Fahad E. Alotaibi, MD, MSc*‡
Gmaan A. AlZhrani, MD*‡
Muhammad A.S. Mullah, MSc§
Abdulrahman J. Sabbagh, MD*‡¶
Hamed Azarnoush, PhD*||
Alexander Winkler-Schwartz, MD*
Rolando F. Del Maestro, MD, PhD*

*Neurosurgical Simulation Research Center, Department of Neurosurgery, Montreal Neurological Institute and Hospital, McGill University, Montreal, Quebec, Canada; ‡Department of Neurosurgery, National Neuroscience Institute, King Fahad Medical City, Riyadh, Saudi Arabia; §Department of Epidemiology, Biostatistics and Occupational Health, McGill University, Montreal, Quebec, Canada; ¶Faculty of Medicine, King Saud bin Abdulaziz University for Health Sciences, Riyadh Saudi Arabia; ||Department of Biomedical Engineering, Tehran Polytechnic, Tehran, Iran

Correspondence:
Fahad E. Alotaibi, MD,
Neurosurgical Simulation Research Centre,
Department of Neurosurgery, Montreal Neurological Institute and Hospital,
McGill University,
3801 University St, Room W201,
Montreal, QC,
Canada H3A 2B4.
E-mail: fahad.alotaibi2@mail.mcgill.ca

Received, June 30, 2014.
Accepted, November 7, 2014.
Published Online, January 16, 2015.

WHAT IS THIS BOX?
A QR Code is a matrix barcode readable by QR scanners, mobile phones with cameras, and smartphones. **The QR Code above links to Supplemental Digital Content from this article.**

Assessing Bimanual Performance in Brain Tumor Resection With NeuroTouch, a Virtual Reality Simulator

BACKGROUND: Validated procedures to objectively measure neurosurgical bimanual psychomotor skills are unavailable. The NeuroTouch simulator provides metrics to determine bimanual performance, but validation is essential before implementation of this platform into neurosurgical training, assessment, and curriculum development.

OBJECTIVE: To develop, evaluate, and validate neurosurgical bimanual performance metrics for resection of simulated brain tumors with NeuroTouch.

METHODS: Bimanual resection of 8 simulated brain tumors with differing color, stiffness, and border complexity was evaluated. Metrics assessed included blood loss, tumor percentage resected, total simulated normal brain volume removed, total tip path lengths, maximum and sum of forces used by instruments, efficiency index, ultrasonic aspirator path length index, coordination index, and ultrasonic aspirator bimanual forces ratio. Six neurosurgeons and 12 residents (6 senior and 6 junior) were evaluated.

RESULTS: Increasing tumor complexity impaired resident bimanual performance significantly more than neurosurgeons. Operating on black vs glioma-colored tumors resulted in significantly higher blood loss and lower tumor percentage, whereas altering tactile cues from hard to soft decreased resident tumor resection. Regardless of tumor complexity, significant differences were found between neurosurgeons, senior residents, and junior residents in efficiency index and ultrasonic aspirator path length index. Ultrasonic aspirator bimanual force ratio outlined significant differences between senior and junior residents, whereas coordination index demonstrated significant differences between junior residents and neurosurgeons.

CONCLUSION: The NeuroTouch platform incorporating the simulated scenarios and metrics used differentiates novice from expert neurosurgical performance, demonstrating NeuroTouch face, content, and construct validity and the possibility of developing brain tumor resection proficiency performance benchmarks.

KEY WORDS: Brain tumor, NeuroTouch, Performance metrics, Virtual reality simulator

Operative Neurosurgery 11:89–98, 2015 DOI: 10.1227/NEU.0000000000000631

The current system of neurosurgical training is based on an apprenticeship model. The assessment of resident psychomotor skills by a series of consultant surgeons is both subjective and incomplete.[1,2] Valid objective criteria for technical skills assessment are not included in neurosurgical curriculum because these criteria have not been developed.

Supplemental digital content is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.neurosurgery-online.com).

Virtual reality simulator technology provides opportunities for deliberate practice in which learners achieve the desired outcomes in safe learning environments. Studies have demonstrated that virtual reality simulation can play important roles in the acquisition of surgical skills.[2-5] The ImmersiveTouch system developed at the University of Illinois has been validated for ventriculostomy.[6-9] There is no validated assessment tool to measure bimanual technical skills performance for complex neurosurgical procedures such as cerebral tumor resection. The National Research Council (Canada), working with the Neurosurgical Simulation Research Centre at Montreal Neurological

Institute and Hospital and other research groups, has developed NeuroTouch, a virtual reality simulation platform with haptic feedback.[10-15] NeuroTouch is based on finite-element mechanics, can simulate brain deformations, and uses real-time computing to generate metrics to measure bleeding, to measure simulated brain tumor and normal tissue removal, and to perform other assessments of psychomotor performance.[12-15]

This study was designed to answer 2 questions: Does the complexity of the simulated operative task influence neurosurgical bimanual performance, and is the NeuroTouch platform a valid tool for assessment of bimanual neurosurgical skills? The hypotheses evaluated to assess these questions were that the complexity of simulated brain tumor characteristics would significantly influence neurosurgical bimanual performance, that neurosurgeon performance would be less influenced by this brain tumor complexity, and that novel performance metrics would differentiate neurosurgical bimanual performance among residents and neurosurgeons.

METHODS

All participants signed a consent approved by the McGill University Ethics Review Board before entering the trial. Six board-certified neurosurgeons and 12 neurosurgery residents from different postgraduate years in the McGill program were included in this study (6 junior residents, years 1-3; 6 senior residents, years 4-6). Demographic data collected included age, sex, handedness, resident training level, hours of video games and musical instruments played weekly, and meningioma experience. After task completion, each participant assessed the tasks and NeuroTouch using a 5-point Likert scale questionnaire.

Simulation Scenarios

To address the study questions, 4 simulated brain tumor scenarios involving 2 tumors each, 8 tumors in total, with differing visual and tactile cues resulting in color, stiffness, and tumor border complexity and continuous random bleeding points were developed.[14] The colors chosen for scenarios 1 and 2 were black (simulated malignant melanoma) to give maximal color difference between these tumors and the background normal tissue simulating white matter. In scenarios 3 and 4, simulated glioma-like brain tumor appearance derived from an actual patient's malignant glioma image was chosen against a white matter–like background to provide more realism (Figure 1). Because black tumors have a distinct interface and glioma-like tumors have a more difficult interface to visualize, it was initially considered that glioma-like tumors would be more complex to remove. To accurately represent the range of human brain tumor stiffness, a tactile cue in our scenarios, we assessed multiple samples from 11 different human glial tumors immediately after operative removal and measured their brain tumor stiffness (Young modulus).[10,14] The left tumors in all 4 scenarios were designed hard-stiffness tumors (Young modulus, 15 kPa); the right tumors in all scenarios were soft-stiffness tumors (Young modulus, 3 kPa). For many of the tier 1 and 2 metrics assessed in this study a previous pilot study had demonstrated that tumors of hard stiffness were more difficult to resect.[14] The stiffness of the background-simulated normal tissue was the same as that of the soft brain tumor, which resulted in our ability to design and modify an important visual and tactile cue: the distinctness of the simulated tumor–white matter interface. This interface was altered by creating an interdigitating indistinct border, making it more difficult to define with haptic and/or visual feedback and thus increasing the complexity of resection and possibility of removal of normal tissue surrounding the tumor. In scenario 1, both tumors had a distinct border interface between the tumor and the simulated white matter. The 2 tumors in scenario 2 had indistinct borders. Both tumors in scenario 3 had distinct borders, whereas the 2 tumors in scenario 4 had indistinct borders.

Simulated Operative Resection Procedures

This study was conducted using the previously described NeuroTouch platform.[10-15] All operators were acquainted with the system because they had enrolled in a previous trial involving resection of simulated tumors with NeuroTouch.[14] The goal was defined as resection of 8 simulated brain tumors with minimal removal of background tissue, representing simulated normal brain tissue. This was accomplished in a predefined sequence using a bimanual technique with a simulated ultrasonic aspirator used for tumor removal with the dominant hand and a simulated suction device (sucker) to control bleeding sites in the nondominant hand. Participants began by resecting the left tumor followed by the right tumor in scenario 1 and followed this sequence for scenarios 2 through 4. A period of 3 minutes was allowed to resect each tumor because in previous studies this time period allowed complete resection of a simulated tumor of this shape and size, and participants could not revisit the left tumor once beginning resection of the right.[14] A demonstration of the task is shown in the supplemental video (see **Video**, **Supplemental Digital Content 1**, http://links.lww.com/NEU/A708, which shows a video demonstration of resection of simulated black tumors).

NeuroTouch Metrics

Tier 1 and 2 metrics were designed to assess the safety, quality, and efficiency of simulated operative procedures and have previously been assessed in a pilot study.[14] Tier 2 metrics also evaluate independent hand motor skills, and advanced tier 2 metrics were specifically designed to assess motor and cognitive neurosurgical bimanual skills interaction while achieving the simulated tumor resection goal (Figure 2).

Tier 1 Metrics

The following are tier 1 metrics: amount of blood loss, the volume in cubic centimeters of blood loss during tumor resection, with the operator goal being maximal tumor resection with minimal blood loss; tumor percentage resected; percentage of the tumor resected, with the operator goal being to maximize tumor resection without removal of surrounding tissue[14]; and brain volume removed, volume in cubic centimeters of simulated normal brain tissue removed during tumor resection, with the operator goal being removal of no normal brain tissue during each tumor resection.[14]

Tier 2 Metrics

Tier 2 metrics included total tip (simulated ultrasonic aspirator and sucker instruments) path length, the path traversed by the tip of the tool measured in millimeters,[14] with the operator goal being the use of the most efficient and safe path trajectory of each instrument to resect each tumor; and maximum force applied and sum of forces used, measures of the maximum and sum of forces in Newtons applied to tumor and normal brain tissue by each simulated instrument,[14] with the operator goal being to use instrument force efficiently without causing tissue injury.

Advanced Tier 2 Metrics

There are 4 advanced tier 2 metrics. The first is the efficiency index, the percentage of time spent actively resecting each tumor divided by total

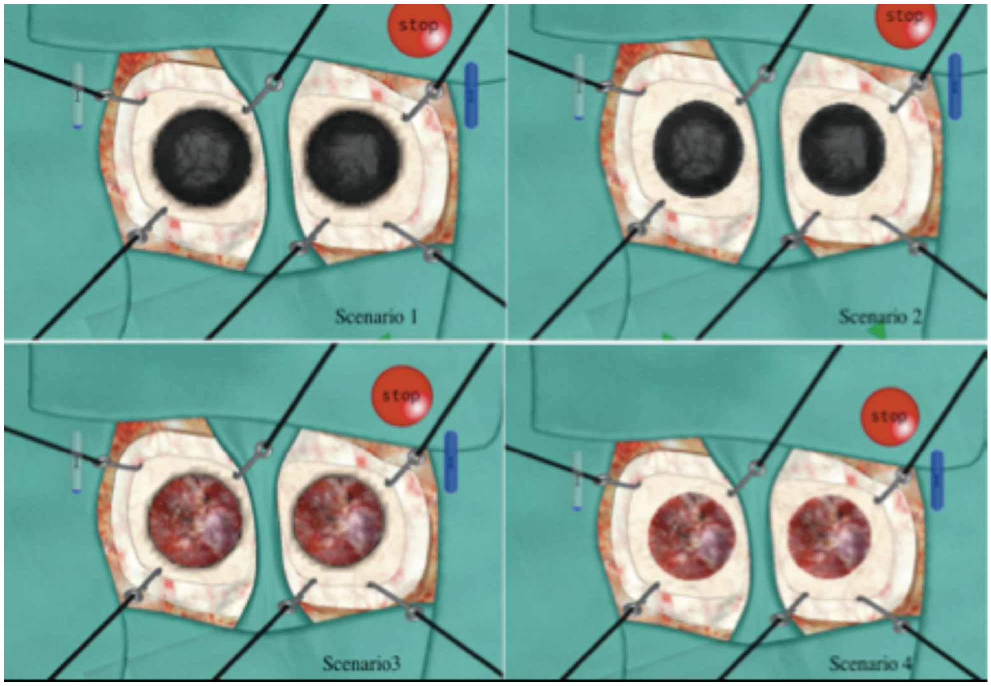

FIGURE 1. *The 4 scenarios and 8 tumors assessed. In each scenario, the left tumor is of hard stiffness (15 kPa), whereas the right tumor is of soft stiffness (3 kPa). Scenario 1, black tumors with distinct borders; scenario 2, black tumors with indistinct borders; scenario 3, glioma-colored tumors with distinct borders; and scenario 4, glioma-colored tumors with indistinct borders.*

time allowed for the task, with the operator goal being to use each tool efficiently, minimizing any unnecessary interruptions in surgical performance. This index measures a cognitive-motor skills interaction, ie, planning next steps simultaneously while engaged with the present one. The second is ultrasonic aspirator path–length index, ie, the percentage of ultrasonic aspirator total tip path length interacting directly with the tumor divided by the overall ultrasonic aspirator total tip path length, with the operating goal being to minimize unnecessary movement of the ultrasonic aspirator outside the intratumor operative field. The third is the coordination index, the percentage of time the simulated sucker is used simultaneously with the ultrasonic aspirator to control bleeding divided by overall sucker use time, with the operator goal being appropriate introduction of the sucker into the operative field to control bleeding without interrupting and/or compromising ultrasonic aspirator function. This index assesses 2-hand interaction ability. The last metric is the ultrasonic aspirator bimanual forces ratio, which is the ratio between average forces applied by the ultrasonic aspirator when used simultaneously with the sucker to average forces applied by the ultrasonic aspirator alone, with the operator goal being the application of identical and safe forces with ultrasonic aspirator regardless of sucker use. This index measures the quality of 2-hand interaction.

Statistical Analysis

Mean (SD) scores are used for demographics and Likert scale data. Because we assessed 18 participants and each participant performed 8 operations on 8 different tumor types, the correlated outcomes were assessed by use of linear mixed-effects models.[16,17] Outcome variables were transformed appropriately (eg, log) to satisfy the normality assumption of the residuals for fitted models. See the **Supplemental Digital Content 2** (http://links.lww.com/NEU/A709) for a detailed outline of the models used for statistical analysis. Results were considered statistically significant at values of $P < .05$.

RESULTS

Demographics and Likert

Mean age was 47.3 years (SD, 11.5 years) for neurosurgeons, 31 years (SD, 3.1 years) for senior residents, and 29 years (1.1 years) for junior residents. All neurosurgeons and 83.3% of residents were right handed, and 83.3% were male. Neurosurgeons had removed a mean of 193 (183.2) meningiomas; senior residents, 11.2 (10.8) meningiomas; and junior residents, 0.3 (0.8) meningioma. No participants played video games or musical instruments.

The Likert questionnaire measured NeuroTouch experience satisfaction, NeuroTouch as a training tool, and task visual and tactile realism (Table 1). Junior residents, senior residents, neurosurgeons, and the group containing all participants (All Groups) completed the postsimulation with above-average scores for each item. The strongest responses to the items in the Likert scale were that users felt overall satisfaction with their NeuroTouch experience and that the system would be useful for training neurosurgical skills. Interestingly, junior residents self-evaluated their performance (3.3) much higher than senior

Tier 1	Tier 2	Advanced Tier 2
Amount of Blood Loss	Ultrasonic Aspirator Total Tip Path Length	Efficiency Index
	Sucker Total Tip Path Length	Ultrasonic Aspirator Path-Length Index
Tumor Percentage Removed	Ultrasonic Aspirator Sum of Forces Utilized	Coordination Index
	Sucker Sum of Forces Utilized	
Brain Volume Removed	Ultrasonic Aspirator Maximum Force Applied	Ultrasonic Aspirator Bimanual Forces Ratio
	Sucker Maximum Force Applied	

Safety	Quality	Efficiency	Bimanual Motor and Cognitive Interactive Skills
Amount of Blood Loss	Tumor Percentage Removed	Ultrasonic Aspirator Total Tip Path Length	Ultrasonic Aspirator Path-Length Index
Brain Volume Removed			
Ultrasonic Aspirator Maximum Force Applied		Sucker Total Tip Path Length	Coordination Index
Sucker Sum of Forces Utilized			
Ultrasonic Aspirator Maximum Force Applied		Efficiency Index	Ultrasonic Aspirator Bimanual Forces Ratio
Sucker Maximum Force Applied			

FIGURE 2. *Organization of metrics used in this study based on safety, quality efficiency, and bimanual performance.*

residents (2.5) and neurosurgeons (2.8). Results outline that residents and neurosurgeons considered the system to have visual and sensory realism demonstrating face and content validity of the NeuroTouch platform. This is consistent with results seen when medical students and residents assessed NeuroTouch in a competitive environment.[13]

Influence of Tumor Complexity on Neurosurgical Performance

When we fitted 13 different models, 1 model for each metric, the mean values for tumor complexity and participant group varied for the majority of the assessed metrics (Tables 2 and 3). Metrics with statistically significant differences for residents,

TABLE 1. Evaluation of the NeuroTouch Simulator on a 5-Point Likert Scale[a]

	Junior Residents	Senior Residents	Neurosurgeons	All Groups
Difficulty of the challenge	3.3 (0.5)	3.3 (1.0)	3.5 (0.6)	3.4 (0.7)
Visual realism	3.3 (0.5)	2.8 (1.0)	3.2 (0.8)	3.4 (0.8)
Sensory realism	3.3 (1.2)	3 (0.6)	3.5 (0.6)	3.3 (0.8)
Overall satisfaction	3.3 (1.2)	3 (0.9)	3.7 (0.5)	3.8 (0.9)
Training neurosurgical skills	3.7 (1.0)	3.3 (0.8)	3.8 (0.8)	3.6 (0.8)
Performance self-assessment	3.3 (0.5)	2.5 (1.1)	2.8 (1.0)	2.9 (0.9)

[a]Higher numbers mean respondent is more satisfied/in agreement.

neurosurgeons, and all participants (all groups) are shown in Table 4.

Tumor complexity had a statistically significant impact on neurosurgical bimanual neurosurgeon and resident performance on multiple metrics, including blood loss, tumor percentage resected, brain volume removed, ultrasonic aspirator and sucker total tip path lengths, ultrasonic aspirator and sucker maximum force applied and sum of forces used, and efficiency index. The tactile cue of tumor stiffness markedly influenced performance because, regardless of the tumor color, border, or participant, except for brain volume removed, resecting hard vs soft tumors significantly decreased performance. Controlling for tumor color and border, a participant operating on a hard tumor removed 2.6% less tumor than when operating on a soft tumor. When log transformations were used for fitting linear mixed models, as in ultrasonic aspirator sum of forces used, transitioning from hard to soft stiffness tumors resulted in a 2-fold [exp (0.69) = 1.99] decrease in the geometric mean of ultrasonic aspirator sum of forces used, no matter who was performing the task or what color or tumor border was encountered. Tumor border distinctness, both a visual and tactile cue, influenced performance because operating on tumors with indistinct vs distinct borders significantly increased tumor percentage resected and brain volume removed for all groups.

Neurosurgeon bimanual psychomotor performance was significantly less influenced than resident by increasing simulated tumor complexity. The tumor visual cue color influenced only resident surgical performance while operating on black vs glioma-colored tumors, resulting in significantly higher blood loss and lower tumor percentage resected. For the tactile cue tumor stiffness, after

TABLE 2. Descriptive Statistics of Tier 1 and 2 Metrics[a]

Group	Tumor Type	Total Blood Loss, cm^3	Tumor Removed, %	Brain Volume Removed, cm^3	Ultrasonic Aspirator Total Tip Path Length, mm	Ultrasonic Aspirator Maximum Force Applied, N	Ultrasonic Aspirator Sum of Forces Used, N	Sucker Total Tip Path Length, mm	Sucker Maximum Force Applied, N	Sucker Sum of Forces Used, N
Junior residents	Soft	0.16	97.88	0.18	1407.8	0.10	86.6	707.0	0.10	109.0
	Hard	0.26	94.39	0.21	1916.5	0.14	166.0	1002.6	0.14	168.3
	Glioma	0.15	98.63	0.20	1640.3	0.12	127.6	865.5	0.11	127.1
	Black	0.27	93.64	0.19	1684.0	0.12	125.0	844.1	0.13	150.2
	Distinct	0.24	92.82	0.10	1591.4	0.12	125.7	800.2	0.12	146.4
	Indistinct	0.18	99.45	0.29	1733.0	0.12	126.9	909.4	0.12	130.9
Senior residents	Soft	0.12	99.56	0.20	1464.7	0.09	83.7	667.7	0.11	106.1
	Hard	0.41	96.45	0.21	1847.5	0.12	123.5	912.9	0.14	179.4
	Glioma	0.17	99.08	0.20	1581.9	0.11	107.3	761.8	0.11	124.4
	Black	0.36	96.94	0.21	1730.3	0.10	100.0	818.9	0.13	161.1
	Distinct	0.30	96.44	0.11	1601.8	0.12	116.8	783.0	0.13	137.7
	Indistinct	0.23	99.57	0.30	1710.4	0.10	90.4	797.6	0.11	147.8
Neurosurgeons	Soft	0.23	99.83	0.21	1194.9	0.11	75.7	529.3	0.10	82.9
	Hard	0.20	98.72	0.24	1520.3	0.17	162.9	674.9	0.14	136.6
	Glioma	0.11	99.43	0.21	1339.9	0.14	114.0	605.6	0.12	100.2
	Black	0.17	99.12	0.23	1375.4	0.13	124.6	598.7	0.12	119.3
	Distinct	0.15	98.57	0.12	1209.4	0.16	130.9	546.2	0.12	103.8
	Indistinct	0.13	99.98	0.32	1505.8	0.12	107.7	658.1	0.12	115.7

[a]Values are means of each tumor complexity assessed (n = 6) and participant group (n = 6).

TABLE 3. Descriptive Statistics of Advanced Tier 2 Metrics[a]

Group	Tumor Type	Efficiency Index	Coordination Index	Ultrasonic Aspirator Path Length Index	Ultrasonic Aspirator Bimanual Forces Ratio
Junior residents	Soft	60.9	60.2	45.0	130.6
	Hard	59.7	60.0	44.6	159.1
	Glioma	62.8	63.4	45.4	131.5
	Black	57.9	56.8	44.3	158.1
	Distinct	59.5	58.7	44.6	151.4
	Indistinct	61.2	61.5	45.0	138.2
Senior residents	Soft	66.2	67.2	41.0	105.8
	Hard	60.7	62.7	42.2	117.1
	Glioma	64.0	63.9	42.8	110.3
	Black	62.9	66.0	40.4	112.6
	Distinct	64.9	66.4	43.4	114.6
	Indistinct	61.9	63.5	39.8	108.2
Neurosurgeons	Soft	79.6	76.6	61.4	109.2
	Hard	71.7	70.9	55.9	118.6
	Glioma	76.4	72.8	61.6	120.8
	Black	74.9	74.7	55.7	106.9
	Distinct	75.4	74.2	60.8	117.1
	Indistinct	75.9	73.3	56.5	110.7

[a]Values are means of each tumor complexity assessed (n = 6) and participant group (n = 6).

adjustment for tumor color and border, residents operating on hard vs soft tumors removed a statistically significant 3.3% less tumor, whereas neurosurgeons removed a nonstatistically significant 1.1% less tumor.

Group Analysis

Regardless of tumor complexity, significant differences were found between neurosurgeons and junior residents and between neurosurgeons and senior residents on efficiency index and ultrasonic aspirator path length index (Table 5 and Figure 3). Coordination index demonstrated a significant difference between junior residents and neurosurgeons and a trend between neurosurgeons and senior residents. Ultrasonic aspirator bimanual brain forces ratio outlined significant difference between junior and senior residents (Figure 3). The average force applied by the ultrasonic aspirator when used simultaneously with the sucker was 33% higher by junior compared with senior residents. For the ultrasonic aspirator brain force ratio and sucker total tip path length, there was a trend approaching significance when neurosurgeons and junior residents were compared.

DISCUSSION

Does Tumor Complexity Influence Neurosurgical Bimanual Skills Performance?

To assess this question, simulated tumor scenarios were specifically designed with differing color (black and glioma-like), stiffness (hard and soft), and tumor borders (distinct and indistinct), challenging the participant with varying visual and tactile cues. To further model the realism of the operative environment, multiple bleeding points were incorporated. Our study is the first to demonstrate that tumor complexity using the metrics assessed in this study significantly influences neurosurgical bimanual skill performance during resection of simulated tumors using the NeuroTouch platform. Studies using the Immersive-Touch ventriculostomy simulator could not differentiate performance until task difficulty was increased, further outlining the importance of task complexity in simulation training scenarios.[8,9]

Tumor Color

Increasing tumor complexity impaired resident bimanual psychomotor performance significantly more than that of neurosurgeons. Removing black vs gliomas-like tumors resulted in significantly increased blood loss and decreased tumor percentage resected by novices (residents) but not experts (neurosurgeons). Residents had more difficulty controlling bleeding from black tumors, which may have contributed to the decreased tumor percentage resection seen by limiting the resident's operative visual field or focusing the resident attention on bleeding control rather than tumor removal. The reason that controlling bleeding from black tumors is more difficult for residents is unclear and needs further investigation because, in our initial conceptualization, black tumors were considered easier to remove than gliomas-like tumors. These results confirm that visual cues such as tumor color influence resident psychomotor skills using some of the scenarios assessed in this study. This would also be consistent with the concept that neurosurgeons have acquired skills that allow them to be less dependent on tumor color as an important cue during

TABLE 4. Simulated Tumor Color, Stiffness and Border Distinctness Significantly Influencing Neurosurgical Bimanual Performance[a]

Metrics	Residents (n = 12)	Neurosurgeon (n = 6)	All Groups (n = 18)
Amount of blood loss, cm^3[b]			
Hard vs soft	1.18	0.80	1.05
Black vs glioma	0.73	0.35[c]	0.61
Tumor percentage removed			
Indistinct vs distinct	−4.87	1.42	3.72
Hard vs soft	−3.30	−1.12[c]	−2.57
Black vs glioma	−3.56	−0.30[c]	−2.47
Brain volume removed, cm^3			
Indistinct vs distinct	0.20	0.20	0.20
Ultrasonic aspirator total tip path length, mm			
Hard vs soft	445.7	325.4	405.6
Sucker total tip path length, mm			
Hard vs soft	270.4	145.6	228.8
Ultrasonic aspirator sum of forces used, N[b]			
Hard vs soft	0.59	0.88	0.69
Ultrasonic aspirator maximum force applied, N			
Hard vs soft[b]	0.37	0.46	0.40
Sucker sum of forces used, N			
Hard vs soft	66.3	53.7	60.0
Sucker maximum force applied, N			
Hard vs soft	0.03	0.004	0.034
Efficiency index			
Hard vs soft	−3.35[c]	−7.84	−4.85

[a]Mean value comparisons of tumors with different complexity with $P < .05$.
[b]Results in log scale.
[c]Not statistically significant.

TABLE 5. Summary of Statistical Results From Linear Mixed-Effects Models[a]

Metrics	Junior Residents (n = 6)	Senior Residents (n = 6)
Efficiency index	−15.3 ($P < .001$)	−12.2 ($P = .003$)
Ultrasonic aspirator path length index	−13.8 ($P = .05$)	−17.1 ($P = .02$)
Coordination index	−13.7 ($P = .02$)	−8.8 ($P = .10$)
Ultrasonic aspirator bimanual forces ratio	30.9 ($P = .09$)	−2.5 ($P = .82$)
Suction total tip path length	295.6 ($P = .06$)	188.2 ($P = .19$)

[a]Effect of specific metrics on junior and senior residents with neurosurgeons (n = 6) serving as the reference category.

the bimanual resection of brain tumors. Our results suggest that tumor color has to be carefully incorporated into the design of complex virtual reality scenarios to properly assess resident bimanual performance and improvement in these skills.

Tumor Stiffness

To attempt to model the force feedback that a surgeon may experience while using instruments to remove a tumor, we measured the stiffness of multiple samples taken from resected gliomas and incorporated these values into our scenarios. A significant increase in blood loss for both the resident and neurosurgeon groups and a decrease in tumor percentage resected by residents but not neurosurgeons were seen when hard (Young modulus, 15 kPa) vs soft (Young modulus, 3 kPa) tumors were operated on. Residents lost more blood than neurosurgeons during these procedures, which may have contributed to the decreased tumor percentage removed by the resident group, consistent with the results seen for the black visual color cue. For residents and neurosurgeons, the tactile cue of tumor stiffness significantly influences many more bimanual performance metrics than color or tumor border distinctness. Forces used (sum of forces and maximum forces) with the ultrasonic aspirator were significantly higher during resection of hard vs soft tumors for both groups. Although the amount of forces applied on hard tumors was similar for both groups, residents removed significantly less tumor percentage when operating on hard and black tumors compared with soft and glioma-colored tumors. The difference in the force applied during tumor resection observed in the neurosurgeons group was related to less force applied to soft rather than increased force on hard tumors. A neurosurgeon operating on a patient or supervising a resident has no method to know the forces being applied by instruments to tumor or surrounding brain. A surrogate used to validate improper force application is brain injury resulting from the sudden use of excessive force or the use of too much force over time. This resultant brain injury may involve increased brain edema and brain or cranial nerve damage, resulting in increased patient morbidity. Learning how to prevent these types of force application surgical errors in simulated environments could significantly affect patient safety. Conceptually, operators could be continuously provided with a visual readout of his/her force application during simulated surgical procedures, which could be visually compared with expert proficiency performance benchmarks. Instrument force application could then be modified appropriately either during the procedure by the learner or later with the help of an instructor. It would appear reasonable that simulated virtual reality scenarios focused on improving this aspect of patient safety should be a high priority.

Ultrasonic aspirator and sucker total tip path lengths were longer and the amount of blood loss was higher when residents resected hard vs soft tumors. The mean differences in the total tool tip length and the amount of blood loss were higher for the residents compared with neurosurgeons. These higher mean

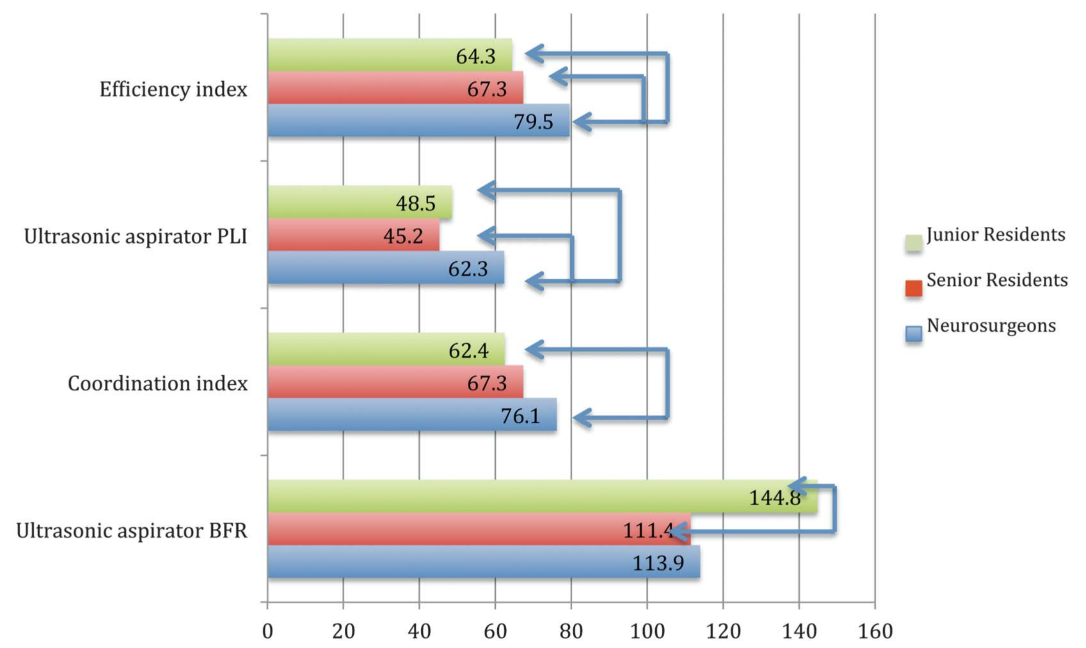

FIGURE 3. *Advanced Tier 2 metrics of resident and neurosurgeon groups. Arrows indicate which groups are statistically different from each other ($P < .05$). BFR, bimanual forces ratio; PLI, path length index.*

differences could be explained by coordination index results, which outline that residents have significantly lower coordination indexes than neurosurgeons. This finding suggests that residents have not yet obtained the ability to simultaneously use their bimanual psychomotor skills. When using the sucker to control different bleeding points, residents decrease the efficient use of the ultrasonic aspirator, and when focusing on tumor resection, they decrease efficient sucker use. As a result of these inefficient bimanual activities, residents lose more blood when operating on hard and black tumors despite using a longer sucker total tip path length. The efficiency index for neurosurgeons was 15.3% higher than for junior and 12.3% higher than for senior residents and was significantly higher during resection of hard vs soft tumors, consistent with the concept that neurosurgeons appear to focus the majority of allotted time to surgical task completion. Although resident bimanual performance is more influenced by the tactile cue stiffness than that of neurosurgeons, this tumor attribute deserves much more careful study in neurosurgical psychomotor skills assessment and training.

Distinctness of Tumor Border

The distinctness of tumor borders challenges the ability of both residents and neurosurgeons to carry out safe resection because both groups resected significantly less tumor percentage and removed significantly more simulated normal brain tissue when resecting tumors with indistinct borders. This finding suggests that, even for experienced operators, the extent of brain tumor resection remains a difficult decision based only on tumor visual or tactile cues when an indistinct tumor border is present. Our results are consistent with the conclusion that the identification and operator interaction with the distinctness of the tumor border interface is one of the most difficult aspects of brain tumor resection, and this interface should be a critical focus in further studies. This problem continues to center intraoperative technology innovation on improving neurosurgical performance on the tumor–normal tissue interface, hoping to help neurosurgeons achieve maximum safe tumor resection and improve neurosurgical patients' outcome.[18-21]

Do the Proposed Metrics Differentiate Resident and Neurosurgeon Performance?

For 3 of the 4 advanced tier 2 metrics using the scenarios assessed in our study, the efficiency index, ultrasonic aspirator path length index, and coordination index, the most significant leap in operative skill occurs during the transition from senior resident to attending neurosurgeon, suggesting that major improvements in the psychomotor skills involved in these metrics continue to occur after completion of residency training. The efficiency index and ultrasonic aspirator path length index for neurosurgeons are significantly higher than those for both senior and junior residents, consistent with this study hypothesis, demonstrating the construct validity of NeuroTouch. Despite the lower ultrasonic aspirator path length index for the senior compared with the junior resident, junior residents have a lower efficiency index (Figure 3). This decreased ultrasonic aspirator movement by junior residents suggests that, when they interrupt tumor resection during the operative procedure, junior residents decrease ultrasonic aspirator movement whereas senior residents tend to continually move the ultrasonic aspirator during this time, possibly to adjust their working angle. These differences in ultrasonic aspirator instrument handling translate into a higher path length index for junior residents. The positive correlation between efficiency index and ultrasonic aspirator path length index only for junior residents provides support for this explanation of these results. As would be expected, the coordination index data are consistent with neurosurgeons being statistically better in simultaneous bimanual performance than junior residents, and this approached significance for senior residents. These results and the results of ultrasonic aspirator bimanual forces ratio outline significant differences between junior and senior residents that are beginning to help us understand how operator experience plays an important role in bimanual skill acquisition during execution of the complex motor functions involved in brain tumor resection.

Strengths and Limitations

The 2 study questions that have been addressed using NeuroTouch technology provide some insight into how experts (neurosurgeons) and novices (residents) actually perform simulated brain tumor operations and what visual and tactile cues along with what instrument forces and bimanual psychomotor skills they use.[14,22] There are 15 members of the NeuroTouch Consortium on 3 continents, and a critical component of their collaborative studies is the standardization of validated performance metrics.[10-14,21] The development of validated metrics, like those developed in this study, allows the comparison of data obtained from all centers assessing the NeuroTouch platform. Guided by these validated metrics, thresholds can be determined for proficiency-based benchmarks, helping to develop training curriculum and self-assessment programs to maximizing resident performance.[14,22]

Our study results need to be interpreted with caution. First, the operators were allowed to use a simulated ultrasonic aspirator and sucker only for the tumor resection, not representative of the complex interactive skills necessary for patient tumor resections. Second, short task duration and level of color, stiffness, and tumor border distinctness may not discriminate quality of performance among our limited number of operators, resulting in our inability to find significant differences in some of the metrics used. Further studies are being performed to address these concerns. The usefulness of these metrics to other neurosurgical operations and operations carried out by other surgical specialties is currently being explored and will contribute to the understanding of the universality of their application.[15] Third, the use of neurosurgeons and residents from only 1 institution may have resulted in our inability to find more significant differences between the neurosurgeon and resident groups. The interesting finding that, for 3 of the 4 advanced tier 2 metrics studied, the major improvement in operative skills occurs after residency training may be related to the small sample size or may be an artifact of the neurosurgeons and resident involved. Serially tracking of residents during their training until and after graduation would be useful in understanding the sequence of psychomotor skill acquisition during residency and further modification of these skills after these residents become practicing neurosurgeons. The NeuroTouch Consortium provides an avenue to investigate all these important issues. Fourth, although this study was focused on an assessment of the influence of tumor complexity on the bimanual psychomotor performance of expert and novice groups, it is clear that, without the demonstration that virtual reality simulators like NeuroTouch enhance resident operative room performance, their use will be limited.[22,23]

CONCLUSION

The NeuroTouch platform using the scenarios and metrics incorporated into this study is able to differentiate between expert and novice groups on the basis of their level of training. Our study is the first to demonstrate significant differences in neurosurgical bimanual psychomotor performance of neurosurgical groups based on simulated tumors complexity demonstrating face, content, and construct validity of the NeuroTouch system and the possibility of developing brain tumor resection proficiency performance benchmarks.

Disclosures

This work was supported by the Di Giovanni Foundation, the Montreal English School Board, the B-Strong Foundation, the Colannini Foundation, and the Montreal Neurological Institute and Hospital. Dr Del Maestro is the William Feindel Emeritus Professor in Neuro-Oncology at McGill University. Dr Azarnoush held the Postdoctoral Neuro-Oncology Fellowship from the Montreal Neurological Institute and Hospital. The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES

1. Gray JD. Global rating scales in residency education. *Acad Med.* 1996;71(suppl 1):S55-S63.
2. Gurusamy K, Aggarwal R, Palanivelu L, Davidson BR. Systematic review of randomized controlled trials on the effectiveness of virtual reality training for laparoscopic surgery. *Br J Surg.* 2008;95(9):1088-1097.
3. Park J, MacRae H, Musselman LJ, et al. Randomized controlled trial of virtual reality simulator training: transfer to live patients. *Am J Surg.* 2007;194(2):205-211.
4. Korndorffer JR Jr, Dunne JB, Sierra R, Stefanidis D, Touchard CL, Scott DJ. Simulator training for laparoscopic suturing using performance goals translates to the operating room. *J Am Coll Surg.* 2005;201(1):23-29.
5. Grantcharov TP, Kristiansen VB, Bendix J, Bardram L, Rosenberg J, Funch-Jensen P. Randomized clinical trial of virtual reality simulation for laparoscopic skills training. *Br J Surg.* 2004;91(2):146-150.
6. Chan S, Conti F, Salisbury K, Blevins NH. Virtual reality simulation in neurosurgery: technologies and evolution. *Neurosurgery.* 2013;72(suppl 1):154-164.
7. Luciano C, Banerjee P, Lemole GM Jr, Charbel F. Second generation haptic ventriculostomy simulator using the ImmersiveTouch system. *Stud Health Technol Inform.* 2005;119:343-348.
8. Banerjee PP, Luciano CJ, Lemole GM Jr, Charbel FT, Oh MY. Accuracy of ventriculostomy catheter placement using a head-and hand-tracked high-resolution virtual reality simulator with haptic feedback. *J Neurosurg.* 2007;107(3):515-521.

9. Lemole M, Banerjee PP, Luciano C, Charbel F, Oh M. Virtual ventriculostomy with "shifted ventricle": neurosurgery resident surgical skill assessment using a high-fidelity haptic/graphic virtual reality simulator. *Neurol Res.* 2009;31(4):430-431.
10. Delorme S, Laroche D, DiRaddo R, Del Maestro RF. NeuroTouch: a physics-based virtual simulator for cranial microneurosurgery training. *Neurosurgery*. 2012; 71(1 suppl operative):32-42.
11. Choudhury N, Gélinas-Phaneuf N, Delorme S, Del Maestro R. Fundamentals of neurosurgery: virtual reality tasks for training and evaluation of technical skills. *World Neurosurg.* 2013;80(5):e9-e19.
12. Rosseau G, Bailes J, del Maestro R, et al. The development of a virtual simulator for training neurosurgeons to perform and perfect endoscopic endonasal transsphenoidal surgery. *Neurosurgery*. 2013;73(suppl 1):85-93.
13. Gélinas-Phaneuf N, Choudhury N, Al-Habib AR, et al. Assessing performance in brain tumor resection using a novel virtual reality simulator. *Int J Comput Assist Radiol Surg.* 2014;9(1):1-9.
14. Azarnoush H, Alzhrani G, Winkler-Schwartz A, et al. Neurosurgical virtual reality simulation metrics to assess psychomotor skills during brain tumor resection. *Int J of comput Assist Radiol Surg.* 2014:1-16.
15. Varshney R, Frenkiel S, Nguyen LH, et al. Development of the McGill simulator for endoscopic sinus surgery (MSESS): a new high fidelity virtual reality simulator for endoscopic sinus surgery. *Am J Rhinol Allergy.* 2014;28(4):330-334.
16. Diggle P, Heagerty P, Liang KY, Zeger S. *Analysis of Longitudinal Data*. Oxford, United Kingdom: Oxford University Press; 2002.
17. Laird NM, Ware JH. Random-effects models for longitudinal data. *Biometrics*. 1982;38(4):963-974.
18. Barone DG, Lawrie TA, Hart MG. Image guided surgery for the resection of brain tumours. *Cochrane Database Syst Rev.* 2014;1:CD009685.
19. Kurimoto M, Hayashi N, Kamiyama H, et al. Impact of neuronavigation and image-guided extensive resection for adult patients with supratentorial malignant astrocytomas: a single-institution retrospective study. *Minim Invasive Neurosurg.* 2004;47(5):278-283.
20. Wirtz CR, Albert FK, Schwaderer M, et al. The benefit of neuronavigation for neurosurgery analyzed by its impact on glioblastoma surgery. *Neurol Res.* 2000;22 (4):354-360.
21. Pogue BW, Gibbs-Strauss S, Valdés PA, Samkoe K, Roberts DW, Paulsen KD. Review of neurosurgical fluorescence imaging methodologies. *IEEE J Sel Top Quantum Electron.* 2010;16(3):493-505.
22. Gélinas-Phaneuf N, Del Maestro RF. Surgical expertise in neurosurgery: integrating theory into practice. *Neurosurgery*. 2013;73(suppl 1):30-38.
23. Kirkman MA, Ahmed M, Albert AF, et al. The use of simulation in neurosurgical education and training. *J Neurosurg.* 2014;121(2):228-246.

***Supplemental digital content** is available for this article. Direct URL citations appear in the printed text and are provided in the HTML and PDF versions of this article on the journal's Web site (www.neurosurgery-online.com).*

Acknowledgments

We would like to thank Robert DiRaddo, PhD, group leader, Simulation, Life Sciences Division, National Research Council of Canada at Boucherville, and all his team, including Denis Laroche, MSc, Valérie Pazos, PhD, Nushi Choudhury, M.Eng., and Linda Pecora, for their support in the development of the scenarios used in these studies. We would also like to acknowledge the support of Mahmoud Al-Yamany, MD, and Dr Lahbib Soualmi, National Neuroscience Institute, Department of Neurosurgery, King Fahad Medical City, Riyadh, Saudi Arabia.

COMMENTS

This is an interesting study of the NeuroTouch stimulator used with junior residents, senior residents, and attending neurosurgeons. Interestingly, the majority of the metrics seem to make a far greater leap from senior residents to attending neurosurgeons than from junior resident to senior resident. The findings would be improved significantly by being able to serially track metrics in individual trainees all the way until they become attending neurosurgeons. Regardless, the authors are to be commended for their findings in the increasingly important area of discovering ways to train residents outside of the operating room in an environment of work hour restrictions and lower volume of complex cases in some training centers.

Manish K. Aghi
San Francisco, California

This communication addresses a relevant and actual topic in neurosurgery, ie, the use of virtual reality simulators to maximize learning of surgical skills in an environment that is more and more regulated and hungry for measurements. A general caveat is that virtual reality is only as good as its predictive value of the competency of the trainee to perform a specific neurosurgical procedure better than his/her counterpart not exposed to virtual reality training.

If we lose sight of this paramount link, then virtual reality becomes an end in itself and not a tool to accomplish better resident training/better patient outcome. We encourage the authors to provide a validation study and look forward to it.

Mario Ammirati
Columbus, Ohio