Nondominant Hand Skills Spatial and Psychomotor Analysis During a Complex Virtual Reality Neurosurgical Task—A Case Series Study

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BACKGROUND: Virtual reality surgical simulators provide detailed psychomotor performance data, allowing qualitative and quantitative assessment of hand function. The nondominant hand plays an essential role in neurosurgery in exposing the operative area, assisting the dominant hand to optimize task execution, and hemostasis. Outlining expert-level nondominant hand skills may be critical to understand surgical expertise and aid learner training.

OBJECTIVE: To (1) provide validity for the simulated bimanual subpial tumor resection task and (2) to use this simulation in qualitative and quantitative evaluation of nondominant hand skills for bipolar forceps utilization.

METHODS: In this case series study, 45 right-handed participants performed a simulated subpial tumor resection using simulated bipolar forceps in the nondominant hand for assisting the surgery and hemostasis. A 10-item questionnaire was used to assess task validity. The nondominant hand skills across 4 expertise levels (neurosurgeons, senior trainees, junior trainees, and medical students) were analyzed by 2 visual models and performance metrics.

RESULTS: Neurosurgeon median (range) overall satisfaction with the simulated scenario was 4.0/5.0 (2.0-5.0). The visual models demonstrated a decrease in high force application areas on pial surface with increased expertise level. Bipolar-pia mater interactions were more focused around the tumoral region for neurosurgeons and senior trainees. These groups spent more time using the bipolar while interacting with pia. All groups spent significantly higher time in the left upper pial quadrant than other quadrants.

CONCLUSION: This work introduces new approaches for the evaluation of nondominant hand skills which may help surgical trainees by providing both qualitative and quantitative feedback.

KEY WORDS: Case series, Instrument utilization, Neurosurgery, Nondominant hand, Simulation, Surgical technical skills, Virtual reality

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In surgery, the interaction of dominant and nondominant hands is essential to accomplish operative goals.[1-3] This bimanual psychomotor performance can be constrained by the skill level of the nondominant hand.[4-7] The mastery of nondominant hand skills in assisting the dominant hand to optimize task execution, exposing operative regions, and hemostasis is critical for learners to perform surgical tasks safely and efficiently.[8] In brain tumor surgery, understanding expert-level nondominant hand skills necessary to perform complex procedures such as the subpial resection is lacking. Outlining these skills is crucial in revealing the composites of surgical expertise to provide trainees with personalized feedback to help improve nondominant hand skills.

ABBREVIATIONS: JT, junior trainees; **MS,** medical students; **NS,** neurosurgeons; **PGY,** postgraduate year; **ST,** senior trainees.

This study first focused on assessing the face and content validity of a simulated complex virtual reality subpial tumor resection scenario. Then, using data from this simulation platform, we investigated the nondominant hand skills essential for successful completion of the task. Visual and quantitative models developed in this work were used to explore differences in nondominant hand skills between skilled and less-skilled groups. Our research questions were as follows: (1) Do visual models regarding force and time utilization indicate differences in nondominant hand skills between expertise groups? (2) How efficiently and precisely do skilled groups use their nondominant hand in comparison with less-skilled groups during tumor resection? (3) What are some common nondominant hand skill features that exist across skilled and less-skilled groups and those acquired with increasing training and expertise?

METHODS

Subjects

A consecutive case series of 50 participants from a single Canadian university enrolled in this retrospective study between March 2015 and May 2016 at a single time point, with no follow-up. Data were anonymized. Five left-handed participants were removed from the analysis because of differing instrument utilization between right-handed and left-handed participants[3,9] (Figure 1). The remaining 45 right-handed participants were classified a priori as neurosurgeons (13), seniors (3 neurosurgical fellows and 9 senior residents [postgraduate year 4-6]), juniors (9 junior residents [post graduate year 1-3]), and medical students (11) (Table 1). All participants signed a consent form approved by the university ethics board.

Simulation Scenario

The NeuroVR platform (CAE Healthcare) allowed users to interact with a 3-dimensional (3D) operative environment through a microscope while providing haptic feedback on contact with the simulated tissues (Figure 2A).[10-13] This simulation platform was a prototype that has not been approved by the U.S. Food and Drug Administration. The simulated scenario involved a previously described complex brain tumor subpial resection procedure (Figure 2B).[14,15] The tumor was placed under the pia mater, adjacent to critical brain areas such as a main blood vessel and motor and sensory strips (Figure 2F). The task was performed using a simulated ultrasonic aspirator in the dominant hand to resect tumor and a bipolar forceps in the nondominant hand for supportive movements such as lifting or moving the pia mater to assist the dominant hand and cauterizing bleeding tissues (Figure 2D and 2E, see Video). Both instruments were activated by foot pedals. Background sounds of mechanical ventilation and heartbeats were included. Participants were instructed to remove the tumor completely within 13 minutes[15] while minimizing bleeding and damage to adjacent structures. No feedback was provided during or after each task.

Participant Rating of the Task

After task completion, participants completed a 10-item questionnaire to assess the face and content validity of the subpial resection (Table 2). Participants were asked to rate their neurosurgical simulation experience and satisfaction on a 5-point Likert scale. A median score of ≥3.0 was deemed sufficient for the face and content validity and overall satisfaction.[16]

Performance Data

The NeuroVR platform provides a csv (comma-separated value) file containing the coordinates of instrument tip location, instrument activation, force application, tumor and tissue volumes, bleeding, and instrument-tissue contacts. Force application and distance were measured in Newtons (N) and millimeters (mm), respectively. Data were recorded at 20-ms increments (50 recordings/s).

Force Heatmap and Time Scatter Models

3D tumor and brain mesh models were extracted from the simulator software. Brain pia mater surface was divided into 4 quadrants, numbered counterclockwise starting from the right upper quadrant (Q1, Q2, Q3, and Q4)[17] with the center of the tumor, represented on the pial surface as the reference point (Figure 2C). Visualization of bipolar force application on the pia mater was provided by 2 models: (1) 3D force heatmap was created to represent bipolar force application on the pia mater, and (2) time scatter was generated to demonstrate spatial distribution of bipolar-pia mater interactions. For both models, mean values (force or time) were recorded at each grid point (pixel) on the pia mater for each task. These values were averaged for each group to generate heatmap and scatter models for 4 groups. Force and time quantities were represented with color scales. For the time scatter model, only grid points with bipolar contact were shown.

Performance Metrics

Bipolar nondominant hand skills were assessed by 2 groups of metrics. The first group focused on performance while using the bipolar to assist the dominant hand while resecting tumor. Metrics in this category included total time spent interacting with the pia mater, average force application on pial surface, total force application on pial surface, bipolar average tip distance from the center reference, and bipolar precision. The bipolar precision metric was based on the standard error values of bipolar tip distance from the center reference, assessing the distance variation of the bipolar-pia mater interactions.

The second group metrics explored nondominant hand utilization in the 4 pial quadrants during the entire task. At each quadrant, 3 performance metrics were calculated: percentage time spent while the bipolar was in contact with pial surface, average force application, and total force application.

Statistical Analyses

The first group of metrics was compared between 4 expertise groups. The second group of metrics was compared between 4 quadrants within each expertise groups. Outliers were observed by boxplot. No data exclusion was made. Normality of data distribution was determined by using the Shapiro-Wilk test for each metric ($P > .05$). Statistical analysis was performed by using one-way analysis of variance for normally distributed metrics. The Levene test was used to check equality of variances, based on median ($P > .05$). One-way analysis of variance was followed by

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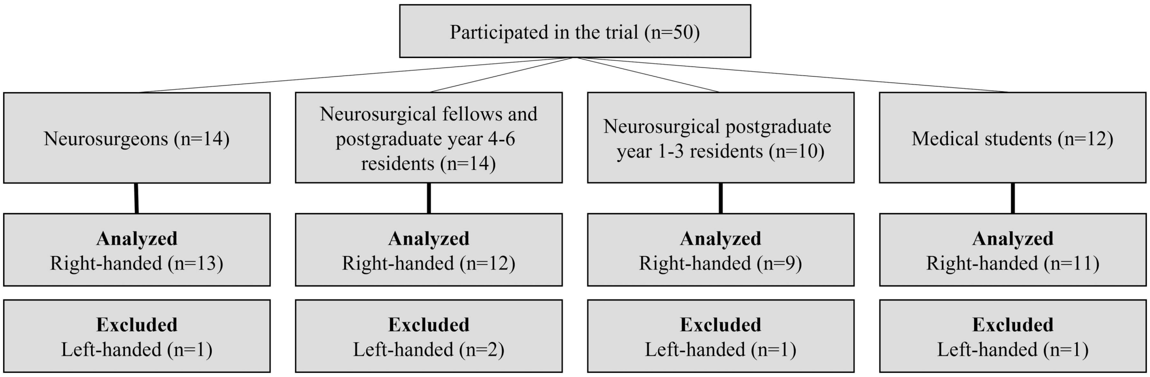

FIGURE 1. *Study participants.*

the Tukey-Kramer or Games-Howell post hoc tests in case of equal and unequal variances, respectively. For non-normally distributed metrics, the Kruskal-Wallis test was followed by the Dunn post hoc procedure with the Bonferroni correction for multiple tests. $P < .05$ was considered statistically significant. MATLAB (MathWorks) r.2021a and IBM SPSS Statistics v.27 were used for the analyses. This study is reported in line with the Preferred Reporting of Case Series in Surgery (PROCESS) Guideline.[18]

RESULTS

The participant demographics and previous simulation experience are outlined in Table 1.

Rating of the Task

The simulated subpial tumor resection median scores and ranges for face and content validity on a 5-point Likert scale and participants' satisfaction with the simulated task are listed in Table 2. Neurosurgeons rated the overall visual realism of the simulated task a median (range) of 4.0 (1.0-5.0). The sensory realism was rated 3.0 (2.0-5.0) with the feel of the simulated pia rated (4.0 [2.0-4.0]) higher than the simulated tumor (3.0 [2.0-4.0]). Neurosurgeons also agreed with using the simulator for technical skills training (4.0 [2.0-5.0]) with 85% recommending integrating simulation into training. These results were consistent with face and content validity.[16]

Force Heatmap and Time Scatter Models

In the 3D force heatmap model, all groups had high bipolar pia force application in Q2, the left upper pial region (Figure 3). Higher force applied areas are shown in red. Neurosurgeons and seniors demonstrated smaller red areas when compared with junior and medical student groups. In the bipolar time scatter model, red areas represented grid points with average time spent greater than 1 second. All groups had red areas mainly at the left upper quadrant. Neurosurgeons and seniors demonstrated more focused bipolar-pia mater interactions around the tumoral region. The results from both models indicate that higher skilled groups were using their nondominant hand gentler (lower force) and more centralized around the tumor. These parameters were statistically investigated with the performance metrics in the next sections.

TABLE 1. **Demographics of Participants**

	Neurosurgeons (n = 13)	Senior trainees (neurosurgical fellows and residents PGY 4-6, n = 12)	Junior trainees (neurosurgical residents PGY 1-3, n = 9)	Medical students (n = 11)
Mean age, years	45 ± 7.5 (33-59)	32 ± 2.3 (29-35)	30 ± 3.3 (37-38)	24 ± 1.3 (23-26)
Male/female	13/0	12/0	7/2	5/6
No. of complete subpial resections performed	210 ± 286 (0-800)	10 ± 14 (0-45)	0.7 ± 2 (0-7)	0 ± 0
No. of partial subpial resections performed	27 ± 82 (0-300)	20 ± 35 (0-130)	4 ± 11 (0-35)	0 ± 0
Used simulator previously	6 (46%)	9 (75%)	5 (56%)	3 (27%)
Used NeuroVR previously	5 (38%)	8 (67%)	5 (56%)	1 (9%)

PGY, postgraduate year.
Represented formula: mean ± SD (range).

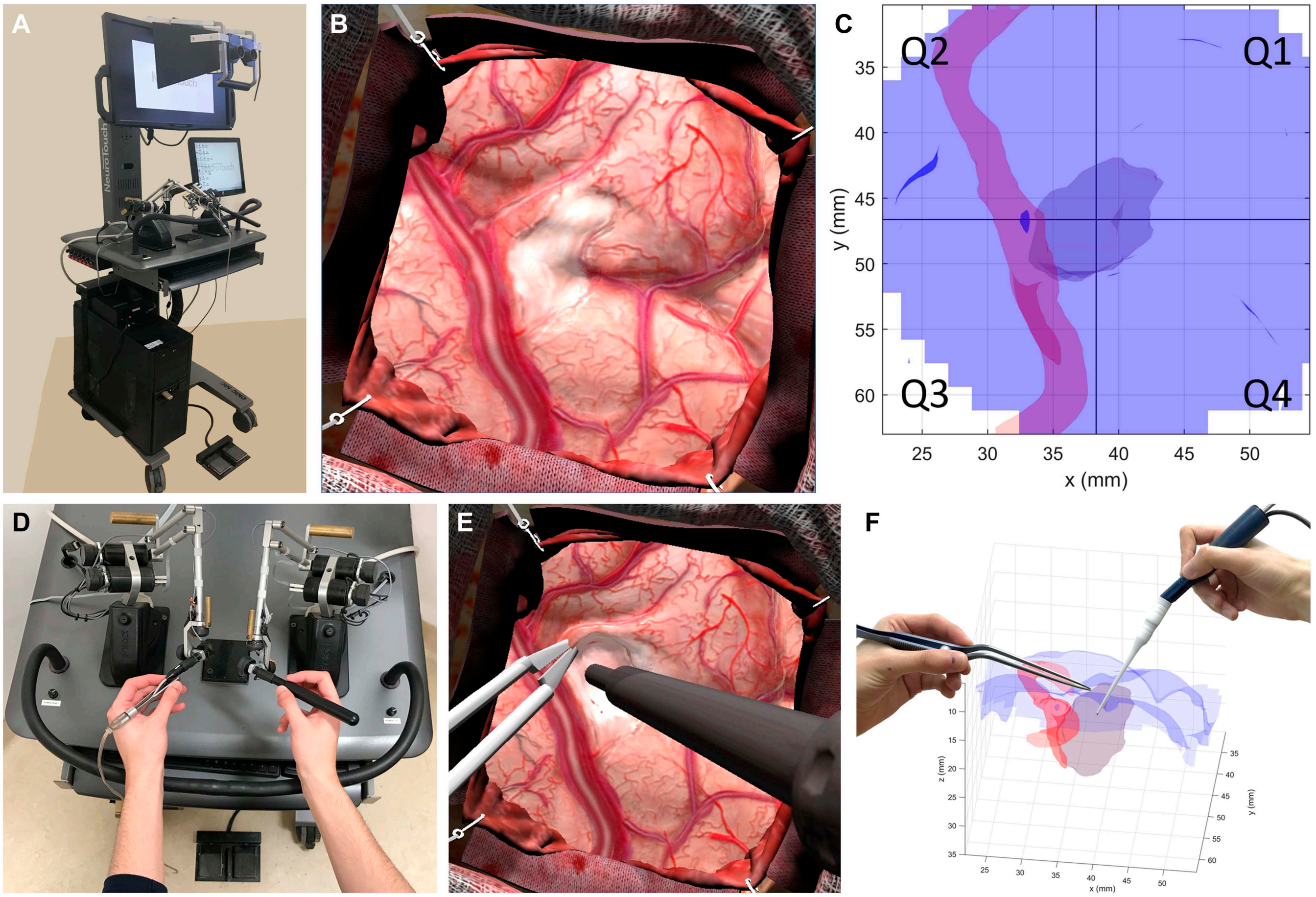

FIGURE 2. *Scenario setting.* **A**, *The NeuroVR platform.* **B**, *User view of the scenario. A whitish color tumor is present in the simulated motor cortex with the simulated rolandic vein separating the motor and sensory cortex; major blood vessel lies very close to the tumor at the left side.* **C**, *3D model of the tumor, from the top view, with 4 quadrants in counterclockwise order. The tumor (middle) and blood vessel (red) lie under the pia mater.* **D**, *The instruments. Users interact with the virtual environment with the simulated ultrasonic aspirator held in the dominant hand to resect tumor and the bipolar held in the nondominant hand to assist in exposing the tumor and to cauterize possible bleeding points. Both instruments were activated by foot pedals.* **E**, *A demonstration of bipolar use. Participants are required the pull the pia mater off the tumor from the brain-tumor edge to allow access to the tumor regions beneath.* **F**, *An illustration of use of a real ultrasonic aspirator and bipolar on the simulated tumor resection scenario—3D side view. The tumor (gray) and blood vessel (red) are seen under the pia mater (blue). 3D, 3-dimensional.*

Psychomotor Analysis

The quantitative analysis demonstrated that the neurosurgeons (P = .048) and seniors (P = .047) spent significantly more bipolar time interacting with the pia than medical students, and these groups applied less average bipolar force to pial surface than the medical student group (P = .039 and P < .001, respectively) (Figure 4). Seniors' average force application to pial surface was significantly lower than juniors' (P = .015). Total bipolar force application on pial surface was not significantly different between groups (Figure 4).

Subpial tumor resection necessitates using the bipolar in contact with the pia mater around the tumor operational field. Bipolar contacts on the pia were more centralized for neurosurgeons within 12 mm radius from the tumor center while in other groups, many bipolar contacts outside of this radius were identified (Figure 5A). The average bipolar distance from the center reference increased from neurosurgeons to less-skilled groups and was significantly smaller in neurosurgeons than medical students (P = .020, Figure 5B). In addition, neurosurgeons were more precise with their bipolar contacts on the pia (lower distance variation from the center reference) during tumor resection compared with medical students (P = .017, Figure 5C).

Quadrant Metrics

Nondominant hand instrument utilization was evaluated for each quadrant by 3 different metrics. Regarding time spent, the

TABLE 2. Participant Rating of the Simulated Subpial Resection Task (Median [Range])

Validity statements	Neurosurgeons	Senior trainees	Junior trainees
Sensory realism of the “feel” of the simulated pia (1-completely unrealistic, 5-completely realistic)	4.0 (2.0-4.0)	3.0 (1.0-4.0)	4.0 (2.0-4.0)
Sensory realism of the “feel” of the simulated tumor (1-completely unrealistic, 5-completely realistic)	3.0 (2.0-4.0)	3.0 (1.0-4.0)	4.0 (3.0-4.0)
Color of the simulated tumor (1-completely unrealistic, 5-completely realistic)	4.0 (2.0-5.0)	4.0 (3.0-5.0)	4.0 (3.0-5.0)
Overall visual realism of the simulation task (1-completely unrealistic, 5-completely realistic)	4.0 (1.0-5.0)	4.0 (1.0-5.0)	4.0 (2.0-5.0)
Overall sensory realism (the feel of the different tissues) of this simulation task (1-completely unrealistic, 5-completely realistic)	3.0 (2.0-5.0)	3.0 (1.0-4.0)	3.0 (2.0-4.0)
If this simulator was available in my program, I would use this simulation scenario for training of the technical skills simulated (1-completely disagree, 5-completely agree)	4.0 (2.0-5.0)	4.0 (2.0-5.0)	4.0 (1.0-5.0)
Would you recommend integrating simulation training (using virtual reality operative simulation) into a curriculum during neurosurgery training program as a mandatory block? (Yes/No)	85% Yes	67% Yes	78% Yes
Difficulty of the simulated tumor resection scenario (1-very easy, 5-very hard)	4.0 (3.0-5.0)	3.0 (2.0-4.0)	4.0 (2.0-5.0)
Self-rating of performance on the simulated scenario on a scale of 5 (1-very poor, 5-excellent)	2.5 (1.0-4.0)	3.0 (2.0-4.0)	3.0 (1.0-3.0)
Overall satisfaction with the simulated task (1-completely unsatisfied, 5-completely satisfied)	4.0 (2.0-5.0)	4.0 (2.0-4.0)	4.0 (1.0-5.0)

most favorable quadrant was Q2 for all groups having a statistically higher time spent than other quadrants. Neurosurgeons were the only group who spent time in Q3 as much as Q2, with no statistical significance between these 2 quadrants (*P* = .107). Neurosurgeons spent significantly more time in Q3 than Q4 (*P* = .023) (Figure 6).

All groups had the highest average force application in Q2; however, for juniors and medical students, no significant differences between quadrants were found (Figure 6). Average force application was significantly higher in Q2 than Q4 for neurosurgeons, and it was significantly higher in Q2 than Q1 for seniors. A significantly higher total force application was observed in Q2 than in any other

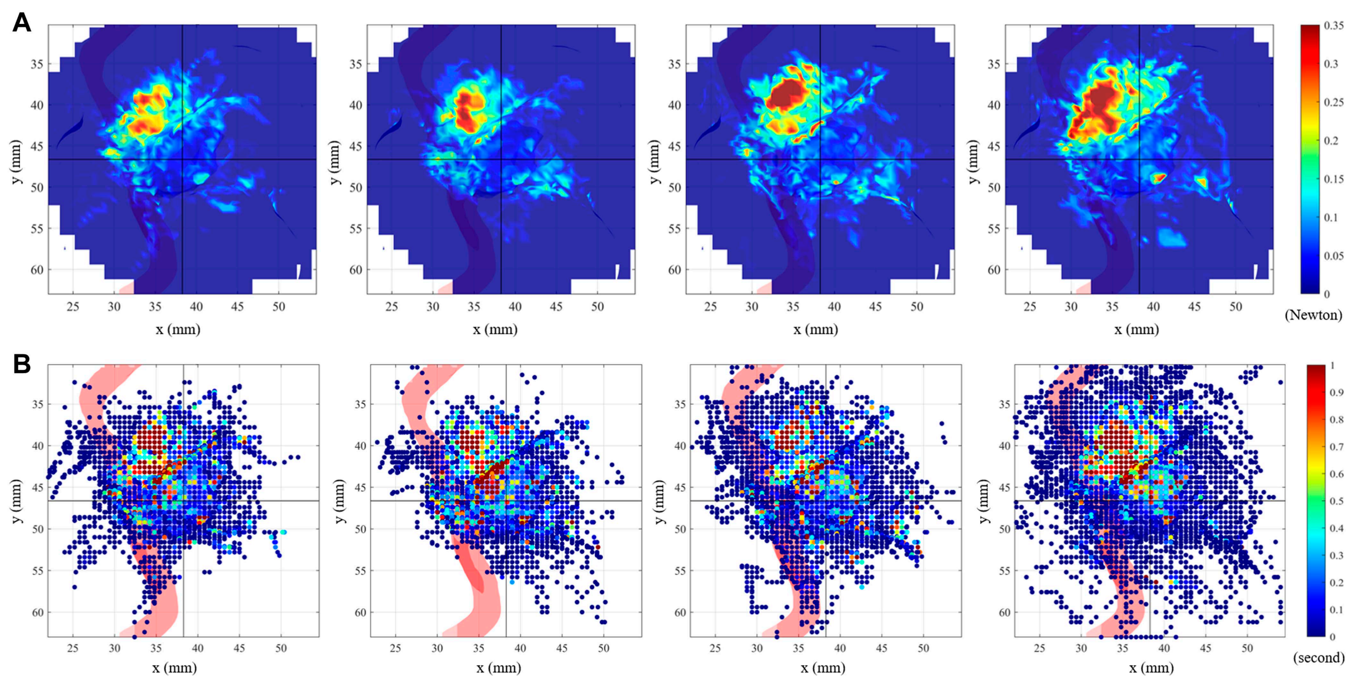

FIGURE 3. *Spatial distribution of bipolar-pia mater interactions.* **A**, *Force heatmap: Blue surface represents the pia mater. Force application (Newtons) is averaged across participants within each group and shown in 4 quadrants according to the color scale.* **B**, *Time scatter: represents 2-dimensional (x–y) bipolar-pia mater interactions. Each grid point is colored according to the average time spent (seconds) when the instrument is in contact with the pia mater at that location. Only points in which time spent is greater than 0 are shown.*

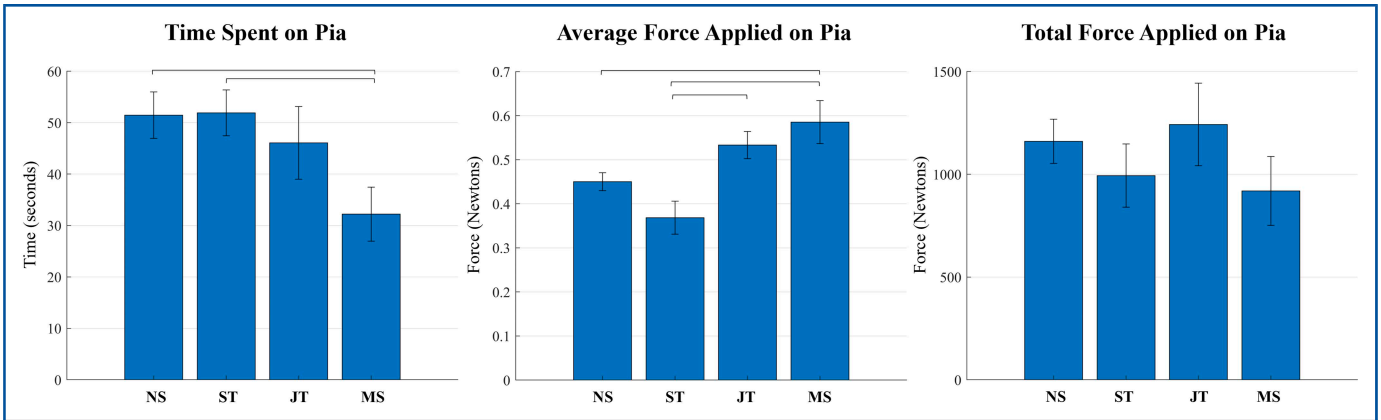

FIGURE 4. *Psychomotor evaluation. The performance metrics included time spent on the pia (seconds), average force application on the pia (Newtons), and total force application on the pia (Newtons) while resecting the tumor. Groups were NS (n = 13), ST (n = 12), JT (n = 10), and MS (n = 11). Values represent mean. Bars represent standard errors. Horizontal lines represent statistically significant differences (P < .05). JT, junior JT, junior trainees MS, medical students; NS, neurosurgeons; ST, senior trainees.*

quadrant for all groups, except that for neurosurgeons there was no statistical difference between Q2 and Q3. Neurosurgeons applied significantly more total force at Q3 than Q4 (*P* = .027).

DISCUSSION

Virtual reality neurosurgical simulation, with haptic feedback, provides large data sets allowing a quantitative assessment of simulated surgical performance.[12,14] These data sets have been used to evaluate surgical bimanual psychomotor performance metrics and differentiate skilled and less-skilled groups.[1,3,8,9,19,20] The goal of these applications was to determine the critical bimanual technical skills that underlie expert performance and to create personalized feedback systems that allow surgical instructors develop formative and summative educational platforms.

This study focused on nondominant hand skills involved in bipolar forceps utilization during a complex simulated subpial tumor resection task and the validation of this virtual reality surgical procedure. Neurosurgeons' rating of overall visual, sensory, and color realism with the scenario was consistent with face and content validity, and this simulation's construct validity has previously been demonstrated.[21]

Our visual models and quantitative analysis have shown that skilled groups use the bipolar more focally around the tumoral region with lower force application. Average force application decreased from medical students to seniors where seniors had significantly less average bipolar force application than both juniors and medical students. Neurosurgeons applied slightly higher forces than seniors and significantly lower forces than medical students. This discontinuous technical skill pattern (an increase in force after a decreasing trend) may be caused by overly cautious phases involved during training. Neurosurgeons may continue modulating their instrument utilization after training and slightly increase their forces with increasing competence. Total bipolar pial force application was not statistically different between groups. Less-skilled groups had higher average force application over less time resulting in similar total force application to skilled groups who used lower average forces over longer times. Similarly in previous studies, lower instrument force utilization reflected higher expertise level.[9,22,23] All groups contacted the bipolar at the left upper pial region the most, indicating that this quadrant may offer the most ergonomic hand position.

Intraoperative surgery involves many components encompassing knowledge, judgment, and technical skills. Surgeons develop and maintain a muscle memory, defined as "psychomotor skills script," which allows for being prepared and efficient in the operating room.[24] Our results demonstrated this script exists with the nondominant hand in the neurosurgeon group, where they use bipolar more precisely and focused around the tumoral region. A previous study in laparoscopic radical prostatectomy outlined 3 deficiencies noted between trainees and experienced surgeons, one of which is the lack of synchronized nondominant hand movements.[25] Virtual reality simulators allow for outlining less-skilled technical skills and provide trainees feedback to improve. The cognitive load during training can be decreased by mastering nondominant hand skills separately. Trainees may more quickly obtain expert-level psychomotor skills by spatial awareness and self-modifying their movements with unlimited repetitions in risk-free simulated environments.[26,27] By revealing expert-level skills, this study enables providing trainees with both visual and quantitative feedback to master their nondominant hand skills. The efficacy of such automated feedback methods can be compared with traditional expert-mediated instruction.

Focused nondominant hand skill training may provide significant advantages. A laparoscopic randomized controlled trial demonstrated that nondominant hand training improved dominant hand function skills, a phenomenon known as intermanual transfer of skill learning.[7] Functional near-red spectroscopy investigations of nondominant hand use resulted in bilateral sensory-motor cortex activation while dominant hand use only localized to

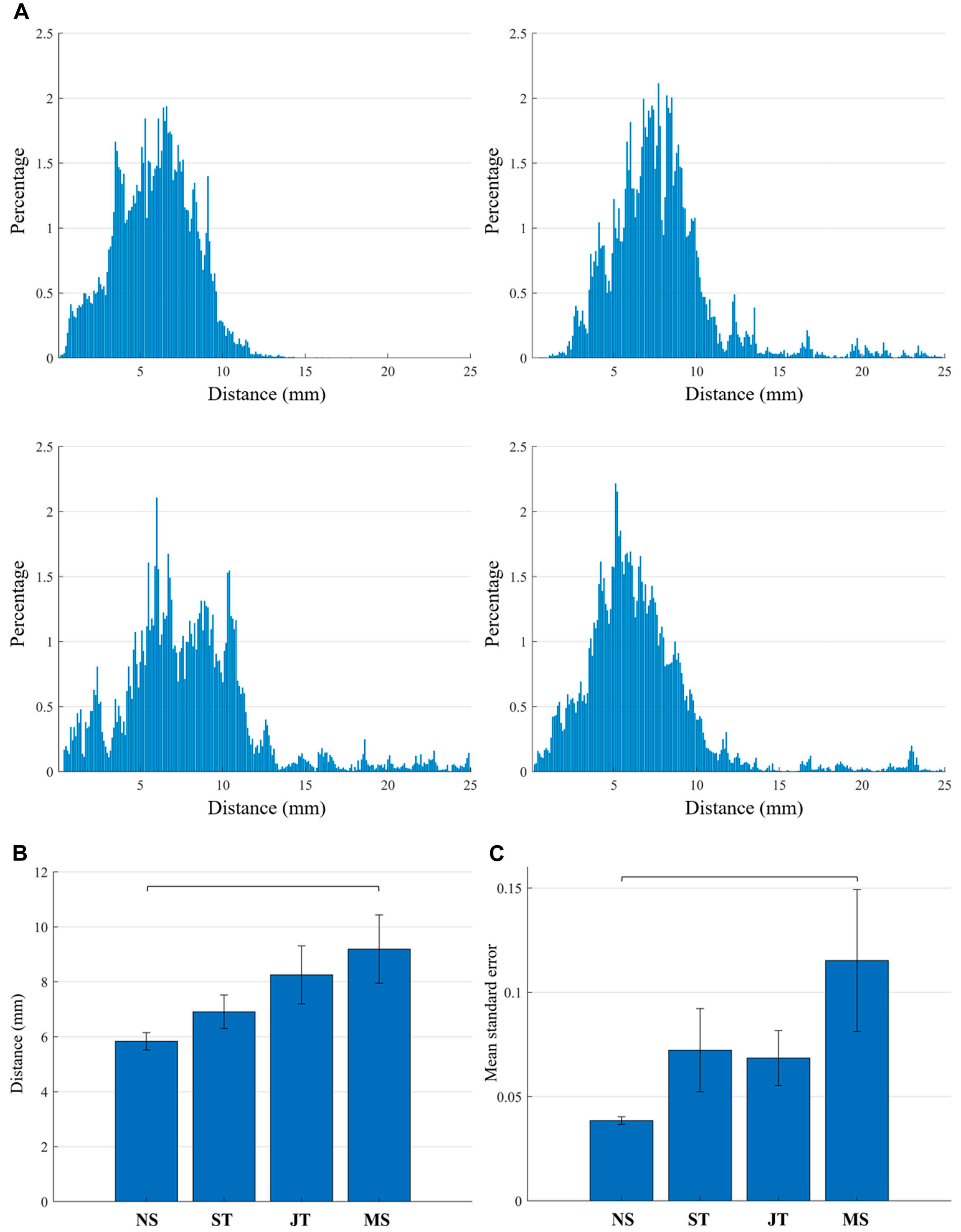

FIGURE 5. *Bipolar precision analysis.* A*, Bipolar tip distance from the center for each group. X dimension represents mm distance from the center reference, and Y dimension represents the percentage of being on a particular distance range (0.1 mm).* B*, Average bipolar distance (mm) from the center of the tumor for each group.* C*, Precision of bipolar use: Standard error of bipolar distance from the center during the time while the tumor is being resected was calculated to find precision for each individuals' bipolar function. *P < .05. JT, junior trainees; MS, medical students; NS, neurosurgeons; ST, senior trainees.*

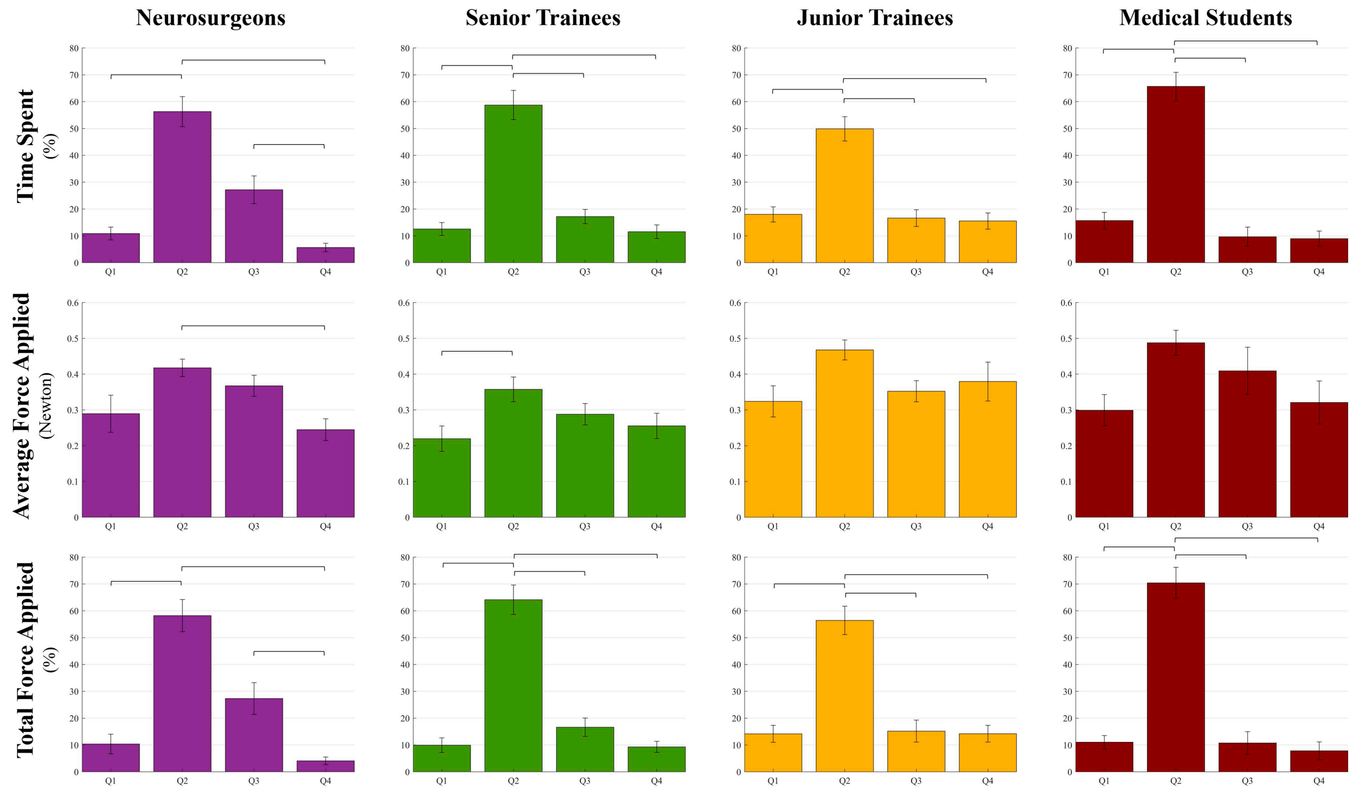

FIGURE 6. *Quadrant metrics. Percentage time spent (%), average force application (Newtons), and total force application (percentagewise) were calculated per quadrant. Values represent mean. Bars represent standard errors. Horizontal lines indicate statistically significant differences (P < .05).*

the contralateral hemisphere, suggesting nondominant hand training activates critical bilateral brain regions involved in motor control which may improve dominant hand motor system function.[28] Other investigations demonstrate a greater competence of the nondominant limb/hemisphere to rely on sensory input, thus improving motor function.[29] Further studies outlining the interdependence of dominant and nondominant hand function in surgery seem warranted. Previously, a support vector machine algorithm was used to differentiate expertise in subpial resection procedures in which 3 of the 4 performance metrics selected by the algorithm were related to bipolar utilization (mean acceleration, maximum force, and instrument tip separation).[2] In another study, 16 of the total of 31 performance metrics chosen by 4 machine learning algorithms to differentiate expertise into 4 groups were related to bipolar use,[1] consistent with the important role of the nondominant hand in neurosurgical procedures.

Limitations

Virtual reality simulation is a cutting-edge technology; however, these systems fail to represent many elements of the dynamic operating room environment. In this study, users were not able to change the view angle or the instruments. These limitations may affect participants' surgical performance and their conception of realism. A critical bipolar skill to be mastered is cauterization of bleeding vessels. Owing to limits in data acquisition skills such as cauterization, tissue-related analyses such as pial retraction and deformation were not studied in this study. As simulation platforms advance and provide more detailed real-life interactions and data, more comprehensive assessments can be performed. Our study included a post hoc analysis with metrics representing an overall assessment of the performance. Ongoing works focus more action-oriented assessments of nondominant hand skills using advance methodologies, such as deep learning.[30] Instrument utilization differ between right-handed and left-handed individuals performing virtual reality procedures, where instrument utilization of left-handed participants is usually a mirrored version of those of right-handers.[3,9] Having small number left-handed participants excluded from the study prevented exploring their bipolar-pia interactions. The small cohort involved from one institution may have limited the detection of differences between groups involving some metrics. With a broader cohort, the generalization of results can be increased.

CONCLUSION

This work introduces novel qualitative and quantitative approaches for outlining the nondominant hand skills involved during a virtual reality tumor resection. These visual models and performance metrics provide objective assessment of technical skills. Such systems may aid in the future development of competency-based training curricula.

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Disclosures

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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VIDEO. The simulated subpial tumor resection task. Users interact with the 3D environment. The whitish area at the center represents the tumor, which is adjacent to critical brain areas such as the main blood vessel at left-hand side and motor and sensory strips around. Tissues had bleeding capacity. Ultrasonic aspirator, at the dominant hand, was used to remove the tumor while bipolar, at the nondominant hand, was used to assist the dominant hand and cauterize bleeding tissues. Sounds of mechanical ventilation and heart monitor were included.
