# Virtual Reality Tumor Resection: The Force Pyramid Approach

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**BACKGROUND:** The force pyramid is a novel visual representation allowing spatial delineation of instrument force application during surgical procedures. In this study, the force pyramid concept is employed to create and quantify dominant hand, nondominant hand, and bimanual force pyramids during resection of virtual reality brain tumors.

**OBJECTIVE:** To address 4 questions: Do ergonomics and handedness influence force pyramid structure? What are the differences between dominant and nondominant force pyramids? What is the spatial distribution of forces applied in specific tumor quadrants? What differentiates "expert" and "novice" groups regarding their force pyramids?

**METHODS:** Using a simulated aspirator in the dominant hand and a simulated sucker in the nondominant hand, 6 neurosurgeons and 14 residents resected 8 different tumors using the CAE NeuroVR virtual reality neurosurgical simulation platform (CAE Healthcare, Montréal, Québec and the National Research Council Canada, Boucherville, Québec). Position and force data were used to create force pyramids and quantify tumor quadrant force distribution.

**RESULTS:** Force distribution quantification demonstrates the critical role that handedness and ergonomics play on psychomotor performance during simulated brain tumor resections. Neurosurgeons concentrate their dominant hand forces in a defined crescent in the lower right tumor quadrant. Nondominant force pyramids showed a central peak force application in all groups. Bimanual force pyramids outlined the combined impact of each hand. Distinct force pyramid patterns were seen when tumor stiffness, border complexity, and color were altered.

**CONCLUSION:** Force pyramids allow delineation of specific tumor regions requiring greater psychomotor ability to resect. This information can focus and improve resident technical skills training.

**KEY WORDS:** Brain tumor resection, Ergonomics, Force pyramid, Neurosurgical simulation, NeuroTouch/NeuroVR, Surgical technique, Virtual reality

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The innovative force pyramid methodology provides information on the spatial distribution of instrument force application while identifying critical tumor regions requiring advanced bimanual technical skills to resect. Excessive force utilization can lead to normal brain injury, and there are currently no methods providing neurosurgeons with objective measured feedback on force application to specific tumor and brain regions during operative procedures.[1] This new method therefore enhances our ability to assess the cognitive and technical determinants of surgical expertise.

Our group has developed metrics, "maximum force applied" and "sum of forces utilized," to evaluate forces during the resection of simulated tumors using the NeuroVR virtual reality simulation platform (CAE Healthcare, Montréal, Québec and the National Research Council Canada, Boucherville, Québec).[2-14] These metrics have allowed us to explore "expert" (neurosurgeon) and "novice" (senior, junior resident, and medical student) operative behavior.[2-7,10,14] Dominant hand ergonomics

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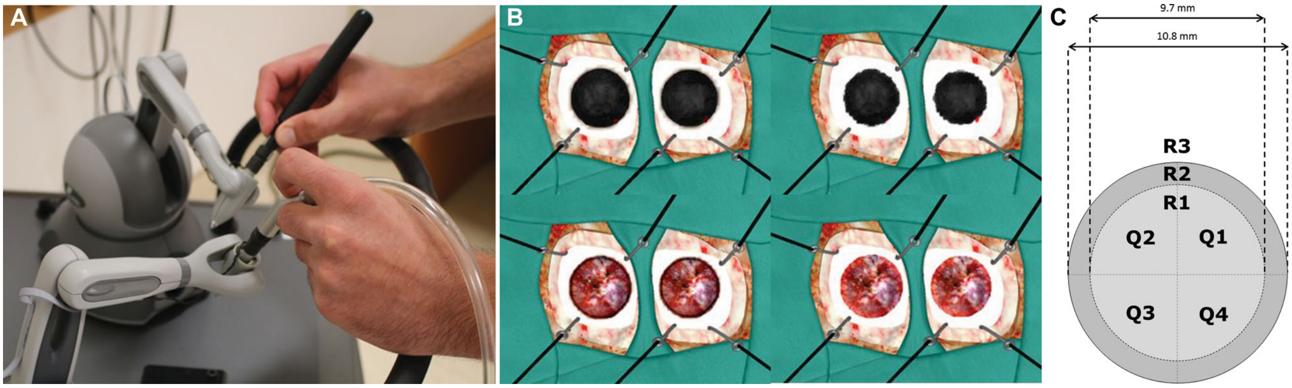


**FIGURE 1.** **A**, *Right-handed operator's hand positions holding a simulated ultrasonic aspirator in the dominant hand and a simulated sucker in the nondominant hand.* **B**, *The 4 scenarios completed by participants. Scenario 1: black, distinct borders, hard and soft. Scenario 2: black, indistinct borders, hard and soft. Scenario 3: glioma-like, distinct border, hard and soft. Scenario 4: glioma-like, indistinct border, hard and soft.* **C**, *Top view of an ellipsoidal tumor outlining the R1, R2, and R3 regions divided into quadrants Q1 to Q4.*

play a role in determining the location and magnitude of force application.[6] However, dexterity varies significantly between dominant and nondominant hands, and fine muscle control of the nondominant hand is a learned skill requiring significant practice.[15,16] In this investigation, the force pyramid concept was employed in a bimanual trial requiring participants to use: a simulated aspirator in the dominant hand for tumor resection and a simulated sucker in the nondominant hand to control bleeding. This allowed the generation of force pyramids for both dominant and nondominant hands, and bimanual force pyramids representing total forces applied by both instruments during the procedure. Central to this idea is awareness of the "surgical fingerprint," an operator-specific force pyramid structures continually modulated by education and experience.

This study was designed to answer 4 questions: (1) Do ergonomics and handedness influence the force pyramid structure? (2) What are the differences between dominant and nondominant hand force pyramids? (3) What is the spatial distribution of forces among tumor quadrants? (4) What differentiates "expert" and "novice" groups regarding their force pyramids?

## METHODS

### Subjects

Six board-certified neurosurgeons and 14 neurosurgery residents (7 juniors, PGY 1-3 and 7 seniors, PGY 4-6) participated. To control for the variable of experience with the NeuroVR (CAE Healthcare and the National Research Council of Canada), one of the entry criteria to our study was prior participation of subjects in a trial involving the neurosurgical simulation platform.[5,6] All signed a consent form approved by the institute's ethics review board before taking part.

### NeuroTouch/NeuroVR Simulator

The previously described NeuroTouch (National Research Council Canada), now known as NeuroVR (CAE Healthcare), virtual reality simulation platform was used in this study.[2-14] The procedures were performed with an aspirator in the dominant hand to resect the tumor and a sucker in the nondominant hand to control bleeding (Figure 1A). Instrument intensities were controlled at constant values.[2]

### Study Design

The goal outlined to participants was to resect each simulated tumor with minimal injury to surrounding "normal" tissue. Four simulated tumor scenarios were presented to each participant, each containing 2 ellipsoidal tumors (tumor A on the left and tumor B on the right), for a total of 8 tumors (Figures 1B and C). To understand the influence of tumor diversity on performance, tumors had unique stiffness (Young's modulus in kilopascal), border complexity, and color characteristics (Figure 1B).[2] Table shows the tumor characteristics and tumor sequences presented to participants.

Resection was carried out in a predefined sequence (Table, left to right). Participants were given a sufficient 3 min to resect each tumor.[2] Scenarios were divided into 3 regions: the exposed tumor surface (R1), the tumor embedded beneath pial surface (R2), and the surrounding "normal" brain tissue (R3).[2,5,6] To assess intratumoral spatial distribution of applied forces, the top view of the tumors was divided into 4 quadrants (Q1-Q4, counterclockwise from the top-right quadrant; Figure 1C).[6]

### Spatial Analysis

The position and force application data associated with each instrument was recorded every 20 ms by the NeuroVR (Figure 2A). The xyz positions (in mm) were rounded to the nearest 0.5 mm value (Figure 2B). Forces associated with the same xyz position were averaged. The force values were then summed along the z-axis (depth of the tumor) to obtain the total forces applied at each xy position of the scenario

**TABLE. Tumor Sequence and Characteristics**

| Scenario | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|
| Tumor | A | B | A | B | A | B | A | B |
| Color | Black | Black | Black | Black | Glioma like | Glioma like | Glioma like | Glioma like |
| Border | Distinct | Distinct | Indistinct | Indistinct | Distinct | Distinct | Indistinct | Indistinct |
| Stiffness | Hard (15 kPa) | Soft (3 kPa) | Hard (15 kPa) | Soft (3 kPa) | Hard (15 kPa) | Soft (3 kPa) | Hard (15 kPa) | Soft (3 kPa) |

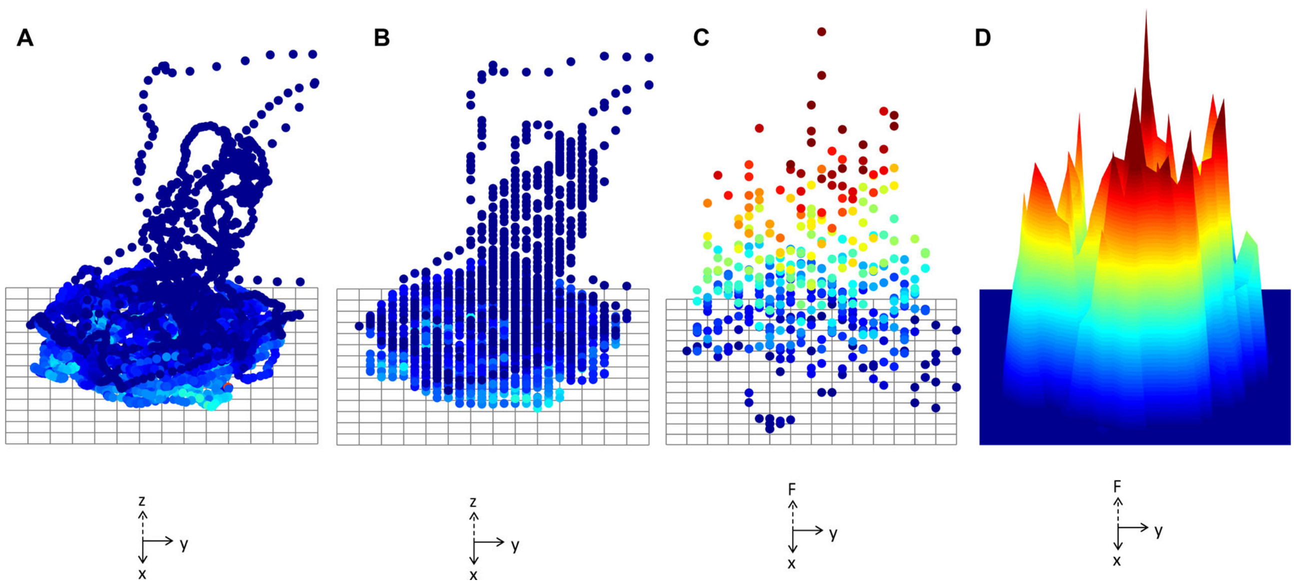


**FIGURE 2.** **A**, *Points represent the 3-dimensional xyz position data of the instrument throughout the procedure, with color corresponding to the magnitude of force applied (0 N in dark blue to 0.2 N in dark red).* **B**, *The 3-dimensional xyz position data is rounded to the nearest 0.5 mm value, placing all the points on a "grid." Force values are averaged where 2 points exist at the same location. Colors correspond to the magnitude of force applied (0 N in dark blue to 0.2 N in dark red).* **C**, *Force values of all points with the same xy coordinates are summed. Points now represent the total force applied (z-axis) at each xy location of the scenario. Colors correspond to the magnitude of force applied (0 N in dark blue to 0.2 N in dark red).* **D**, *A surface is added to the figure seen in C to enhance visualization of the force pyramid structure.*

(tumor and surrounding tissue), as previously described (Figure 2C and D).[6]

A force pyramid was created for each tumor resected, for the dominant and nondominant hand (Figure 2D). The bimanual pyramids were generated by the addition of dominant and nondominant pyramid force values at corresponding xy positions. Average force pyramids for each group and tumor characteristic were obtained by averaging force values at corresponding xy positions. All force pyramids were similarly scaled and colored using a standardized scale ranging from 0 N (dark blue) to 0.2 N (dark red). Figures representing highest forces areas were created by locating forces above 70% of the maximum force applied, as previously described.[6]

## Time and Adjusted-Force Distributions

Two additional pyramid types were created to control for time spent at each tumor position (figures not shown). A time pyramid was created by calculating the number of times each instrument occupied a specific xy position. The adjusted-force pyramid was subsequently generated by dividing the force pyramid by the time pyramid at corresponding xy positions. The figure obtained shows the amount of force applied in newtons per second spent at each location.

## Quadrant Distribution

For all pyramid types, the percentage of force, time, or adjusted force per quadrant was estimated by calculating the sum of force, time, or adjusted force in each quadrant (regions R1 and R2) and dividing by the sum of force, time, or adjusted force in all quadrants (regions R1 and R2).

## Statistical Analyses

All statistical analyses were performed using IBM SPSS Statistics 23 software (IBM Corporation, Armonk, New York). Due to small sample sizes, the distribution data were analyzed using nonparametric tests. The Mann–Whitney *U*-test was used to compare right- and left-handed participants, with *P*-values $<.05$ indicating significance. The

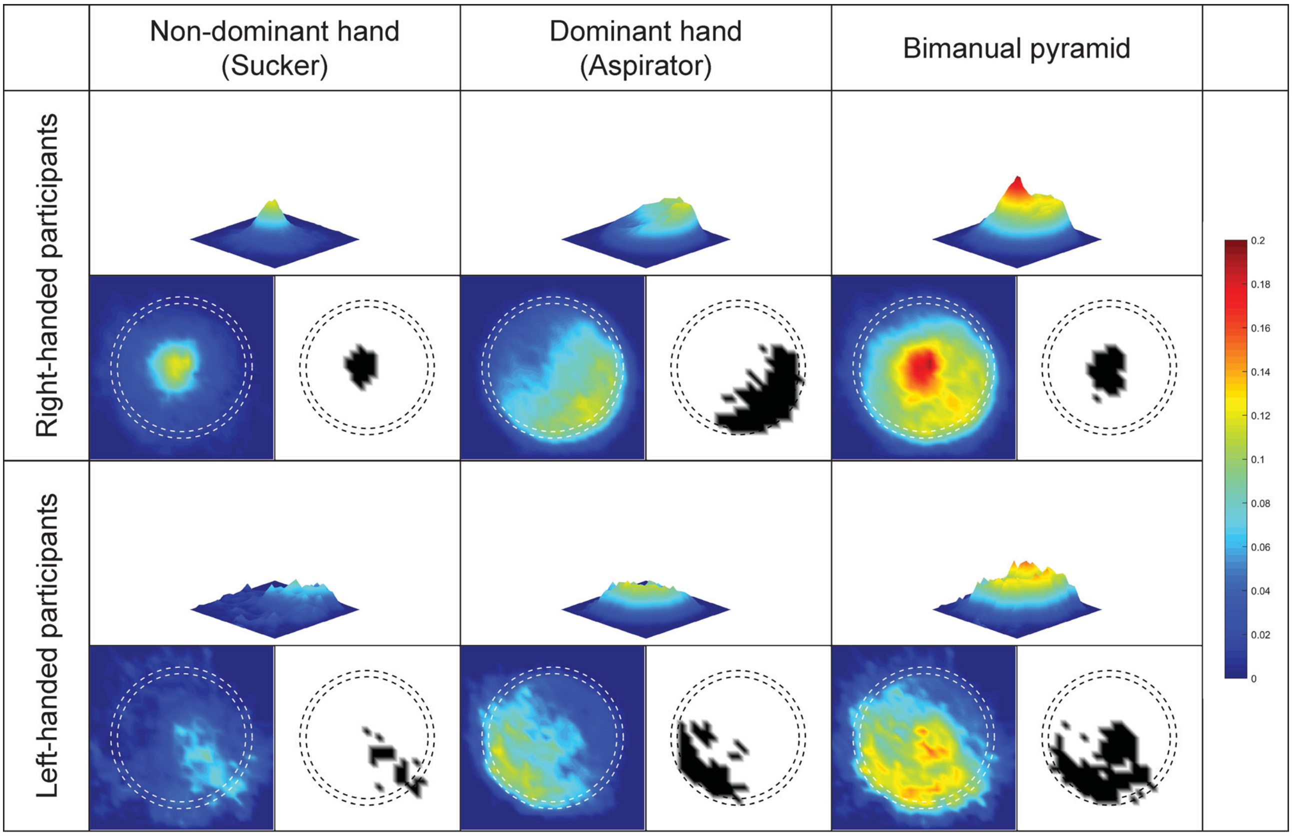


**FIGURE 3.** *Nondominant, dominant, and bimanual force pyramids (3-dimensional and top views) for the all right-handed (n = 17) and left-handed (n = 3) participants. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for all 8 tumors. The highest forces for nondominant force pyramids are located predominantly at the center and in Q4. The dominant force crescent for right-handed participants is in Q4, whereas the left-handed group's corresponding crescent is in Q3. The bimanual force pyramids' highest forces are located at the center for right-handed, and predominately in Q3 for left-handed participants. The color map on the left outlines the colors corresponding to different forces in Newtons.*

Kruskall–Wallis test, followed by Dunn's test for nonparametric pairwise comparison, was used to compare the 4 quadrants of participants, with $P$-values <.05 indicating significance. Error bars show the standard error of the mean (SEM).

## RESULTS

### Demographics

Mean age is 47.3 ± 11.5 for neurosurgeons, 31.1 ± 2.9 for senior residents, and 29.1 ± 1.1 for junior residents. All neurosurgeons and 72.7% of residents were right handed, and 90% were male.

### Right- and Left-Handed Force Pyramids

Force pyramids and their top views, representing the performance of all individuals in each group for all 8 tumors, for right- (n = 18) and left-handed participants (n = 3, 2 junior and 1 senior resident) are provided in Figure 3. Despite the small number of left-handed individuals (n = 3), both our qualitative (Figure 3) and quantitative (Figure 4) results confirm that right-handed operators apply significantly more force in Q4 than in Q2 ($P$ < .001), while left-handed participants apply significantly more force in Q3 than in Q1 ($P$ = .01).[6]

Because there were no left-handed neurosurgeons and only 1 left-handed senior resident in the trail, the results may be skewed. Further studies that include a larger number of left-handed participants are needed to accurately assess hand ergonomics in this group. Due to these issues, left-handed participants were excluded from subsequent analyses.

### Force Pyramids of Right-Handed Participants

Nondominant force pyramids' highest forces are located at the center of the tumor (Figure 5). These forces are not significantly different when neurosurgeon, senior, and junior resident force distributions are compared.

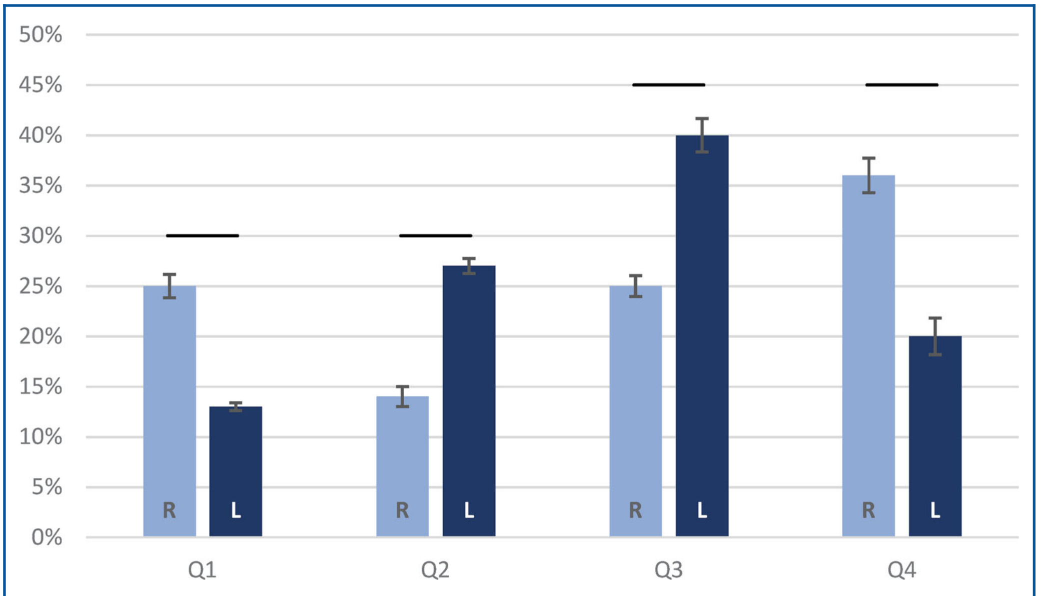


**FIGURE 4.** *Force distribution per quadrant (in percent ± SEM) for right- (labelled "R", n = 17) and left- (labeled "L", n = 3) handed groups. Lines indicate quadrants that are significantly different (P < .05).*

Dominant force pyramids' highest forces are predominantly located in Q3 and Q4 (Figure 5). Neurosurgeons' highest forces are confined within a crescent-shaped area in Q4, at the tumor-normal tissue interface extending into R2, consistent with our previous findings.[6] The crescent extends into Q3 for seniors, while the junior residents' highest forces involve the majority of Q3 and Q4, from R1 extending into R2 and R3.

Bimanual force pyramids are characterized by the presence of the dominant hand crescent, seen in neurosurgeons, and the nondominant central peak, seen in all groups. For residents, the predominant central peak is due to the higher forces applied by the nondominant hand. For neurosurgeons, the multiple force peaks observed are related to the near-equal ratio of the forces applied by both instruments.

## Quadrant Distribution of Force Application

Nondominant, dominant, and bimanual force, time, and adjusted-force distributions are outlined in Figure 6. In all tumor types, no significant group differences are observed for any of the quadrants (nondominant $P = .92$, dominant $P = .88$, bimanual $P = .99$).

The nondominant hand force distribution is only significantly different between tumor quadrants for senior residents (junior $P = .17$, senior $P = .01$, neurosurgeon $P = .10$). The dominant hand force distribution reveals that all groups applied significantly more force in Q4 than Q2 (junior $P = .001$, senior $P < .001$, neurosurgeon $P = .003$). No significant differences were found between Q1 and Q3, in all groups (all $P > .99$). Bimanual pyramid force distribution shows significant differences between Q2 and Q4 for senior residents ($P = .006$) and neurosurgeons ($P = .02$).

The time distribution of the nondominant hand shows significant differences between left- and right- side quadrants (junior Q1-Q3 $P = .048$, Q3-Q4 $P = .02$; senior Q1-Q2 $P = .04$, Q1-Q3 $P = .002$, Q3-Q4 $P = .04$; neurosurgeon Q2-Q4 $P = .03$). The dominant hand time distribution demonstrates significantly increased time spent in Q4 compared to Q2, in all groups (junior $P = .006$, senior $P = .02$, neurosurgeon $P = .03$). Time distribution for bimanual pyramids shows significant differences between Q1 and Q3, only in the resident groups (junior $P = .04$, senior $P = .01$).

Adjusted-force pyramids show the amount of force applied at each position for the same unit of time. The nondominant hand adjusted-force distribution shows no significant difference between quadrants, for all groups (junior $P = .47$, senior $P = .56$, neurosurgeon $P = .28$). The adjusted-force distribution of the dominant hand shows significant difference between Q4 and Q2 for all groups (junior $P = .02$, senior $P < .001$, neurosurgeon $P = .001$), between Q3 and Q2 for senior residents ($P = .02$), and between Q4 and Q1 for neurosurgeons ($P = .02$). The adjusted-force distribution for the bimanual pyramids shows a significant difference between Q2 and Q4 only for senior residents ($P = .003$) and neurosurgeons ($P = .01$).

Both qualitative (Figure 5) and quantitative (Figure 6) results confirm that neurosurgeons focus their highest forces in a narrow crescent area in Q4, at the tumor–normal tissue interface. If operator force distribution is related to the difficulty of resection, this would suggest that Q4 presents the greatest challenge to

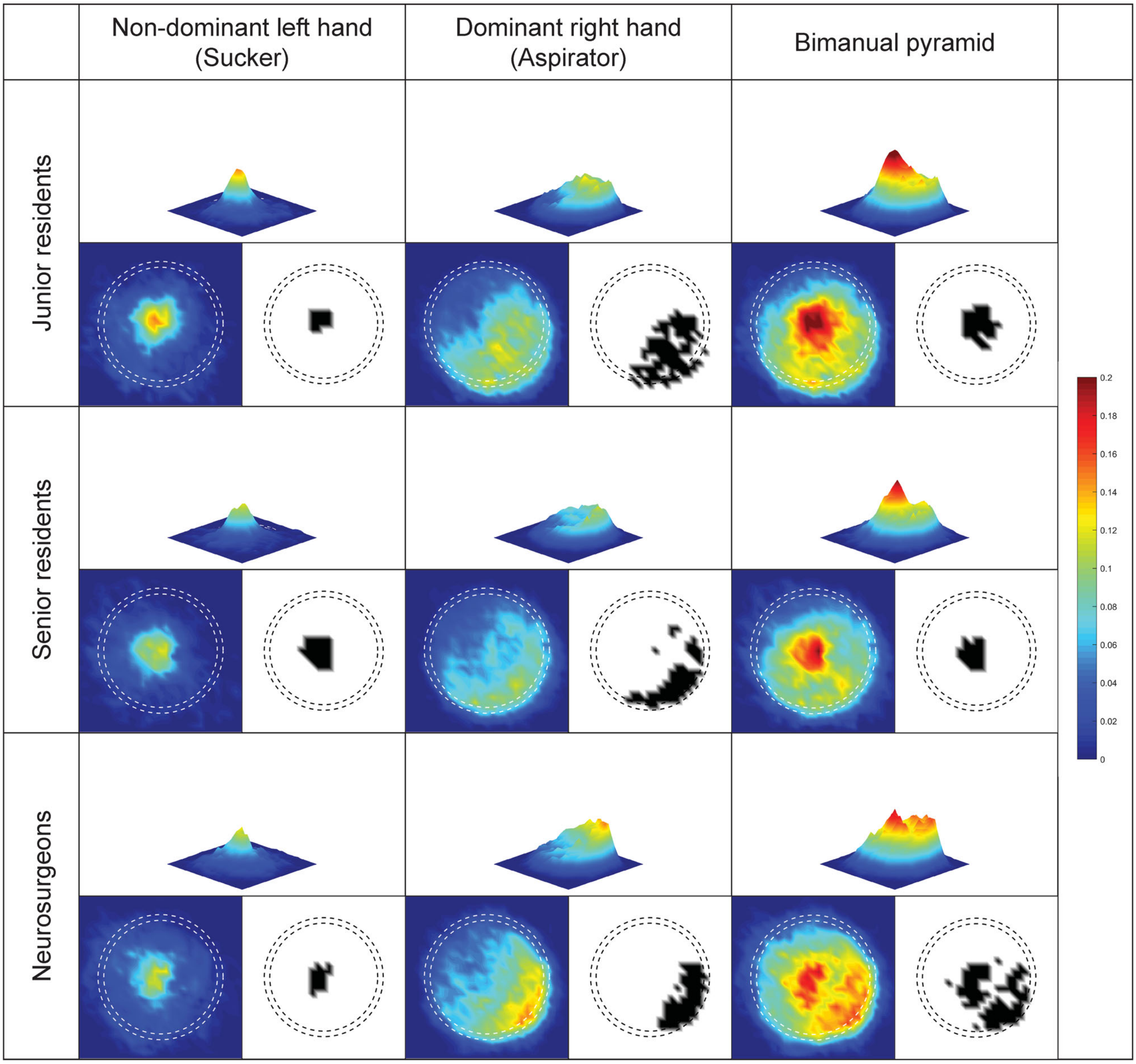


**FIGURE 5.** *Right-handed nondominant, dominant, and bimanual force pyramids (3-dimensional and top views) for junior resident (n = 5), senior resident (n = 6), and neurosurgeon (n = 6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for all 8 tumors. The highest forces for nondominant force pyramids are located predominantly at the center for all groups. The dominant force crescent is located in both Q3 and Q4 crescents for residents, and Q4 for neurosurgeons. The bimanual force pyramids' highest forces are located at the center for residents, and both at the center and in Q4 for neurosurgeons. The color map on the right outlines the colors corresponding to different forces in Newtons.*

right-handed individuals with Q1 and Q3 being intermediate and Q2 being the least difficult.

### Tumor Characteristics

Figure 7 compares the top views for groups resecting tumors with distinct and indistinct borders. Neurosurgeons confined their highest dominant hand forces in Q4, while residents dispersed them broadly. All groups had difficulty at the tumor–normal tissue interface in tumors with indistinct borders, with larger crescent areas in soft tumors for resident groups. Bimanual pyramids of tumors with distinct borders show that residents applied more force with the nondominant

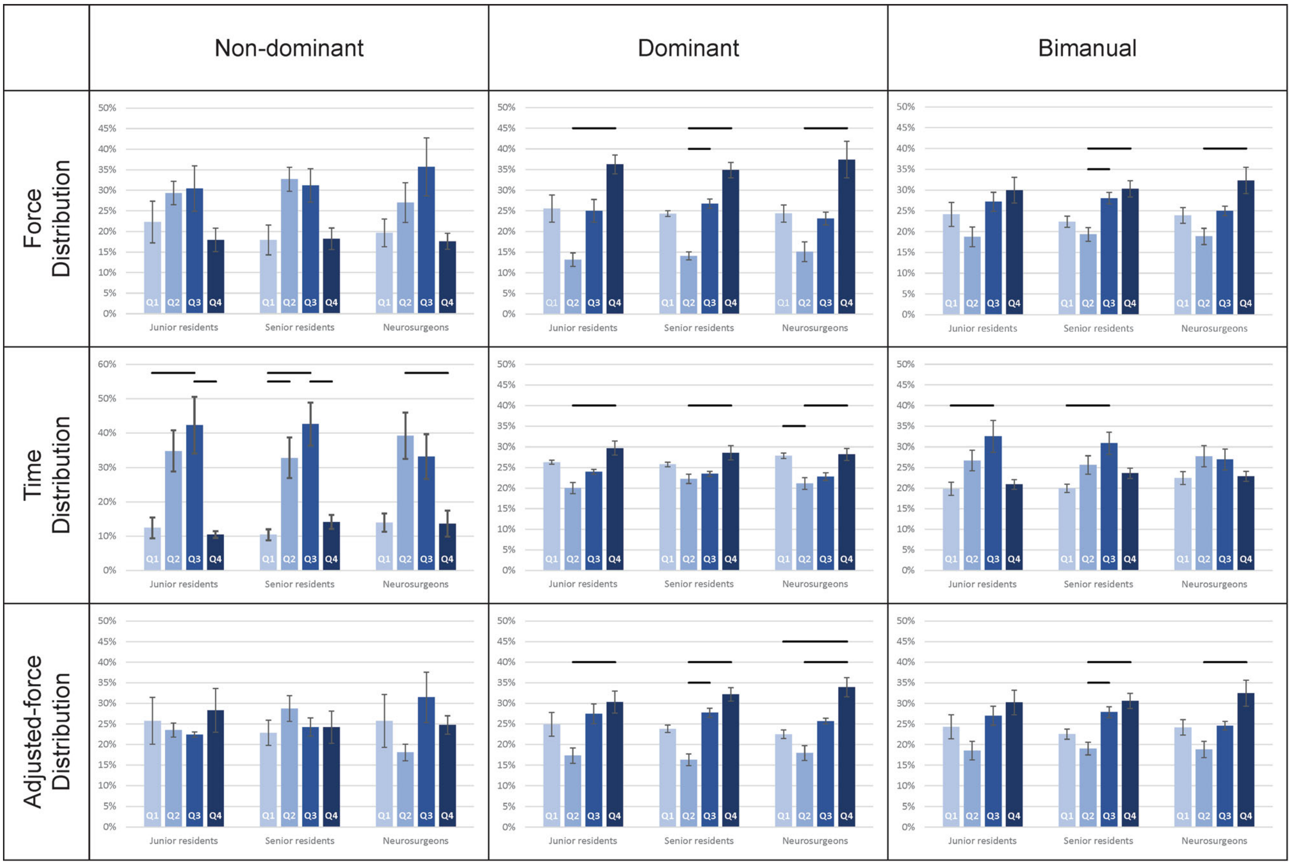


**FIGURE 6.** *Nondominant, dominant, and bimanual force, time, and adjusted-force distributions (in percent ± SEM) per quadrant of right-handed junior residents (n = 5), senior residents (n = 6), and neurosurgeons (n = 6). Lines indicate quadrants that are significantly different (P < .05).*

hand, while neurosurgeons contributed with both hands equally.

The trends observed in Figure 7 were also observed in results from other tumor characteristics outlined in **Figures**, **Supplemental Digital Content 1 and 2**.

## DISCUSSION

### Summary

We have applied novel force pyramid methodology to create and quantify dominant, nondominant, and bimanual pyramids to assess the role of handedness and document differences between neurosurgeon and resident groups.[5,6] The multiple bleeding sources in the present scenario improved realism but necessitated the use of a suction tool in the nondominant hand, allowing the creation of nondominant and bimanual force pyramids. This study is unique in conceptualizing the bimanual force pyramid, derived from the NeuroVR virtual reality platform (CAE Healthcare and National Research Council Canada), to assess and quantify the spatial distribution of all forces applied during simulated tumor resections.

### Ergonomics of Handedness and Force Pyramid Structure

This study confirms previous results that handedness plays a role in the shape and height of force pyramids, and further compares nondominant and bimanual force pyramids of right- and left-handed operators.[6] Although limited by the number of left-handed participants, the quantitative analyses corroborated our qualitative observations, demonstrating significant differences in force distribution between the dominant force pyramids of right- and left-handed participants.[6] The ergonomic factor of operator hand position during tumor resection is hypothesized to be responsible for these findings.[6] Right-handed and ambidextrous participants need to continually fine-tune their dominant hand position holding the aspirator, first flexing their wrist to remove Q3 located tumor, and then internally rotating and further flexing the wrist to resect the lesion at the Q4 tumor–normal tissue interface in region R2 as seen in **Video**, **Supplemental Digital Content 3**. Left-handed and ambidextrous

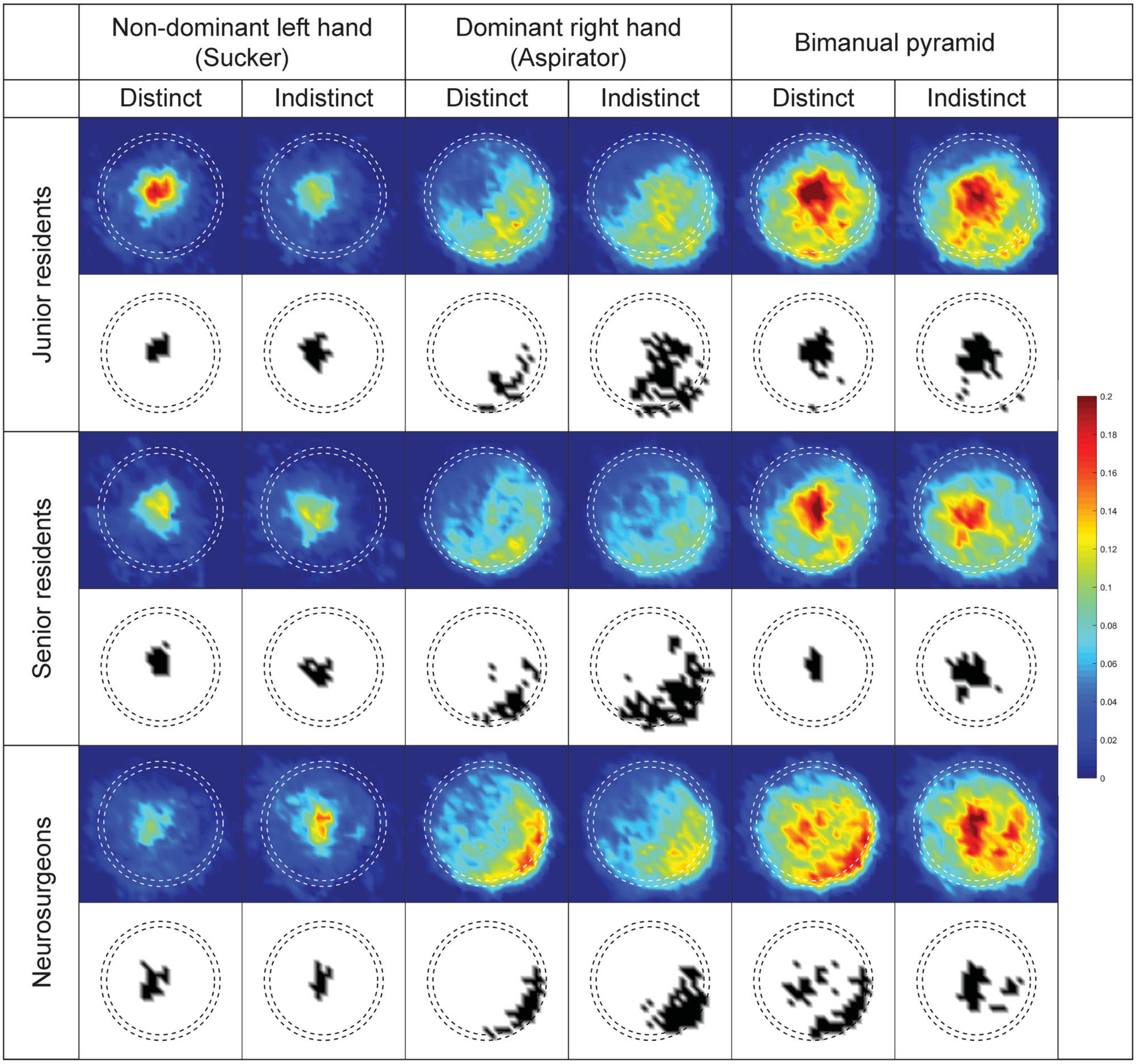


**FIGURE 7.** *Right-handed nondominant, dominant, and bimanual force pyramids (3-dimensional and top views) for junior resident (n = 5), senior resident (n = 6), and neurosurgeon (n = 6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for 4 distinct and 4 indistinct tumors. The highest forces for nondominant force pyramids are located at the center for all groups. The dominant forces for tumors with distinct borders are distributed in a crescent going from Q3 to Q4 for residents, but distributed more widely for tumors with indistinct borders. For both tumor types, neurosurgeons confine these forces to a crescent in Q4. The bimanual force pyramids' highest forces are located at the center for all groups, with the exception of a Q4 crescent for the distinct tumors in the neurosurgeon group. The color map on the right outlines the colors corresponding to different forces in Newtons.*

individuals first begin wrist flexion to remove Q4 tumor and then rotate and further flex their wrist to complete tumor resection in Q3 (**Video**, **Supplemental Digital Content 4**). These ergonomically constrained hand positions may result in inability of the operating hand to receive appropriate sensory feedback to modulate force application at Q4 for right-handed and at Q3 for left-handed operators.[6] To test this hypothesis, we are now investigating the relation between hand ergonomics and instrument force by comparing aspirator spatial orientation and dominant forearm muscle electromyography.

Nondominant pyramids are characterized by a central force peak, consistent with sucker use to control the accumulation of blood at the lowest point (center) of the tumor. Bleeding compromises tumor visibility resulting in repositioning of the sucker at the center and increased force application due to inability to evaluate tumor depth.[7] The novel bimanual force pyramid combines the central peak generated by the nondominant hand and the force crescent generated by the dominant hand, allowing assessment of the spatial distribution of all forces applied by an operator during resection.

These pyramids also provide critical information on specific regions at an increased risk of damage during resection. Studies are under way to analyze the correlation between force application and adjacent normal tissue damage. Surgical educators should be aware that resident handedness and ergonomics may place certain regions at an increased risk of damage.

### Quadrant Force Distribution and Ergonomics

All groups applied significantly less force with their dominant hand in Q2 compared to Q4 when carrying out a simulated brain tumor resection on the NeuroVR. Resection of Q1 and Q3 requires forces midway between those employed to remove tumor in Q2 and Q4. If dominant-hand force distribution relates to ease of resection, results would indicate that right-hand ergonomics differentially affect resection of quadrants Q2 and Q4. Q2 requires minimal wrist flexion and rotation, Q1 and Q3 slightly more, and Q4 requires maximal flexion and internal rotation.

Studies on laparoscopic surgery have demonstrated that hand positions needed to accomplish procedures may involve excessive wrist flexion and increased carpal tunnel pressure, which affect nerve conduction and associated motor and sensory function, resulting in fatigue and decreased surgical performance.[17-21] Other approaches to evaluate ergonomics of dominant and nondominant hands are needed to establish a testable model that optimizes safe tumor resection. Measures of instrument orientation, forearm muscle electromyography, or the utilization of a glove that determines hand and finger position can be explored to increase our understanding of ergonomics.

### Time and Adjusted-Force Pyramids

The significantly greater percentage of time spent in Q2 and Q3 is due to right-handed individuals holding the sucker with their nondominant hand on the left side of the tumor. Since no significant differences are seen in the time-adjusted-force distribution of the nondominant hand, this implies that the average force applied by the sucker is constant throughout the procedure.

The dominant hand time distribution outlines that participants spent a relatively equal amount of time in Q1, Q2, and Q3 but significantly more time Q4. However, the dominant hand adjusted-force distribution shows significant differences between Q4 and Q2 for all groups. This further corroborates our hypothesis suggesting that Q4 is the most technically complex to resect, while Q2 is the least difficult.

The bimanual distribution shows the greater contribution of the nondominant hand to the total forces employed by residents, while neurosurgeons' dominant and nondominant hands are equally responsible for the total forces applied. This would suggest that "experts" have learned to distribute forces uniformly between their two hands when using multiple instruments, a behavior enhanced by experience gained after residency.

### Strengths and Limitations

Our results are consistent with the concept of the "surgical fingerprint," that operators evolve unique dominant, nondominant, and bimanual force pyramid structures continually modulated by education, repetition, and experience. The force pyramid approach to virtual reality tumor resection allows the delineation of specific tumor regions that may require greater psychomotor skills to remove; this information can help focus and improve technical skills training of residents thereby improving patient outcomes. Other surgical specialties may also find force pyramid analysis useful in resident training using NeuroVR.[11-13,22,23]

Limitations associated with virtual reality studies must be considered when interpreting results. Although the addition of bleeding improved realism, the specific tumor scenarios and short task duration may not allow us to differentiate groups. A scenario involving resection of an irregular and complex tumor is being studied to address this issue. We have also begun to assess the role of tools other than the aspirator and the sucker such as surgical patties and the bipolar coagulator, to understand their role in force application during tumor removal. Our small sample size and the fact that all participants were from a single institution may also limit the applicability of our results to other groups. Our ongoing studies include a larger number of participants from multiple institutions.

The NeuroVR simulation platforms allow the analysis of both the surgical process and the resulting product. The recorded data on hand movements, forces applied, etc., can be used to provide users with accurate and objective feedback on their technical skills and overall performance, and to assess their development with accumulated experience. Our research focuses on hand ergonomics, and aims to increase our understanding of the way "experts" use their hand ergonomics to efficiently resect virtual reality tumors. This understanding will allow the development of a testable "virtual reality tumor resection performance" model that would provide a framework to answer more complex questions in the context of neurosurgical simulation and make predictions of outcomes in the operating room. Research on hybrid simulations such as the placental tumor model and other animal models are ongoing to assess skills transfer to the operating room and the concurrent or predictive validity of the NeuroVR.[24,25]

## CONCLUSION

The innovative force pyramid approach to virtual reality tumor resection provides spatial distribution and quantification of instrument force application while identifying critical tumor regions requiring advanced bimanual technical skills to resect, thereby enhancing our ability to assess the cognitive and technical determinants of surgical expertise.

## 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 H Azarnoush held the Postdoctoral Neuro-Oncology Fellowship from the Montreal Neurological Institute and Hospital. Robin Sawaya holds the Christian Geada Brain Tumor Research Studentship from the Montreal Neurological Institute. Dr Del Maestro is the William Feindel Emeritus Professor in Neuro-Oncology at McGill University. 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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# COMMENTS

The authors wrote an interesting paper that provides the neurosurgical community with an innovative tool to assess and train young neurosurgeons. It is not clear - and easy to determine - whether these parameters, measurements, and simulation approaches in general will impact on real surgical performance. We hope that this method will pave the way to broader international studies aiming at assessing how simulation can change neurosurgery residents' learning curves and performance in the operating room.

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I think the main question is whether or not this method of analysis, utilizing VR and bio-sensors can give us insights that are complementary to the more traditional methods of evaluations (ie sewing bovin spinal dura then test for cerebrospinal fluid leak, dissecting and sewing rat femoral arteries). The subtleties of surgeries, ie how hard and where to hold an instrument, the percentage of time wasted on unnecessarily switching instruments, and how often the instrument/hands compromise the line of vision, cannot always be easily taught or measured. Needless to say, the VR system used in this study does not simulate reality, but I think it is a reasonable first step and has potential.

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