20 teaching hospitals across Canada. Its main components are a stereovision system, bimanual haptic tool manipulators, and a high-end computer. The simulation software engine runs 3 processes for computing graphics, haptics, and mechanics. Training tasks were built from magnetic resonance imaging scans of patients with brain tumors.

RESULTS: Two training tasks were implemented for practicing skills with 3 different surgical tools. In the tumor-debulking task, the objective is complete tumor removal without removing normal tissue, using the regular surgical aspirator (suction) and the ultrasonic aspirator. The objective of the tumor cauterization task is to remove a vascularized tumor with an aspirator while controlling blood loss using bipolar electrocautery.

CONCLUSION: NeuroTouch prototypes have been set up in 7 teaching hospitals across Canada, to be used for beta testing and validation and evaluated for integration in a neurosurgery training curriculum.

KEY WORDS: Computer simulation, Craniotomy, Neurosurgery, Teaching, Training

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WHAT IS THIS BOX?
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Hospitals are under pressure to constantly monitor their expenditure plans, including the cost of surgical procedures. The majority of surgical training (90%) is performed in the operating room,[1] where residents learn procedures by assisting surgeons with hundreds of operations. This training system decreases the efficiency of the surgeon and increases operating room time by as much as 35%,[2] increasing associated costs. Simulation offers a cost-effective alternative to traditional training approaches. A return-on-investment analysis for hospitals purchasing simulators indicated that the payback period was 6 months, based on savings in training costs and increased operating room efficiency.[3]

ABBREVIATIONS: DOF, degrees of freedom

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Following the widely adopted training model for airplane pilots, medical virtual simulators have been developed over the past 2 decades and are now commercially available for minimally invasive surgical procedures based on endoscopy, such as gastroscopy, colonoscopy, bronchoscopy, laparoscopy, cystoscopy, ureteroscopy, hysteroscopy, and arthroscopy; for endovascular interventions; and for other specialized procedures. In a double-blind experiment comparing apprenticeship training with and without a virtual simulator, residents trained on a virtual laparoscopic cholecystectomy simulator completed the intervention in 29% less time and were 5 times less likely to injure the patient.[4] More recently, one study determined that 1 hour of training spent on a virtual laparoscopic cholecystectomy simulator was equivalent to 2.28 hours training spent in the operating room.[5] A review of 23 validation studies with 612 participants confirmed that virtual laparoscopy simulators decreased the time taken to complete a task, increased accuracy, and decreased errors.[6] It has also been suggested that virtual simulation could provide an objective assessment of surgical skills proficiency.[7,8]

In a prospective study of 1108 neurosurgical cases, 78.5% of errors during neurosurgery were considered preventable. The most frequent errors reported are technical in nature.[9] The increased use of endoscopy in neurosurgery introduces challenges and increases the potential for errors because of issues such as indirect view, elaborate surgical tools, and a confined workspace. The potential usefulness of simulation in the training of neurosurgeons has been compared with its long-established value in aviation[10] and in nuclear submarine operation.[11]

First developed to address the demanding training needs of endoscopic surgeries, virtual simulators developed for otorhinolaryngology, such as endoscopic sinus surgery,[12-14] can have applications in neurosurgery, such as for transsphenoidal pituitary surgery.[15] Virtual simulators with realistic graphics and force feedback have also been developed for ventriculostomy,[16,17] and endoscopic third ventriculostomy,[18,19] some of which have passed several validation steps.[19]

Few developments have been reported for a simulator to train for craniotomy-based interventions. Kockro et al[20] developed Dextroscope, a virtual environment for the planning of craniotomy procedures. Although the Dextroscope has been used for teaching operative anatomy and strategies,[21,22] it lacks the capability to manipulate virtual tissues in real-time through force-feedback devices, which is an essential component of surgical simulators that teach technical skills. Simulators with haptic feedback would potentially allow learning how to use tactile cues.

In 2004, Spicer et al[23] described the essential components of a proposed fully immersive neurosurgical simulator for intracranial procedures and identified the remaining scientific challenges toward its development, such as developing a computational model that provides an accurate response of the brain to mechanical manipulation and realistic fluid dynamics while maintaining real-time haptics and graphics update rates of 1000 Hz and 30 Hz, respectively. A team in Nottingham, United Kingdom, tried to address some of these challenges by developing a simulator that allowed bimanual manipulation of a virtual brain, including prodding, pulling, and cutting, with virtual surgical tools controlled via force-feedback devices.[24-26] These promising developments based on the boundary element method using linear elasticity do not yet permit (1) physically realistic tissue behavior in "large" deformations, ie more than 10% elongation or compression, often encountered in neurosurgery; (2) real-time computing of brain tissue removal; and (3) rendering of bleeding. The Nottingham team was working on the modeling of deep cuts in the tissue, requiring on-the-fly recomputing of the boundary element system. A more detailed review of neurosurgery simulators was recently published by Malone et al.[27]

OBJECTIVE

The objective of this project is to develop a simulator that facilitates the development and assessment of technical skills for craniotomy-based procedures, resulting in the creation and refinement of a curriculum-based program for neurosurgical resident training. The simulator should have a variety of training tasks, ie, short goal-oriented exercises involving surgical manipulations each starting at one stage during a surgical procedure, of increasing difficulty levels and provide feedback to the user on his or her performance and mistakes. The simulator should also have tactile and visual feedback and meet the following requirements.

Microscope

The simulator graphics rendering system should mimic a neurosurgical microscope, ie, allow 3-dimensional visualization through binoculars.

Neurosurgical Tools

The simulator should allow manipulation of neurosurgical tools important for training, ie, tools that are commonly used, difficult to use, or for which few opportunities for training exist. This includes articulated tools and nonarticulated tools, as well as activated and nonactivated tools. The simulator should allow the user to manipulate neurosurgical tools using both hands simultaneously and feel their interaction with biological tissues. The tools should feel realistic in the hands of the user, in terms of shape, behavior, weight, and movement. Graphics rendering of tools should look realistic and should coincide with the handle position, orientation, and state in the case of articulated or deformable tools.

Anatomy and Tissues

The simulator should represent an adequate level of anatomic details for the training task. Tissue textures should look convincing at the surface of the cortex, at the boundary of a tumor, and inside the tissues. Blood vessels at the surface and inside the brain should be represented. Tissues should look and feel like real tissues under the action of gravity and when interacting with a tool, including the rendering of temporary and permanent changes such as deformation, tearing, cutting, burning, pulverization, and aspiration. Differences in tissue stiffness should be perceptible using visual and tactile cues. The stiffness of tissues should be tunable to the user's preference.

Blood

Blood vessels should be realistic in appearance, pulsate normally, bleed when cut, and discontinue bleeding when properly cauterized. Blood from bleeding vessels should accumulate by gravity at the bottom of the wound and should be removable when the proper tools are used.

PATIENTS AND METHODS

Design Method

The development of this neurosurgery simulator, called NeuroTouch, is a joint effort of a team of 50 experts from the National Research Council Canada. This team works in collaboration with an advisory network of 23 teaching hospitals across Canada (Table 1), represented by neurosurgeons of diverse levels of experience and surgeons with a strong track record in education. After commencing in April 2008, the project was critically dependent on semiannual meetings at hospitals with the advisory network to validate the advancements, accumulate recommendations, and classify for implementation.

The team used a methodology inspired by agile development of software[28,29] to create the simulator, including cognitive task analyses of surgical procedures, interviews and surveys with subject matter experts, feature-oriented code implementation, coding task decomposition, pair programming, remote use of a common code repository from development laboratories in 4 cities, automatic post-commit software testing, regular user tests, bug-tracking system, frequent software releases, feedback from prototype trials at advisory network meetings and laboratory visits, and installation of prototypes at hospital beta sites. An important component of the project was to have a postgraduate year 6 neurosurgery resident spend 1 day per week with the team in the development laboratory outlining the critical training requirements from the resident's perspective (Figure 1).

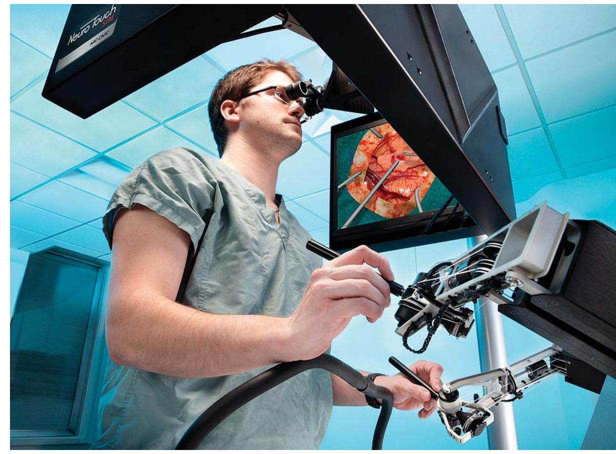

FIGURE 1. *Neurosurgery resident testing a NeuroTouch prototype to provide feedback.*

Hardware

The neurosurgical simulator main components include a 3-dimensional graphics rendering system (stereoscope), a bimanual haptic rendering system, other controls, and 1 or 2 computers (Figure 2). The simulator components are mounted on a frame that allows adjustment of the height of the haptics and stereoscope and adjustment of the tilt angle of the stereoscope. The frame also includes adjustable wrist rests, not shown in Figure 2.

TABLE 1. Advisory Network of Teaching Hospitals in Canada

Hospital	Affiliated University	Location
Victoria General Hospital	University of British Columbia	Victoria, BC
Vancouver General Hospital	University of British Columbia	Vancouver, BC
Alberta Children's Hospital	University of Calgary	Calgary, AB
Foothills Hospital	University of Calgary	Calgary, AB
University of Alberta Hospital	University of Alberta	Edmonton, AB
Royal University Hospital	University of Saskatchewan	Saskatoon, SK
Health Sciences Centre	University of Manitoba	Winnipeg, MB
London Health Science Centre	University of Western Ontario	London, ON
St. Joseph's Healthcare	McMaster University	Hamilton, ON
Toronto Hospital for Sick Children	University of Toronto	Toronto, ON
St. Joseph's Health Centre	University of Toronto	Toronto, ON
Toronto Western Hospital	University Health Centre	Toronto, ON
Kingston General Hospital	Queen's University	Kingston, ON
Ottawa Hospital	University of Ottawa	Ottawa, ON
Centre Hospitalier Universitaire Sainte-Justine	Université de Montreal	Montreal, QC
Montreal General Hospital	McGill University	Montreal, QC
Royal Victoria Hospital	McGill University	Montreal, QC
Montreal Neurological Institute and Hospital	McGill University	Montreal, QC
Hôpital Maisonneuve-Rosemont	Université de Montreal	Montreal, QC
Centre Hospitalier Universitaire de Sherbrooke	Université de Sherbrooke	Sherbrooke, QC
Centre Hospitalier Universitaire de Québec	Université Laval	Quebec City, QC
Saint John Regional Hospital	Dalhousie University	St. John, NB
Queen Elizabeth II Hospital	Dalhousie University	Halifax, NS

FIGURE 2. *NeuroTouch components. Stereoscope (a), haptic systems (b), power supplies and amplifiers for haptic systems (c), computer (d).*

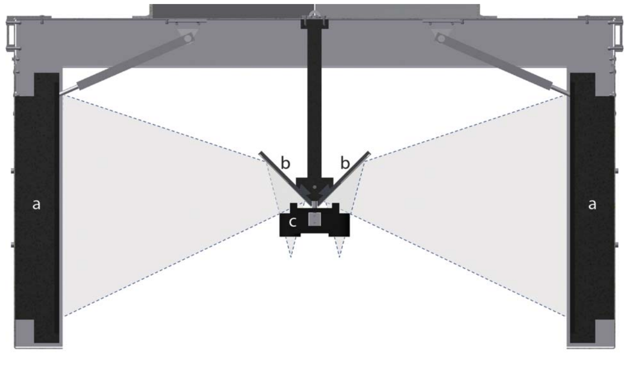

FIGURE 3. *Top view of stereoscope showing dashed lines of sight from LCD screens (a) to mirrors (b), and mock binoculars (c).*

Graphics

The graphics rendering system was designed to mimic a neurosurgical microscope. This system allows 3-dimensional visualization, has a large field of view, minimizes eye strain (far focus, parallel eyes), and has a high resolution. A Wheatstone stereoscope[30] was designed using a binocular eyepiece without lenses, two 17-inch LCD screens with 1280 × 1024 resolution, and 2 first surface mirrors (Figure 3). The size and distance of the screens provide a field of view of 30 degrees and focus at 40 cm to reduce eye strain. The use of lenses was avoided to minimize mismatch in the right and left images caused by peripheral distortion.

Haptics and Peripherals

A haptic system is a device capable of rendering tactile feedback. Haptic systems used in surgical simulators are designed to track the position of tools and render the resistance of tissues that the tools interact with. Tissue resistance depends on its mechanical properties. Surgical haptic systems are typically composed of linkages connected by joints. Each of the 3 Cartesian components of the tool position (up-down, left-right, forward-backward) and the 3 orientation components (azimuth, elevation, and roll) are called degrees of freedom (DOF). At least 6 joints are required to get free handle motion in all 6 DOF. Most joints are equipped with a sensor capable of measuring the rotation between 2 linkages. The tool handle position and orientation with respect to the base joint are inferred using geometry and sensor values. Some joints can also be driven by actuators capable of generating forces acting against rotation.

In our simulator, 2 different types of haptic systems can be used: (1) the Phantom Desktop (Sensable Technologies, Wilmington, Massachusetts), which has 6 sensed DOF and 3 actuated DOF (translations only) (Figure 4A), and (2) the Freedom 6S (MPB Technologies, Montreal, Quebec, Canada), which has 6 sensed DOF and 6 actuated DOF (Figure 4B). The main consequence of these characteristics is that the Phantom Desktop can render forces acting at the tip of a straight surgical tool, whereas the Freedom 6S can render torques and forces acting anywhere along the tool. The systems were chosen based on their ability to minimize the sensation of the linkages and that of the joints, which are proportional to tip inertia and back drive friction, respectively, considering that typical brain tissue resistance to probing is on the order of 100 mN.[31] Other specifications of these 2 systems are listed in Table 2.[32,33] Despite its higher tip inertia, which is most felt when high accelerations are applied to the handle, the Freedom 6S is weight balanced, allowing tool handles to be crafted that feel the same weight as they feel in the operating room, whereas the Phantom Desktop requires the use of an active weight compensation algorithm to achieve the same level of realism in tool weight. The simulator includes 2 haptic systems, 1 for each hand. They can be 2 of the same kind or a combination. Neurosurgical tools were adapted and fixed on the handle on each haptic system.

Foot pedals, tool handle sensors, dial knobs, and push buttons can be used for tool control and other on-the-fly settings and are connected to the main computer via a microcontroller (Arduino).

Computers

The main computer has 2 Xeon Quad-Core X5570 processors running at 2.93 GHz (Intel, Santa Clara, California), and 1 GeForce GTX 285 graphics card (NVidia, Santa Clara, California). The configuration using the 2 Freedom 6S haptic systems requires an auxiliary standard computer to connect 1 haptic system, whereas the other haptic system is connected to the main computer. The main computer and the auxiliary computer are connected via a crossed Ethernet cable.

Simulation Software

The main computer runs the simulation software engine, a distributed-memory software program developed in-house and comprising 3 asynchronous processes updating at multiple rates (Figure 5): graphics

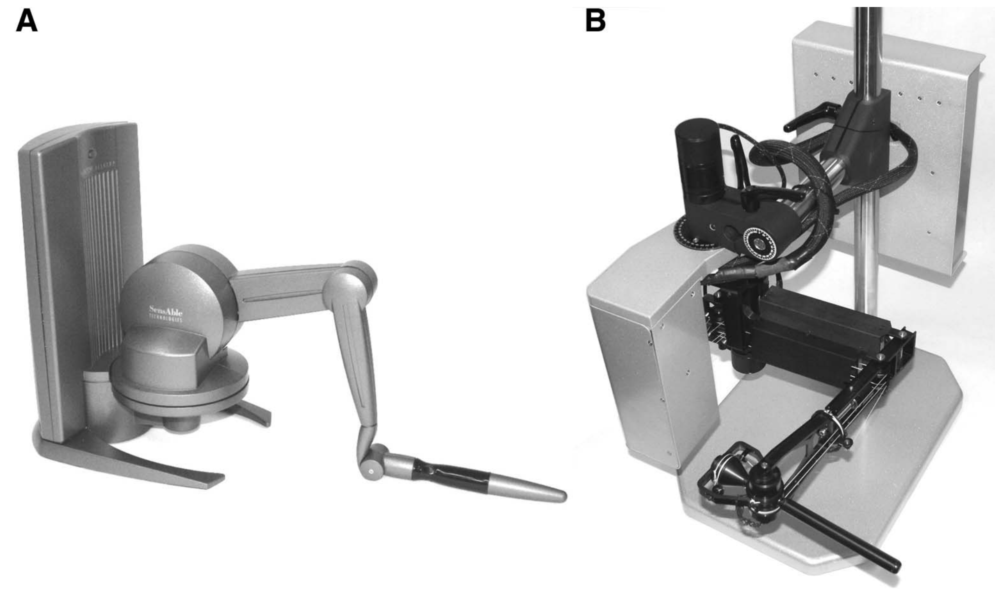

FIGURE 4. *Haptic systems used in simulator.* **A**, *Phantom Desktop.* **B**, *Freedom 6S.*

at 60 Hz, haptics at 1000 Hz, and tissue mechanics at 100 Hz. The multithread implementation of the simulation software engine can run on Linux or Windows 64 bits operating systems.

Graphics

The graphics process displays the surgical workspace 3 dimensionally: the surgical tools, the tissue surfaces, and the blood. To produce each image in the simulator, a high-resolution surface mesh is created from and updated by a lower resolution surface mesh used by the tissue mechanics process. The high-resolution mesh deforms to account for blood accumulation[34] and local effects from surgical tools. Dissection of vascularized tissue triggers bleeding. The bleeding rate depends on presence of large blood vessels going across the surface, the level of vascularization of tissues intersected by the surface, and time. Bleeding can be locally controlled by cauterization. It also adapts in real time to changes in the shape and structure of the model. Bleeding physics is efficiently computed on the graphic card to minimize CPU load. High-resolution textures are overlaid on the mesh to ensure realism. Cast shadows are computed for the entire environment. The resulting image is deformed and blurred to simulate the effects of lens distortion and depth of field.

TABLE 2. Technical Specifications for 2 Haptic Systems Retrieved From Manufacturer's Website[32,33]

Specification	Freedom 6S	Phantom Desktop
Workspace, mm	170 × 220 × 330	160 × 120 × 120
Back drive friction, mN	40	60
Tip inertia, g	125	45
Maximum continuous force, N	0.6	1.75
Maximum peak force, N	2.5 (over 60 s)	7.9
Position resolution, μm	2	23
Stiffness, N/mm	2	1.5-2.4

Haptics

The haptics process reads the position of the haptic handles, computes collisions between tools as well as between tools and tissues, computes reaction forces on the tools, and sends the forces back to the haptic systems. Because tools are often long with sharp tips, 2 collision detection algorithms are used: (1) collision between a cylinder following the tool shaft and nodes at the surface of the tissue and (2) collision between nodes on the tool tip and triangles at the surface of the tissue. Reaction forces on the tool are the cumulative contributions of instantaneous penalty-based forces created between the tool position given by the haptics and the contact forces resulting from the tissue deformation. Friction forces were neglected.

Tissue Mechanics

The tissue mechanics process computes the deformation of the tissues and topology changes associated with tissue rupture, cut, or removal.

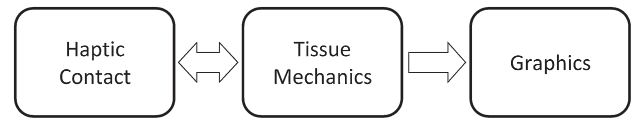

FIGURE 5. *Data flow between 3 asynchronous processes of simulation software engine.*

It is assumed that the deformation of brain tissue, composed of gray matter, white matter, blood, and cerebrospinal fluid, is based on continuum mechanics fundamentals. The accurate approach of using finite element models to solve the brain tissue deformation has often been replaced in real-time applications by simplified techniques that offer significant computation speed gains. They can be classified into 2 categories: simple mechanical models such as spring mass and precomputer models such as precomputed finite element or reduced-order models (see Meier et al[35] for a more comprehensive review). Although the former has limited realism in large deformation and incompressibility, the latter cannot yet simulate topology changes. Building on our experience implementing finite elements solvers for large deformation applications,[36,37] the tissue mechanics processes uses finite elements with explicit time-integration scheme. The mechanical behavior of tissues is modeled as viscoelastic solids using the quasilinear viscoelastic constitutive model for the viscous part,[38] using the following relaxation function:

$$G(t) = g_0 + \sum_{k=1}^{2} g_k e^{-t/\tau_k}$$

where τ_k is relaxation time and g_k is relaxation moduli. The elastic part of tissue behavior is modeled as hyperelastic solids using a compressible form of the generalized Rivlin constitutive model,[38,39] given by the following strain energy density function:

$$W = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + \frac{K}{2}(J - 1)^2$$

where C_{10} and C_{20} are material constants determined from experiments, I_1 is the first invariant of the left Cauchy-Green deformation tensor, K is the bulk modulus, and J is the square root of the third invariant of the left Cauchy-Green deformation tensor and a measure of the volumetric deformation. The bulk modulus is given by:

$$K = \frac{2\mu(1+\upsilon)}{3(1-2\upsilon)}$$

where μ is the shear modulus and υ is the Poisson ratio. The shear modulus is $\mu = 2C_{10}$.

Simulation of tissue removal uses a volume-sculpting technique with level sets.[40-42]

Training Tasks Preparation

Modeling a training task requires a finite element model of the involved biological tissues in the task-specific operating field. This model combines visual and mechanical properties of brain tissues and pathological tissues. It also includes the vasculature with bleeding properties and pulsation. These models were generated from patient scans.

Patients were recruited at the Health Science Centre (Winnipeg, Manitoba, Canada) and at the Queen Elizabeth II Hospital (Halifax, Nova Scotia, Canada) based on the following inclusion criteria: (1) presence of brain tumor, (2) 18 years of age or older, (3) signature of informed consent form. Each patient underwent the following scans if they were not already included in the hospital's standard-of-care imaging protocol: T1-weighted magnetic resonance imaging (MRI) with gadolinium and functional MRI identifying language area. Images were anonymized before being transmitted to the image-processing team.

Cortex, tumor, and blood vessels were segmented on the T1-weighted MRI scan. The cranium was segmented on the computed tomography scan if available. Functional areas were identified from the functional MRI data. The craniotomy location was interactively defined on a 3-dimensional volume rendering of the scan by the operating neurosurgeon, thereby defining an operating field comprising the surgical corridor from the craniotomy to the tumor and surrounding brain tissues (Figure 6). A triangular mesh was created on the surface of the segmented components of the region of interest. From this surface mesh, either an unstructured tetrahedral conforming mesh of the interior or a structured hexahedral nonconformal mesh encompassing the region of interest was created. The number of volume elements in the mesh was adjusted to the computing hardware to meet real-time computation requirements, ie, 60 Hz for graphics and 1000 Hz for haptics. For unstructured conforming meshes, the number of tetrahedrons was approximately 5000. For structured nonconformal meshes, the number of hexahedrons was approximately 700, but the surface mesh used for graphics rendering was made of more than 35 000 triangles. For blood vessels, a vasculature tree composed of bar elements, with an average vessel diameter at each node, was embedded in the brain tissue model.

The tumor and the brain tissues surrounding it are modeled as deformable objects. White matter and gray matter are considered as a single homogeneous tissue. Brain and tumor behave like nonlinear elastic, nearly incompressible tissues. Mechanical properties for brain were obtained from in vitro tensile tests and unconfined compression tests on calf brains obtained from a slaughterhouse and tested within 6 hours post mortem (Figure 7, A-C). The material parameters for Neo-Hookean, Rivlin, and quasilinear viscoelastic constitutive models were obtained by fitting the analytical solution for these models to the experimental data.[43] Elasticity of tumors was estimated from in vitro indentation measurements on 7 excised human gliomas of grades 2 to 4, tested within 30 minutes after excision (Figure 7D).[44] Experimental data suggest that brain stiffness does not change significantly within the 6 hours post mortem.[45] For each tissue, parameters of the quasilinear viscoelastic and Rivlin constitutive models were adjusted to the experimental data (Table 3).

To achieve realistic graphics rendering, a high-resolution volume of visual information corresponding to the simulated tissue area is created. This volume integrates processed information derived from the MRI scan with processed photographs of the type of surgery to be simulated. The volume is then enhanced by expanding the available information using statistical models, for example, to refine or synthesize blood vessels in addition to the embedded vasculature tree. Interactive tools allow an expert to control the appearance of the created model. These data are then sampled in real-time during simulation and overlaid on the simulated geometry, following its deformation.

All anatomic data related to a training task are saved in computer files. However, the process of creating new training tasks is not yet optimized enough to be done autonomously by the end user in a reasonable time frame. For each training task, 60 hours of work were required to build the simulation data from the MRI scan. It would take 30 hours of work to adapt them for a new patient.

RESULTS

NeuroTouch allows simulating brain tumor removal using a craniotomy approach on 3 training tasks using the surgical aspirator, the ultrasonic aspirator, bipolar electrocautery, and microscissors. Tissue stiffness can be adjusted independently at any time during the simulation using 2 dial knobs. In addition to

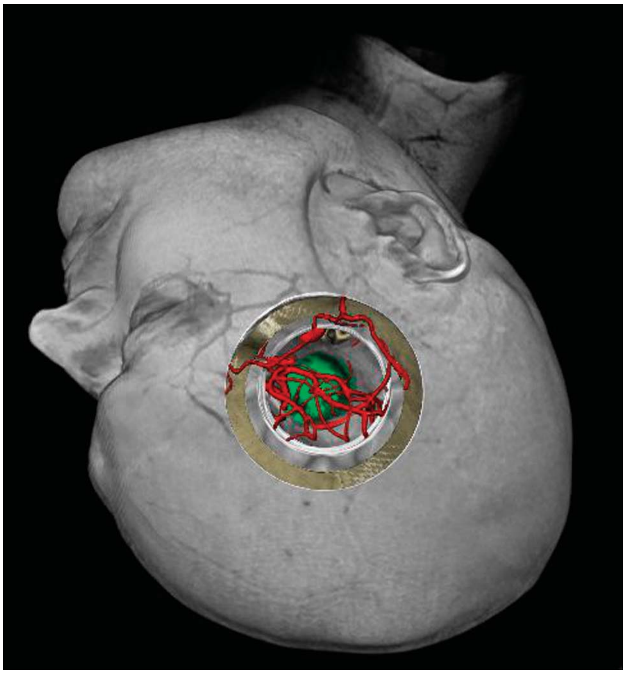

FIGURE 6. *Virtual surgical corridor view through volume rendering of magnetic resonance imaging scan showing segmented tumor (green), blood vessels (red), and cranium (beige).*

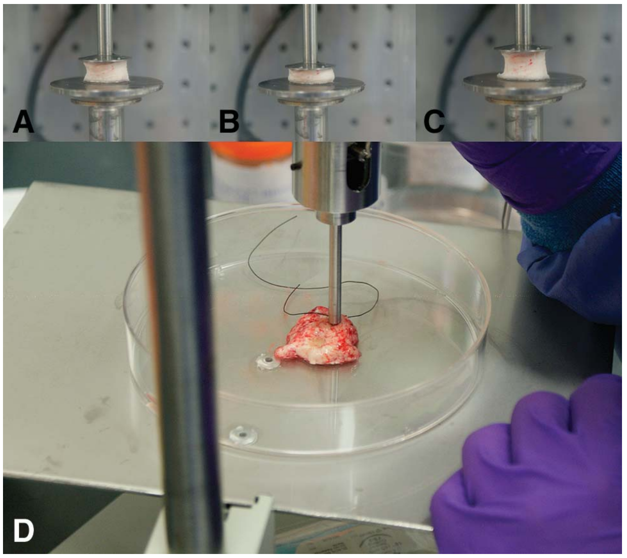

FIGURE 7. *In vitro mechanical testing on animal brain samples showing initial (**A**), compressed (**B**), and stretched states (**C**); in vitro indentation testing on human tumor samples (**D**).*

the deformable tissues, the surgical workspace includes rigid and fixed representations of drapes, skin, cranium, dura, and hooks. These are only displayed.

Realistic tissue textures are displayed on all visible surfaces, including new surfaces appearing after tissue removal. Blood vessels are represented as textures at the surface and throughout the volume of the tissues. The brain and tumor surface pulsates at 60 beats per minute. Blood oozes on new surfaces at a rate proportional to the size of the blood vessels feeding the tissue. It flows on the tissue surface following gravity and accumulates in tissue valleys.

Tumor-Debulking Task

A tumor-debulking task (Figure 8; see Video 1, Supplemental Digital Content 1, which demonstrates the tumor-debulking training task, http://links.lww.com/NEU/A467) introduces the trainee to the use of the aspirator and the ultrasonic aspirator and provides both training and feedback assessment of how to discriminate healthy brain from tumor using touch and visual cues. The aspirator allows removal of tissue and blood. The aspirator handle is made of a real neurosurgery aspirator equipped with a sensor located on the aspirator vent (Figure 9A). The sensor detects whether the vent is open or closed by the user's thumb. When the vent is open, blood in the vicinity of the virtual aspirator tip disappears, and tissues stick to the aspirator tip without being removed. When the vent is open, the aspirator tip can also be used to deform the tissues and feel their stiffness. When the vent is closed, the vacuum pressure increases by a factor, which can be adjusted with a knob, and tissues in the vicinity of the aspirator tip are attracted by the tip. Then, depending on resulting vacuum pressure and tissue stiffness, a piece of tissue might be removed, which would then cause the tissue surface to be released and would leave a pit on the tissue surface.

The ultrasonic aspirator behaves similarly to the aspirator. Its handle has the shape of an ultrasonic aspirator tool, without any sensor or movable part (Figure 9B). The ultrasonic aspirator amplitude can be adjusted with a dial knob and is displayed. A foot pedal allows activation of the ultrasound and results in increased aspiration power. The aspirator and ultrasonic aspirator behavior models are further detailed elsewhere.[40,46]

The task was built from images of a patient with a left frontal meningioma (Figure 10A). The goal of the simulation is to remove tumor completely by defining the tumor normal tissue

TABLE 3. Constitutive Model Parameter Values Used for Brain and Tumor

Solid Behavior	Parameter	Brain	Tumor
Elastic	C_{10}	0.0002 MPa	0.0001 MPa
Elastic	C_{20}	0.0002 MPa	0.0001 MPa
Compressible	υ	0.42	0.42
Viscous	g_1	0.12	0.05
Viscous	τ_1	330 s	330 s
Viscous	g_2	0.8	0.4
Viscous	τ_2	11 s	11 s

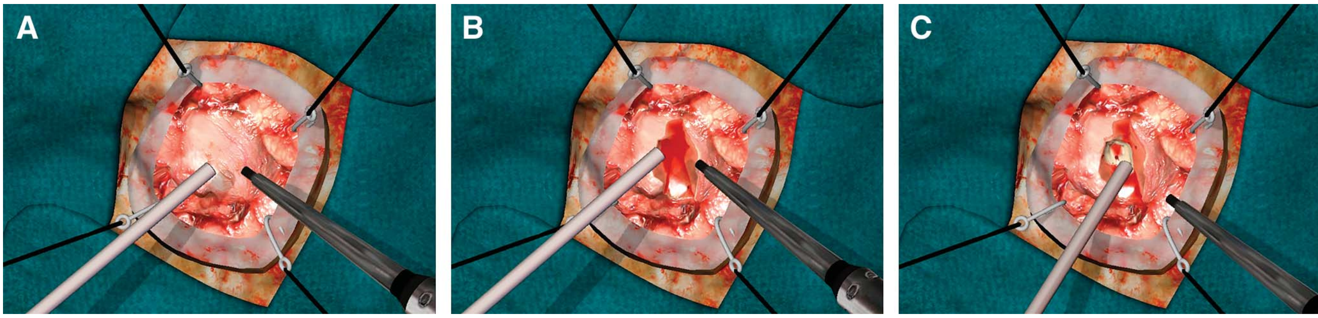

FIGURE 8. *Screenshots of tumor-debulking training task.* **A**, *start of simulation, with suction in left hand and the ultrasonic aspirator in the right hand.* **B**, *the ultrasonic aspirator is used to remove tissue, causing bleeding.* **C**, *suction is used to empty blood pool, showing bleeding arteries as red spots.*

plane, while removing as little healthy brain as possible. The simulator computes several metrics of the trainee performance: time to complete the task, percentage of the tumor volume removed, and percentage of total removed tissue volume that is healthy tissue. The simulation can be performed with only 1 hand, holding either the aspirator or the ultrasonic aspirator or with both hands each holding one tool. Display of the eloquent areas of the brain can be overlaid onto the surgical workspace.

Tumor Cauterization Task

A tumor cauterization task (Figure 11; see Video 2, Supplemental Digital Content 2, which demonstrates the tumor cauterization training task, http://links.lww.com/NEU/A468) introduces bipolar electrocautery to the trainee who has had

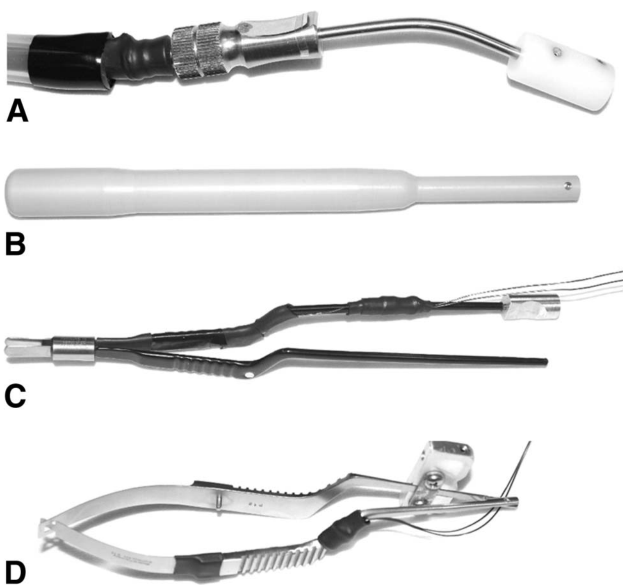

FIGURE 9. *Surgical tool handles for aspirator* (**A**), *ultrasonic aspirator* (**B**), *bipolar electrocautery* (**C**), *microscissors* (**D**).

experience with the aspirator. The bipolar electrocautery allows deformation, grasping, and cauterization of tissue. The bipolar electrocautery handle is made of a real neurosurgery bipolar electrocautery equipped with a sensor capable of measuring the distance between the bipolar electrocautery tips (Figure 9C). When the bipolar closes while its tips are in contact with tissue, the tissue in the vicinity of the tips gets grasped until the bipolar opens. If a foot pedal is pressed while the bipolar electrocautery is opened and the 2 virtual tips are in contact with tissue, the tissue will start to heat up and 2 round areas of whitish color will grow around each tip of the bipolar electrocautery. A buzzing sound will also be heard during bipolar electrocautery activation. A local model simulates tissue heating and color change as a function of time, distance between the bipolar electrocautery tips, and power settings.[47] Properly cauterized vessels will not bleed if removed along with tumor or normal tissue with the aspirator or ultrasonic aspirator.

The task was built from images of a patient with a left frontal oligoastrocytoma that was soft and vascular (Figure 10B). This operative simulation is meant to be performed with the bipolar

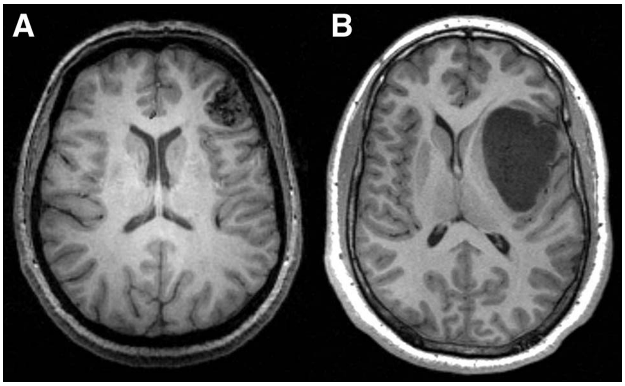

FIGURE 10. *T1-weighted magnetic resonance images of patients used for building training tasks.* **A**, *left frontal meningioma.* **B**, *left frontal oligoastrocytoma.*

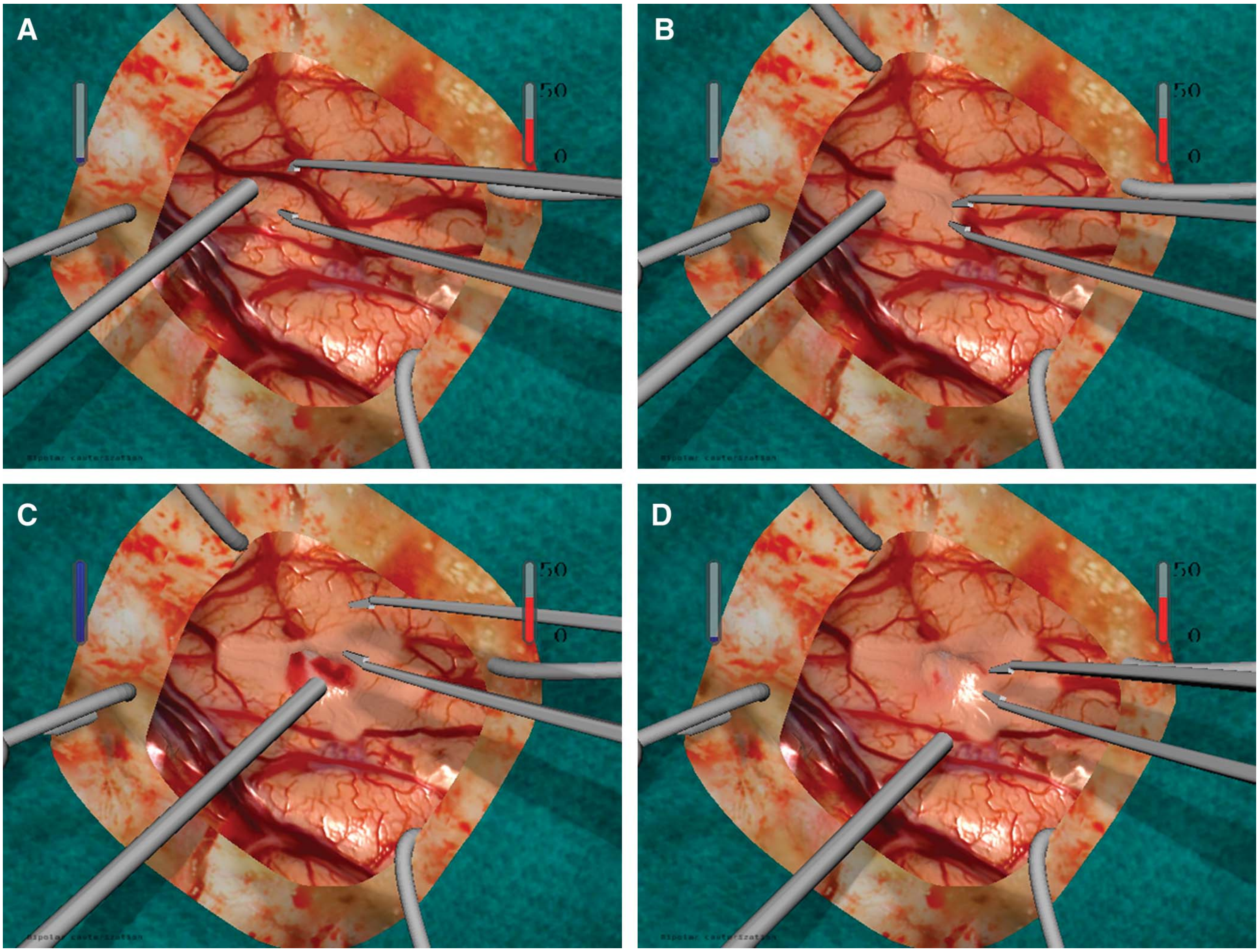

FIGURE 11. *Screenshots of tumor cauterization training task.* **A**, *start of simulation, with suction in the left hand and the bipolar electrocautery in the right hand.* **B**, *bipolar electrocautery is used to cauterize surface vessels, changing their color.* **C**, *suction is used to remove tumor, causing bleeding.* **D**, *deeper vessels are cauterized with the bipolar electrocautery, stopping bleeding.*

electrocautery in the dominant hand and the aspirator in the nondominant hand. The goal of the simulation is to remove as much tumor as possible while minimizing the amount of blood loss. The simulator computes the time to complete the task and the volume of blood loss.

DISCUSSION

Over the past 2 years, we accumulated 121 comments on NeuroTouch from 32 surgeons through our advisory network of teaching hospitals. The comments were classified according to whether they were praise, criticism, or suggestions for each of the following 4 categories: visual, touch, content, and ergonomics. The most praised category was visual, and the most criticized was touch. Most suggestions concerned ergonomics.

The construct of the haptic device mechanisms requires the handles to be slightly more distant from each other in the physical world than they would in the neurosurgery world and than they are in the virtual simulator world. However, this discrepancy was unnoticed by the surgeons who tried the simulator.

Future improvements of the 2 training tasks could focus on implementing finer grasping of tissues with the bipolar electrocautery and heat conduction behavior in the tissues. Also, blunt dissection along anatomic planes and sharp dissection across fibers and membranes could be implemented to allow cutting anywhere in the tissues, not only along a predefined anatomic plane, to increase the range of manipulation errors allowed.

Because the simulator is currently limited to 3 tools and 2 brain tumor tasks, future development work could focus on extending the set of tools to the Penfield dissector, microscissors, retractors, patties, clip appliers for vascular occlusion, endoscope, and endoscopic tools. This will require the modeling and implementing of blunt dissection along anatomic planes and sharp dissection across fibers and membranes. The ability to rapidly change tools during a training scenario could also be implemented. Initial observations of trainee performance in the operating room and using the simulator have suggested that the acquisition of bimanual skills takes significant time and practice. Based on future information from these studies, different levels of training simulation paradigms can be developed using the current tasks, such as turning bleeding on or off and enhancing the boundary between tumor and tissue. New craniotomy-based tasks could be added on resection of deep tumors and clipping of complex aneurysms. Tool trajectory analysis metrics could be used to compute metrics such as smoothness of movement, efficiency of movement, and tremor. Controls could be added to adjust microscope settings. The spatial resolution of the anatomic structures could be increased to represent finer anatomic details, such as layers of the meninges and nerves, through the use of faster algorithms and more powerful computing hardware.

The use of NeuroTouch could potentially be extended to patient-specific rehearsal through the development of an efficient data-processing pipeline to convert medical images of patients into simulation models.

CONCLUSION

NeuroTouch is a virtual simulator with haptic feedback designed for the acquisition and assessment of technical skills involved in craniotomy-based procedures. Prototypes have been set up in 7 teaching hospitals across Canada for beta testing and validation and to evaluate integration of NeuroTouch-simulated surgery into a neurosurgery training curriculum.

Disclosures

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COMMENTS

The authors of this article present an impressive body of work achieved collaboratively between multiple institutions in Canada and with support from the National Research Council of Canada to create a fully immersive neurosurgical simulator. This is a substantial effort that required multidisciplinary collaboration between engineering and neurosurgery and resulted in a real-time haptic-based training system for complex neurosurgical procedures. The result of this collaborative work is the NeuroTouch simulator prototype intended at this stage for training on resecting brain tumors. The objective is to remove a vascularized brain tumor, with the ability to coagulate tumor, cauterize bleeding blood vessels, and cut arachnoid membranes surrounding the tumor.

With such innovations in fully immersive virtual reality simulation programs for neurosurgeons, the introduction of surgical skills training can start outside the operating room, thus redefining the current curriculum-based training for neurosurgical residents.

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This paper presents NeuroTouch—a real-time Virtual Reality based simulator for neurosurgery with a haptic user interface focusing on the training of tumor debulking and tumor cauterization. NeuroTouch is the result of a remarkable multidisciplinary collaboration of experts from the National Research Council Canada and surgeons from Canadian teaching hospitals. An optimal training environment for neurosurgical tasks is guaranteed with the realistic 3d graphics combined with the haptic feedback and the stereo vision system. The surgical models are realistic enough, since their appearances are based on MR scanner data and the mechanical properties are derived from experimental in-vitro measurements.

VR-based surgery simulators in general are now matured enough to consider them for a worldwide regular surgery curriculum.

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