Proficiency Performance Benchmarks for Removal of Simulated Brain Tumors Using a Virtual Reality Simulator NeuroTouch

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OBJECTIVE: Assessment of neurosurgical technical skills involved in the resection of cerebral tumors in operative environments is complex. Educators emphasize the need to develop and use objective and meaningful assessment tools that are reliable and valid for assessing trainees' progress in acquiring surgical skills. The purpose of this study was to develop proficiency performance benchmarks for a newly proposed set of objective measures (metrics) of neurosurgical technical skills performance during simulated brain tumor resection using a new virtual reality simulator (NeuroTouch).

DESIGN: Each participant performed the resection of 18 simulated brain tumors of different complexity using the NeuroTouch platform. Surgical performance was computed using Tier 1 and Tier 2 metrics derived from NeuroTouch simulator data consisting of (1) safety metrics, including (a) volume of surrounding simulated normal brain tissue removed, (b) sum of forces utilized, and (c) maximum force applied during tumor resection; (2) quality of operation metric, which involved the percentage of tumor removed; and (3) efficiency metrics, including (a) instrument total tip path lengths and (b) frequency of pedal activation.

SETTING: All studies were conducted in the Neurosurgical Simulation Research Centre, Montreal Neurological Institute and Hospital, McGill University, Montreal, Canada.

PARTICIPANTS: A total of 33 participants were recruited, including 17 experts (board-certified neurosurgeons) and 16 novices (7 senior and 9 junior neurosurgery residents).

RESULTS: The results demonstrated that "expert" neurosurgeons resected less surrounding simulated normal brain tissue and less tumor tissue than residents. These data are consistent with the concept that "experts" focused more on safety of the surgical procedure compared with novices. By analyzing experts' neurosurgical technical skills performance on these different metrics, we were able to establish benchmarks for goal proficiency performance training of neurosurgery residents.

CONCLUSION: This study furthers our understanding of expert neurosurgical performance during the resection of simulated virtual reality tumors and provides neurosurgical trainees with predefined proficiency performance benchmarks designed to maximize the learning of specific surgical technical skills. (J Surg 72:685-696. © 2015 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: proficiency performance benchmarks, performance metrics, virtual reality neurosurgical simulation, brain tumor resection, neurosurgical oncology, Neuro Touch

COMPETENCIES: Patient Care, Medical Knowledge, Practice-Based Learning and Improvement

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INTRODUCTION

Competency-based education and training has been defined as "an outcomes-based approach to the design, implementation, assessment, and evaluation of medical education programs, using an organizing framework of competencies."[1,2] This approach focuses on having the trainee achieve a set of predefined criteria during his/her training to move to the next level of instruction. This education system emphasizes the acquisition of the minimal competency standard of a profession rather than achieving an "expert" level of skills performance.[3,4] Differences commonly exist between competence and performance, and the unavailability of validated tools to evaluate competency acquisition has made it difficult to apply this educational concept to neurosurgical psychomotor performance.[5-8] To address these issues, clear proficiency performance benchmarks need to be developed and made available for neurosurgical operations to improve resident training and surgical psychomotor performance.[9-11] Assessment of surgical skills in the operating room is difficult given variation in operative procedures, diverse standards, differences in the degree residents operate independently, and the occurrence of unpredictable operative events.[11] Given these variables, it is difficult to accurately measure the range of psychomotor skills employed by competent/expert surgeons during brain tumor resections in the operating room, and therefore assessing and imparting these skills to the resident can result in errors that can affect patient safety.[12] Advancement in computer-based technology has created opportunities for implementing new training paradigms such as competency-based education using proficiency performance benchmarks in neurosurgery.[4,12] Virtual reality (VR) simulators are becoming an important means of training and objectively assessing psychomotor performance.[13-15] These systems allow repeated practice of standardized tasks and provide unbiased and objective measurements of performance in safe learning environments with appropriate demonstrator or metrics feedback or both. VR simulation can play a role in the acquisition and improvement of specific neurosurgical skills, and the ImmersiveTouch system has been validated for ventriculostomy.[8,16-18] The Neurosurgical Simulation Research Centre at the Montreal Neurological Institute and Hospital working with the National Research Council (Canada) and other centers has developed and evaluated a computer-based simulator with haptic feedback (NeuroTouch), which provides surgeons and surgical residents the opportunity for deliberate practice and assessment of their level of psychomotor skills competencies.[12,19-23] NeuroTouch is based on finite element mechanics, which can simulate real-time brain deformations, and it uses real-time computing to generate metrics involving multiple assessments of psychomotor performance.[12] This system can simulate brain tumor and normal tissue removal, can generate and measure bleeding, and can provide continuous haptic feedback allowing the operator to have the tactile sensation of the interaction of his/her hand(s) with the simulated instruments and simulated tissues.[19] Surgical performance using the NeuroTouch platform can be assessed using Tier 1 and Tier 2 metrics derived from the NeuroTouch simulator data consisting of (1) safety metrics including (a) volume of surrounding simulated normal brain tissue removed, (b) sum of forces utilized (SFU), and (c) maximum force applied (MFA) during tumor resection; (2) quality of operation metric, which measures the percentage of tumor removed; and (3) efficiency metrics, including (a) instrument total tip path lengths (TTPL) and (b) frequency of pedal activation (FPA).[12] NeuroTouch provides a system that can begin to address the question of proficiency performance benchmark generation using a simulated VR tumor resection for assessment and training of neurosurgical residents.

The 2 purposes of this study were (1) to provide a descriptive analysis of neurosurgical skills performance obtained for neurosurgeons and neurosurgery residents while resecting a series of simulated brain tumors using the NeuroTouch platform and (2) to develop criterion measures for proficiency performance benchmarks on the NeuroTouch simulator for the resection of simulated tumors of various complexities.

METHOD

Before entering the study, each participant was asked to sign a consent form approved by the McGill University Ethics Review Board. A total of 17 neurosurgeons (board certified) from 3 institutions on 2 continents and 16 neurosurgery residents from different postgraduate years (PGY) in the McGill program (9 junior residents, years 1-3, and 7 senior residents, years 4-6) were included in the study. Demographic data collected before participation in the study included age, sex, handedness, level of training, number of meningioma cases operated on, and number of hours of video games or musical instruments played per week.

SIMULATION SCENARIOS

To address the study purposes, a series of 6 simulated brain tumor scenarios developed by our group in a previous pilot study, which involved 18 tumors of the identical shape with different color and stiffness cues, were employed.[12] In scenarios 1 through 3, the 3 tumors within each individual scenario had the same visual color appearance, namely, black tumors (maximum difference between tumor and background, simulated malignant melanoma metastasis) in scenario 1, gliomalike brain tumor appearance derived from an actual patient's malignant glioma image in scenario 2, and similar-to-background tumors (simulated infiltrated white matter) in scenario 3. To outline 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's modulus).[12,19] In each of these first 3 scenarios, the stiffness of the tumors was "soft" (Young's modulus: 3 kPa) in the upper tumor, "medium" (Young's modulus: 9 kPa) in the lower left tumor, and "hard" (Young's modulus: 15 kPa) in the lower right tumor. The stiffness of the background tissue in all tumor scenarios (simulated white matter) was similar to that of a soft tumor (Young's modulus: 3 kPa). Scenarios 4 through 6 each contained 3 tumors with the same stiffness, namely, soft tumors in scenario 4, tumors with medium stiffness in scenario 5, and hard tumors in scenario 6. Each of these 3 scenarios contained a black tumor, a gliomalike appearance tumor, and a white tumor as can be seen in Figure 1C.

SIMULATED OPERATIVE RESECTION PROCEDURE

Figure 1A outlines the main hardware components of the previously described NeuroTouch VR simulator used in this study.[12,20-24] A number of physical tools can be used to perform different simulated operations and can be held simultaneously, one in each hand.[19] The simulated ultrasonic aspirator and bipolar coagulator are activated by a foot pedal. The physical size, shape, behavior, and tactile feel of these tools are similar to real surgical instruments. Connected to each tool is a haptic micromanipulator device that provides force feedback corresponding to the force interaction between virtual tools and virtual tissues to the hand(s) of the operator.[19] This haptic device provides data from which one can obtain the force that the operator applies with the tool at any given time on the virtual tissue and also provides the real-time tool-tip position in 3-dimensional (3D) space. A display depicts the virtual operating scene together with the virtual tools, which correspond to the physical tools in the hand(s) of the operator. This depiction is in the form of 2 images that are used by a stereoscope to generate the 3D visualization used in the simulations. The fused images can be continuously viewed on an auxiliary display. This stereoscope simulates the neurosurgical microscope used in the operating room to provide a 3D magnification of the field. The simulator software running on a computer continually updates multiple data sets including graphics, haptics, and tissue mechanics information.

Each participant was specifically instructed verbally and in written instructions that the goal of the simulation was to remove each tumor using the simulated ultrasonic aspirator with minimal removal of the background tissue, which represented "normal" brain tissue. In each scenario, the operator used the simulated ultrasonic aspirator in the dominant hand to remove the 3 tumors, in a predefined

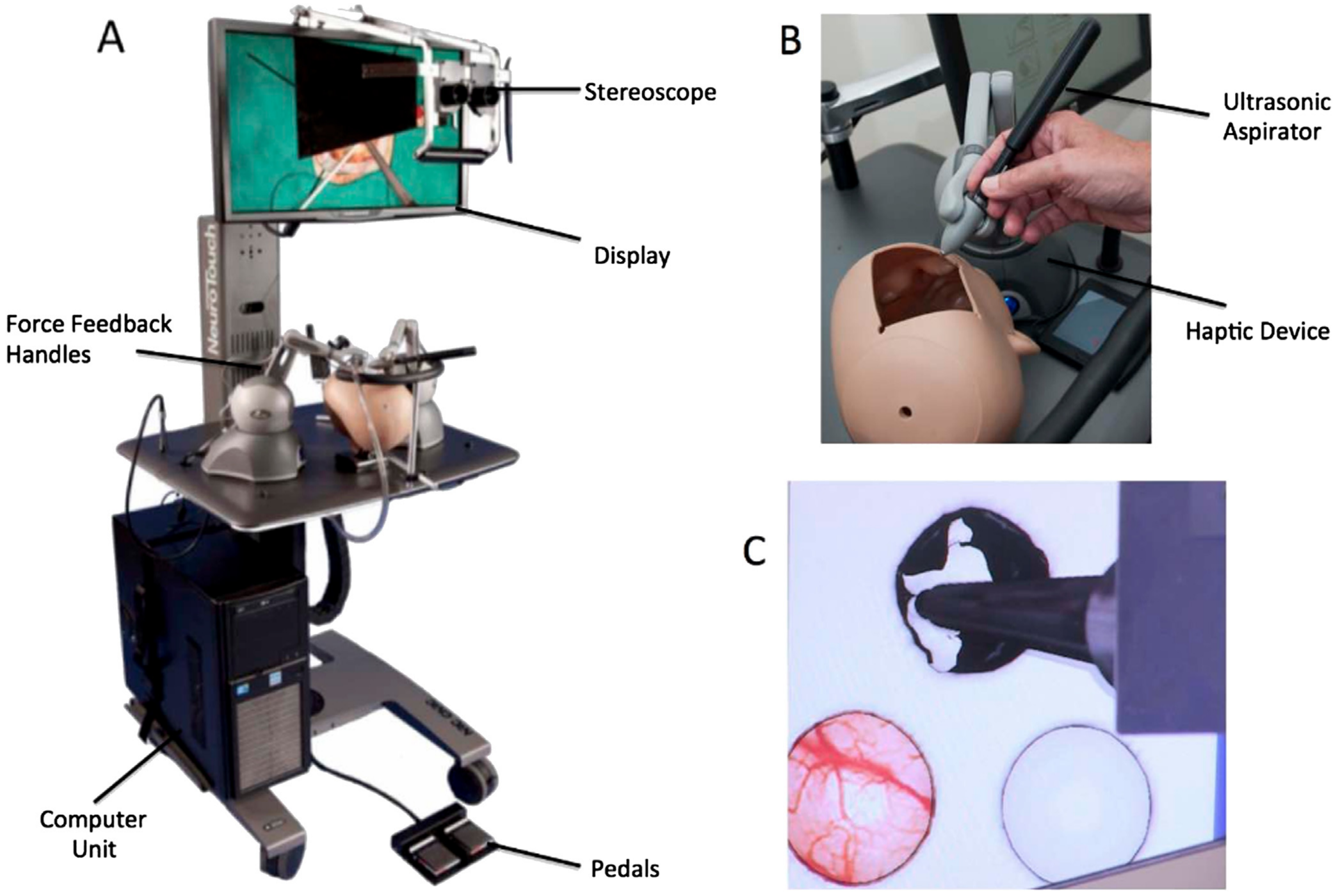

FIGURE 1. (A) The NeuroTouch simulator platform equipped with stereoscopic viewer, display screen, bimanual force feedback handles, and activator pedals. (B) Mannequin head with haptic device, which provides force feedback of the simulated ultrasonic aspirator. (C) View of operating scene with participant using simulated ultrasonic aspirator to resect 1 of 3 simulated tumors in scenario 4.

sequence, one at a time (Fig. 1B and C). A practice scenario was used to familiarize the participant with the task, and data from this scenario were excluded from the analysis. Each participant was given 3 minutes to remove each tumor, with a 1-minute mandatory rest period between tumors. The participants were unaware of the metrics used to assess their performance. A number of metrics have been developed by our group and were used in this study to objectively measure neurosurgical skills performance.[12] Data output from the NeuroTouch system for any task is recorded in a comma-separated values file. The output data are exported to this file at rate of 50 Hz (50 points of data recorded per second or every 20 ms). The Tier 1 metrics provided directly by the NeuroTouch platform comma-separated values file include the following: percentage of tumor removed (tumor percentage resected [TPR]) and volume of simulated "normal" brain tissue in cubic centimeters (cc) surrounding the tumor removed (simulated brain volume removed [BVR]). Tier 2 metrics have to be derived from the NeuroTouch data set output. Force feedback in the comma-separated values file records the amount of force measured (in Newtons) applied by each instrument. SFU samples in Newtons (N) during the simulated operation is measured as the overall applied force employed to resect the tumor by each instrument, whereas MFA measures the maximum force in N that the operator applies on the tumor or the "normal" simulated brain tissue or both by the ultrasonic aspirator during the procedure and is a measure of safe force application. Instrument TTPL in millimeters (mm) and FPA during simulated brain tumor resections are also derived from the data on the comma-separated values file.[12]

STATISTICS

Data were processed using SPSS 20.0 (IBM Corp., NY) and Microsoft Excel (Microsoft, Inc). Mean scores ± standard deviation (SD) for the neurosurgeon and resident groups are presented in a graphical figure for visual comparison. Data were analyzed for all 18 tumors and for each of the 6 tumor subgroups, black, gliomalike, and white colors and soft, medium, and hard stiffness with $n = 6$ in each group.

RESULTS

The demographic data of the 33 participants, 17 neurosurgeons, 7 senior (PGY 4-6) and 9 junior neurosurgery residents (PGY 1-3), involved in this study can be seen in Table 1. A total of 29 participants (87.9%) were males. Mean age for all participants was 35.4 ± 9.3. The mean years of practice for the neurosurgeons was 8 ± 7.2, and the mean number of meningioma resected during their practice was 74.6 ± 34.6. All but 3 participants, 1 neurosurgeon, 1 senior, and 1 junior resident, were right handed. A junior resident played video games for 2 hours a week, and 1 neurosurgical consultant played a musical instrument 1 hour a week. The data on all the metrics used and the 6 tumors subgroups analyzed for the neurosurgeons can be seen in Table 2, and results for the senior and junior resident groups can be seen in Supplementary Tables 1 and 2, respectively. There were differences in the mean values, but owing to the large variability within each group, multivariate and univariate analyses did not demonstrate statistically significant differences between groups on all the dependent variables assessed.

TABLE 1. Demographic Data

Groups	*n* (%)
Neurosurgeons	17
Age (mean ± SD)	41 ± 9.4
Sex	
Male	15(88.2)
Female	2(11.8)
Handedness	
Right	16(94.1)
Left	0
Ambidextrous	1(5.9)
Meningioma case (mean ± SD)	74.6 ± 34.6
Neurosurgery residents	16
Age (mean ± SD)	29.5 ± 3.8
Sex	
Male	14(87.5)
Female	2(12.5)
Handedness	
Right	13(81.25)
Left	2(12.5)
Ambidextrous	1(6.25)
Level of training	
PGY-1	4(25)
PGY-2	3(19)
PGY-3	2(13)
PGY-4	3(19)
PGY-5	3(19)
PGY-6	1(6)

Tumor Percentage Resected

The mean TPR by neurosurgeons (99.65 ± 0.58%) was less than that by senior residents (99.84 ± 0.21%), which was more than that by junior residents (99.76 ± 0.18%; Fig. 2A). As seen in Figure 3A, the lowest mean TPR was seen during the resection of white tumors by neurosurgeons (99.51 ± 0.99%), whereas it was during the resection of hard-stiffness tumors by senior residents (99.75 ± 0.31%) and medium-stiffness tumors by junior residents (99.63 ± 0.29%). The highest mean TPR was seen in tumors with gliomalike appearance for neurosurgeons (99.80 ± 0.59%) and junior (99.63 ± 0.29%) and for black tumors for senior residents (99.94 ± 0.07%).

Simulated "Normal" BVR

The mean BVR was less in neurosurgeons (0.08 ± 0.02 cc) as compared with both resident groups; both senior and

TABLE 2. Means ± SD for the Performance of 17 Neurosurgeons (Experts) Measured for Each Individual Tumor Group ($n = 6$) and for all Tumors ($n = 18$)

Variable	Black Tumors	Glioma Color Tumors	White Tumors	Hard-Stiffness Tumors	Medium-Stiffness Tumors	Soft-Stiffness Tumors	All Tumors
TPR	99.65 ± 0.74	99.80 ± 0.59	99.51 ± 0.99	99.64 ± 0.71	99.75 ± 0.49	99.57 ± 0.77	99.65 ± 0.58
BVR	0.09 ± 0.02	0.08 ± 0.02	0.07 ± 0.02	0.08 ± 0.02	0.09 ± 0.02	0.08 ± 0.02	0.08 ± 0.02
SFU	92.49 ± 45.31	76.71 ± 29.03	78.77 ± 37.83	82.09 ± 35.89	85.79 ± 40.56	80.09 ± 36.22	82.66 ± 36.78
MFA	0.15 ± 0.06	0.16 ± 0.049	0.14 ± 0.05	0.15 ± 0.05	0.14 ± 0.06	0.16 ± 0.05	0.15 ± 0.05
TTPL	1421.6 ± 522.1	1357.8 ± 460.1	1295.8 ± 468.1	1430.8 ± 485.6	1394.7 ± 459.0	1249.6 ± 477.2	1358.4 ± 469.5
FPA	5.3 ± 6.4	5.0 ± 6.4	4.2 ± 3.95	4.8 ± 4.9	4.6 ± 4.6	4.2 ± 4.6	4.5 ± 4.7

junior residents had mean BVR values of 0.09 ± 0.03 cc (Fig. 2B). As seen in Figure 3B, neurosurgeons and senior residents each had the least mean BVR while resecting white tumors (0.07 ± 0.01 cc and 0.08 ± 0.03 cc, respectively), whereas junior residents had less mean BVR while resecting soft-stiffness tumors (0.08 ± 0.02 cc). The highest mean BVR was seen during the removal of black and medium-stiffness tumors for neurosurgeons (0.09 ± 0.02 cc), black tumors for senior residents (0.11 ± 0.04 cc), and gliomalike appearance tumors for junior residents (0.08 ± 0.03 cc).

Sum of Forces Utilized

The mean SFU by neurosurgeons (82.66 ± 36.78 N) was more compared with senior residents (78.02 ± 21.01 N), but both employed far less than the junior residents (129.18 ± 90.92 N; Fig. 3B). As seen in Figure 3C, the lowest mean SFU by neurosurgeons was while resecting tumors with gliomalike appearance (76.71± 29.03 N), and this was also apparent in the senior and junior resident groups (68.86 ± 21.52 N and 115.80 ± 80.13 N, respectively). For all groups, the highest mean SFU was while removing black tumors, 92.49 ± 45.31 N for neurosurgeons, 91.52 ± 24.98 N for senior, and 150.36 ± 111.07 N for junior residents. The highest mean SFU during the resection of all simulated tumors assessed in this study was consistently employed by junior residents.

Maximum Force Applied

The mean MFA by neurosurgeons (0.15 ± 0.05 N) was higher compared with senior residents (0.14 ± 0.02 N), but values for both were less than those for junior residents (0.20 ± 0.10 N; Fig. 2D). As seen in Figure 3D, the lowest mean MFA by neurosurgeons was during the resection of white (0.14 ± 0.05 N) and medium-stiffness (0.14 ± 0.06 N) tumors. In contrast, the lowest mean MFA by senior residents was during the resection of gliomalike appearance tumors (0.12 ± 0.02 N), whereas it was while removing medium-stiffness tumors for junior residents (0.18 ± 0.1 N). The highest mean MFA by neurosurgeons was while resecting tumors with gliomalike appearance (0.16 ± 0.05 N), whereas it was during the removal of black tumors by senior residents (0.15 ± 0.03 N) and during resection of high-stiffness (0.22 ± 0.12 N) and black (0.22 ± 0.12 N) tumors by junior residents. Junior residents consistently had the highest mean MFA values during the resection of all simulated tumors assessed in this study.

Ultrasonic Aspirator TTPL

Neurosurgeons used a longer mean TTPL (1358.4 ± 469.5 mm) as compared with senior residents (1152 ± 297.9 mm), but both were shorter than that used by junior residents (1481.5 ± 452 mm; Fig. 2E). As shown in

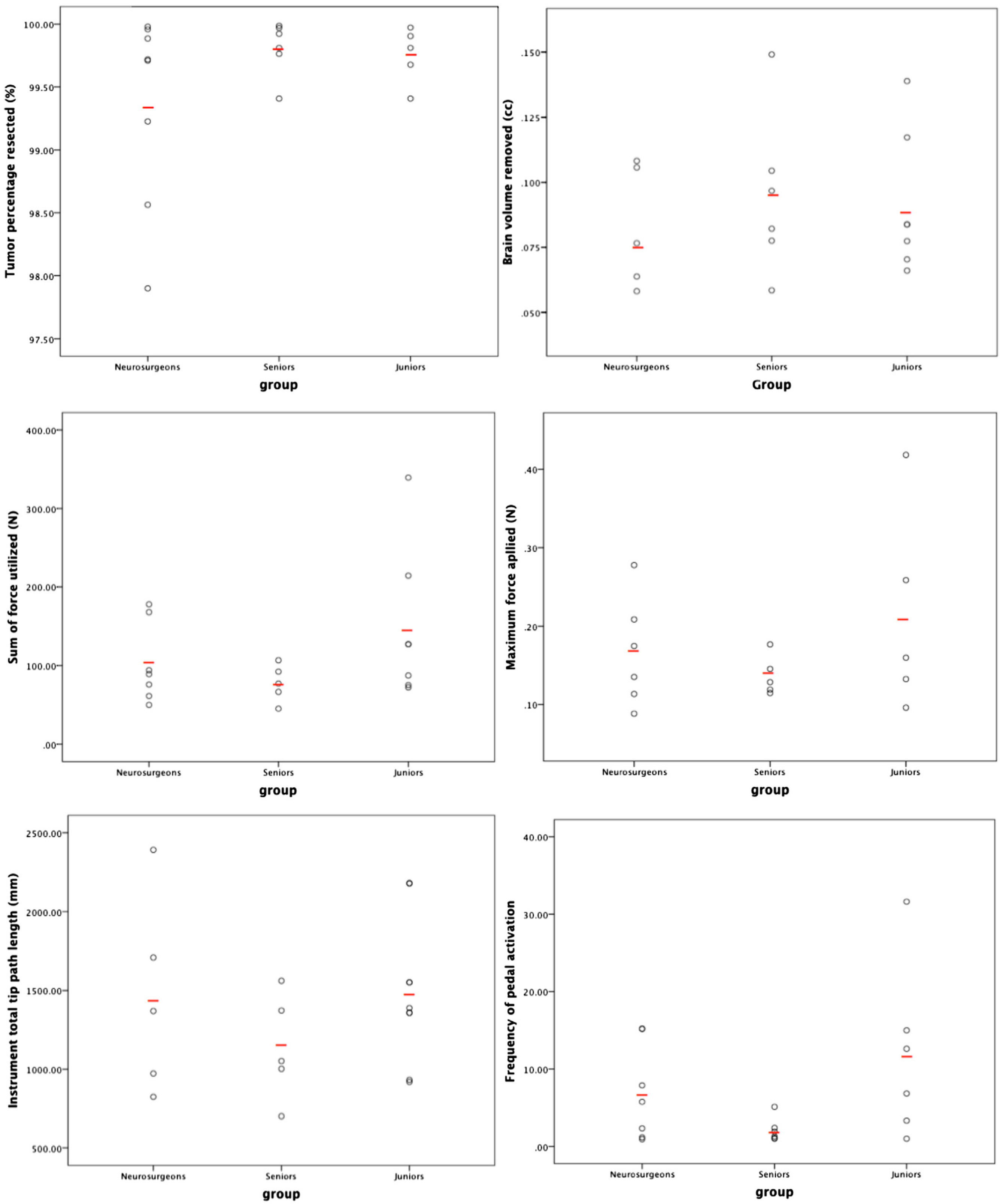

FIGURE 2. Scores plot diagrams, with the cross bar representing the mean values, for neurosurgeons ($n = 17$), senior ($n = 7$), and junior residents ($n = 9$) during the resection of 18 simulated brain tumors.

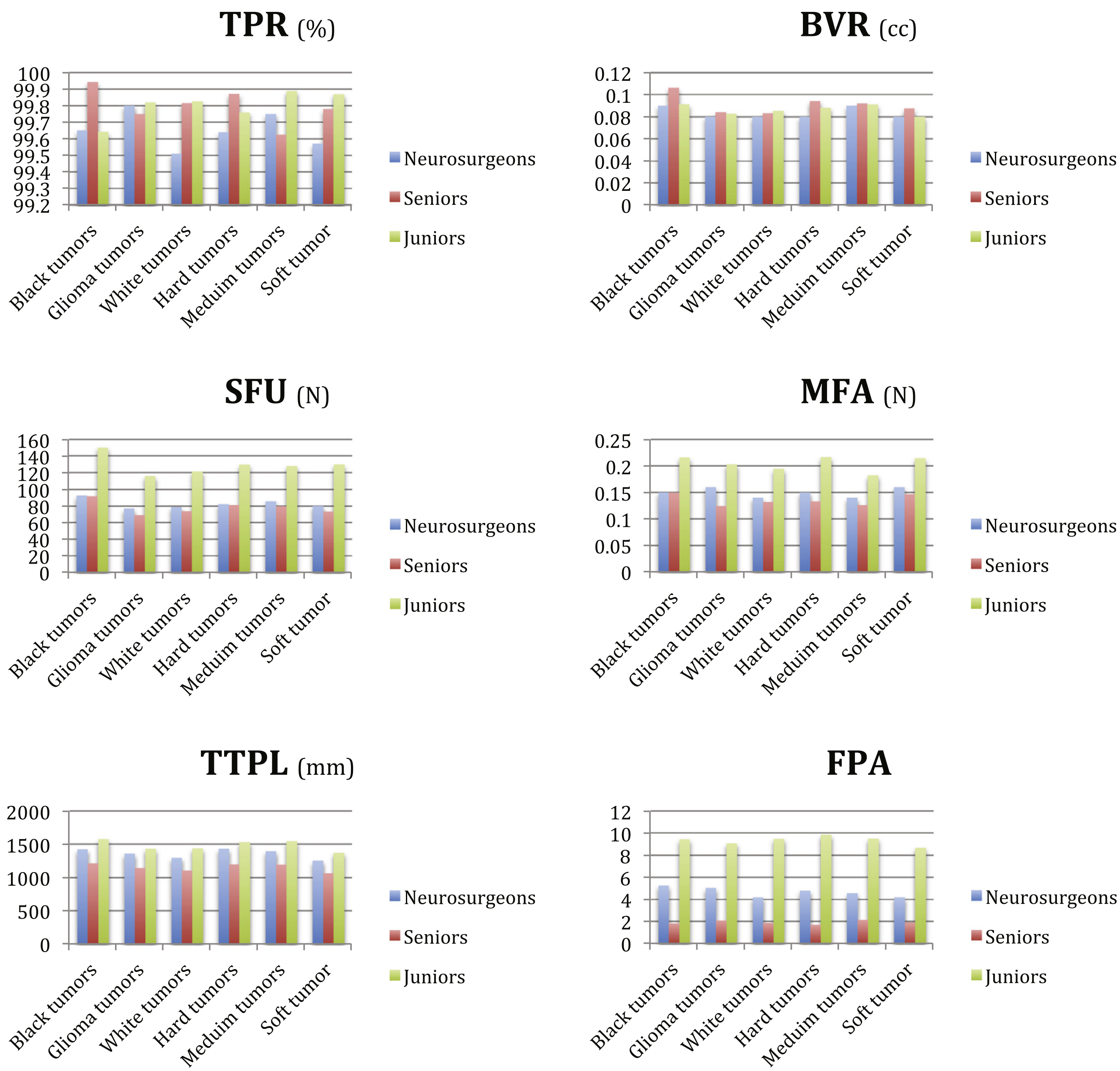

FIGURE 3. Mean performance of neurosurgeons ($n = 17$), senior ($n = 7$), and junior residents ($n = 9$) during the resection of simulated tumors of different tumor color and stiffness, with $n = 6$ in each group.

Figure 3E, neurosurgeons, senior residents, and junior residents used the shortest mean TTPLs for the resection of soft-stiffness tumors—1249.6 ± 477.2 mm for the neurosurgery group, 1066.5 ± 283.3 mm for the senior, and 1370.3 ± 419.3 mm for the junior resident group. Neurosurgeons used the longest mean TTPL during the removal of hard-stiffness tumors (1430.8± 485.6 mm), whereas it was during the resection of black tumors by senior (1213.4 ± 297.2 mm) and junior residents (1577 ± 545.9 mm). The highest mean TTPL during the resection of all simulated tumors assessed in this study was consistently employed by junior residents.

Frequency of Pedal Activation

Neurosurgeons activate the simulated ultrasonic pedal more frequently, with a mean value of 4.5 ± 4.7 times per tumor, when compared with the senior residents, mean value of l.9 ± 1.5, but both of these values were less than that of junior residents, mean value of 9.3 ± 9.6. As shown in Figure 3F, the resection of white (4.2 ± 3.95) and soft-stiffness (4.2 ± 4.6) tumors resulted in the highest mean FPA values for neurosurgeons. For senior residents, the mean FPA was 1.7 ± 1.4 for hard-stiffness tumors, and for junior residents, it was 8.7 ± 9.1 for soft-stiffness tumors. The highest mean

FPA employed was 5.3 ± 6.4 by neurosurgeons in the removal of black tumors, 2.1 ± 1.7 by senior residents for medium-stiffness tumor, and 9.9 ± 9.6 by junior residents for hard-stiffness tumors. As seen for SFU, MFA, and TTPL, junior residents consistently used the highest mean during the resection of all simulated tumors assessed in this study.

DEVELOPMENT OF BENCHMARKS

The neurosurgeons included in this study are involved in different neurosurgical subspecialties including, neurosurgical oncology, functional and epilepsy, skull base, vascular, spine, trauma, and pediatric neurosurgery. The mean scores for neurosurgeons for each tumor group and all 18 tumors are provided in Table 2. To determine the reference criteria to develop proficiency performance benchmarks, we initially calculated the mean neurosurgeon scores ± SD for all 17 neurosurgeons for each metric assessed. Neurosurgeon scores 1 SD above or below this mean score were excluded, and the means were recalculated to determine the proficiency performance benchmarks by the method outlined by Brunner et al.[24] These new mean ± SD proficiency performance benchmark values excluded 2 neurosurgeon scores from TPR (both below 1 SD), SFU (both above 1 SD), and MFA (1 below and 1 above 1 SD). For FPA, 5 scores were excluded (all above 1 SD), whereas 7 BVR (all above 1 SD) and 7 TTPL (3 below and 4 above 1 SD) scores were excluded. The trimmed means ± SD, which represents our metrics reference criteria for simulated tumor removal, are presented in Table 3 and Figure 4.

TABLE 3. Recommended Reference Criteria Values ± SD and Specific Benchmarks for Simulated Tumor Resection Using the NeuroTouch Platform for the Resection of the 18 Tumors Assessed in This Study

Performance Measures	Reference Criterion (Mean ± SD)	Benchmarks
Tumor percentage resected	99.84% ± 0.10%	99.74%-99.94%
Brain volume removed	0.07 ± 0.02 cc	0.05-0.09 cc
Sum of force utilized	70.63 ± 14.99 N	55.64-85.62 N
Maximum force applied	0.15 ± 0.04 N	0.11-0.19 N
Total tip path length	1246.6 ± 283.1 mm	963.5-1529.7 mm
Frequency of pedal activation	3 ± 2 Times	1-5 Times

DISCUSSION

In this study, we objectively measured multiple aspects of neurosurgical psychomotor skills used during the resection of a variety of simulated brain tumors and developed a series of proficiency performance benchmarks that may be useful to aid in the learning of specific neurosurgical psychomotor skills. The NeuroTouch platform provides Tier 1 and Tier 2 metrics, which may be useful in assessing the safety, quality, and efficiency of the operator and together encompass a number of critical aspects of the technical skill necessary to perform brain tumor resections and endoscopic sinus surgery.[12,23] TPR is a Tier 1 metric that assesses the quality of a tumor resection, whereas another Tier 1 metrics, the volume of simulated "normal" tissue surrounding the tumor removed, BVR, is a measure of operator safety. The Tier 2 metrics, SFU, and MFA are also measures of operator safety, whereas aspirator TTPL and FPA assess operator efficiency. Patient safety is paramount during the removal of cerebral tumors.[25-27] The inadvertent removal of adjacent eloquent normal brain tissue can compromise patient outcomes by resulting in permanent postoperative disability and decreased patient survival.[28,29] Care was therefore taken to instruct the participants in this trial to resect each simulated tumor with minimal removal of the surrounding simulated "normal" brain tissue emphasizing the focus on the safety of the simulated procedure.

The results of our study are consistent with the hypothesis that during the VR scenarios assessed in this study; some experienced neurosurgeons (experts) are focused on the most important component of a brain tumor operation, safety. Neurosurgeons removed less surrounding normal brain tissue (mean BVR) during the tumor resection, and this is associated with the least percentage of mean TPR. Senior and junior residents resected the highest mean TPR but removed higher mean BVR than neurosurgeons, with the "novice" junior residents removing the highest mean BVR. Although these differences in BVR appear small, the interface between the tumor and normal tissue may be especially important to focus on in further research, as the expert may use a learned but measured complex psychomotor-cognitive interaction to obtain the desired surgical result in this difficult tumor environment. An appropriate goal of any surgical training program should be imparting this complex information to the trainees.

The Tier 2 metrics related to the safety including SFU and MFA. Brain injury may result from the use of too much force over time or from the sudden use of an inappropriately high force for a specific operative environment or both. The resultant brain injury may involve direct trauma to the brain or cranial nerves or both, increased brain edema, and vessel damage. Many of these operative errors may result in increased patient morbidity and mortality. Junior residents had the highest mean SFU and mean MFA, whereas senior residents had the lowest mean values of SFU and MFA. Interestingly, neurosurgeons used an intermediate amount of mean SFU and MFA, suggesting that neurosurgeons with

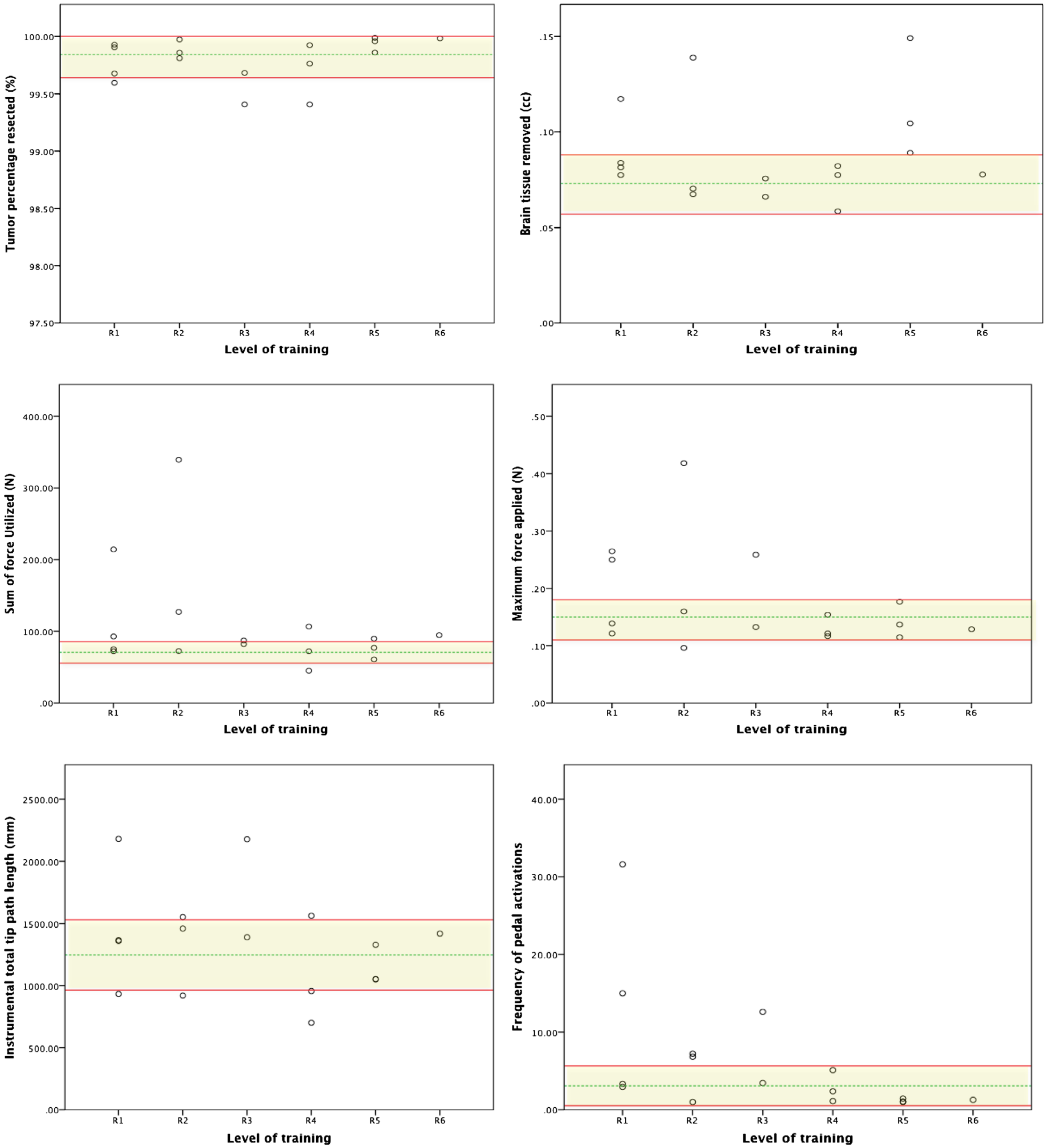

FIGURE 4. Performance benchmarks on all metrics developed using the trimmed mean of the neurosurgeons ($n = 17$).

experience further modify their force application paradigm to maximize the efficiency of safe tumor resection. This is supported by the results of the Tier 2 metrics focused on efficiency, TTPL, and FPA, in which neurosurgeons' mean values were again intermediate between the results seen in the study performed by junior and senior residents. Junior residents consistently used the highest mean SFU, MFA, TTPL, and FPA during the resection of all simulated tumors assessed in this study. These data suggest that junior residents had not yet acquired the safety skills and efficiency cognitive-psychomotor playbook attained by senior residents, and senior residents had not acquired the experience necessary to modulate their force skills related to maximizing operative efficiency.

STRENGTHS AND WEAKNESSES

The major weakness of this study is the inability of the Tier 1 and Tier 2 metrics to show significant differences between the resident and neurosurgical groups. Ericsson has argued that technical skills required to perform a surgical procedure is considerably variable resulting in the individual differences in execution of operative procedures among surgeons.[30] The inclusion of neurosurgeons with a variety of subspecialty expertise in this trial, some with limited opportunity to perform brain tumor operations, may be 1 factor contributing to the wide variability in neurosurgical performance observed in this group. This variability is in need of further investigation as it suggests that even in board-certified neurosurgeons failure to perform specific operations frequently may result in degradation in these operative skills.

The ability of neurosurgeons to modify their force paradigms to attain maximum safety and efficiency suggests that they have used experience to cognitively modulate their skill sets obtained during residency to achieve these goals. Therefore, externalizing these experts' cognitive skills while performing a motor task like the resection of a cerebral tumor and making them visible for the learner in the form of benchmarks allows the learner to observe and practice the skill with guidance resulting in a more meaningful learning process.

In this study, we defined a reference criterion level to develop proficiency performance benchmarks for all metrics obtained from our studies on the variety of simulated tumor removed based on 17 neurosurgeons. Brunner et al[24] used a trimmed mean procedure to develop reference criteria for all minimal invasive surgical trainer VR tasks based on the performance of experts in general surgery. This method was used for our studies as it provides more stringent criterion levels for the trainee to attain and excludes any extreme scores from the recommended criterion levels calculation. In our studies, a minimum of 10 to a maximum of 15 neurosurgeon scores were used to develop benchmarks but further investigations using a large number of neurosurgeons are essential to assess the value of these benchmarks to resident psychomotor education. We have developed reference criteria and proficiency performance benchmarks against which neurosurgical residents' psychomotor performance can be assessed and guided to achieve the specific removal of 18 simulated brain tumors with a wide range of complexities using the NeuroTouch platform. The validation of these metrics and other metrics in ongoing studies is critical to advance the implementation of simulation in neurosurgical training and assessment. At present, 15 members of the NeuroTouch Consortium are spread across 3 continents, and an important problem involving these centers is the standardization and validation of performance metrics.[12] After accomplishing this goal, it will be essential to continuously modify established and new proficiency performance benchmarks in an ongoing dynamic process for each individual metric and neurosurgical operative procedure based on updated research. Guided by these validated metrics, thresholds can be determined for each proficiency benchmark helping to develop training curriculum and self-assessment programs to maximize resident performance.[4,12]

The results of this study need to be interpreted with caution. First, in these studies, the operator was only allowed to use the dominant hand holding the simulated ultrasonic aspirator for the tumor resection, which is not representative of the complex interactive skills necessary for the resection of a patient's tumor. Second, the short duration of the task and the level of color and stiffness complexity may not have been able to accurately discriminate the levels and quality of performance among this limited number of operators resulting in our inability to find significant differences in the metrics used. More complex scenarios with increased color and stiffness complexity along with tumor associated bleeding controlled by a sucker in the nondominant hand and an ultrasonic aspirator in the dominant hand with metrics involving bimanual psychomotor activity have been performed to address these concerns.[31] Third, the performance of each participant was not videotaped and therefore was not available for assessment by a standardized scale as no such validated scale has been developed for simulated procedures in neurosurgery. Fourth, the use of neurosurgeons from only a limited number of institutions with a variety of subspecialty expertise although representative of present neurosurgical practice may have resulted in the wide variability in neurosurgical performance outlined in Figure 2 and also contributed to our inability to find significant differences between the neurosurgical and resident groups. Careful consideration should be given to choosing which "expert" neurosurgeons to include in studies focused on defining proficiency performance benchmarks. Fifth, as seen in Figure 2, assessing senior resident performance from one institution outlines a much more homogenous group than present in the neurosurgeon and junior resident groups. Whether this homogeneity will be a consistent finding when senior residents from multiple institutions are assessed is unclear but needs to be further studied. The serial tracking of residents during training and after graduation would be very useful in understanding the sequence of acquisition of psychomotor skills during residency and further modification of these skills during neurosurgical practice. The NeuroTouch Consortium provides an opportunity to investigate many of these important issues. Sixth, although this study was focused on a descriptive analysis of specific metrics and the development of proficiency performance benchmarks without the demonstration that VR simulators like NeuroTouch enhance resident operative room performance, their use in resident assessment and training will be limited.[2,8]

CONCLUSIONS

NeuroTouch provides an environment to carry out the sustained, deliberate, and goal-directed practice that neurosurgical expertise necessitates. This study furthers our understanding of neurosurgical expertise and provides neurosurgical trainees with predefined proficiency performance benchmarks that can be used to aid in their learning of specific surgical psychomotor skills.

ETHICAL STANDARDS

All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2008.

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SUPPLEMENTARY MATERIALS

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