Tremor Assessment during Virtual Reality Brain Tumor Resection

Samaneh Siyar, MSc,*,† Hamed Azarnoush, PhD,*,† Saeid Rashidi, PhD,‡ and Rolando F. Del Maestro, MD, PhD†

*Department of Biomedical Engineering, Amirkabir University of Technology (Tehran Polytechnic), Tehran, Iran; †Neurosurgical Simulation and Artificial Intelligence Learning Centre, Department of Neurosurgery, Montreal Neurological Institute and Hospital, McGill University, Montreal, Canada; and ‡Science and Research Branch, Islamic Azad University, Tehran, Iran

OBJECTIVE: Assessment of physiological tremor during neurosurgical procedures may provide further insights into the composites of surgical expertise. Virtual reality platforms may provide a mechanism for the quantitative assessment of physiological tremor. In this study, a virtual reality simulator providing haptic feedback was used to study physiological tremor in a simulated tumor resection task with participants from a "skilled" group and a "novice" group.

DESIGN: The task involved using a virtual ultrasonic aspirator to remove a series of virtual brain tumors with different visual and tactile characteristics without causing injury to surrounding tissue. Power spectral density analysis was employed to quantitate hand tremor during tumor resection. Statistical *t* test was used to determine tremor differences between the skilled and novice groups obtained from the instrument tip *x, y, z* coordinates, the instrument roll, pitch, yaw angles, and the instrument haptic force applied during tumor resection.

SETTING: The study was conducted at the Neurosurgical Simulation and Artificial Intelligence Learning Centre, Montreal Neurological Institute and Hospital, McGill University, Montreal, Canada.

PARTICIPANTS: The skilled group comprised 23 neurosurgeons and senior residents and the novice group comprised 92 junior residents and medical students.

RESULTS: The spectral analysis allowed quantitation of physiological tremor during virtual reality tumor resection. The skilled group displayed smaller physiological tremor than the novice group in all cases. In 3 out of 7 cases the difference was statistically significant.

CONCLUSIONS: The first investigation of the application of a virtual reality platform is presented for the quantitation of physiological tremor during a virtual reality tumor resection task. The goal of introducing such methodology to assess tremor is to highlight its potential educational application in neurosurgical resident training and in helping to further define the psychomotor skill set of surgeons. (J Surg Ed 77:643−651. © 2019 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: physiological tremor, neurosurgery, NeuroTouch/NeuroVR, simulation, virtual reality, tumor resection

COMPETENCIES: Patient Care, Practice-Based Learning and Improvement, Systems-Based Practice

INTRODUCTION

Tremor is an unintentional, rhythmic muscle movement involving oscillations (to-and-fro movements) of one or more parts of the body and is most common in the hands.[1] All individuals have physiological tremor which can be influenced by different conditions including anxiety, stress, medications, and alcohol.[2] Therefore, this type of tremor has the potential to affect psychomotor performance during neurosurgical procedures. Assessment of physiological hand tremor during neurosurgical procedures may provide further insights into the armamentarium of the expert surgeon. Since conventional surgical setup and tools do not allow one to make such assessment, virtual reality (VR) simulators could be used as a preliminary platform.

Funding: 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. Samaneh Siyar is a Visiting Scholar in the Neurosurgical Simulation Research and Training Centre. Dr. H. Azarnoush previously held the Postdoctoral Neuro-Oncology Fellowship from the Montreal Neurological Institute and Hospital and is a Visiting Professor in the Neurosurgical Simulation and Artificial Intelligence Learning Centre. Dr. Del Maestro is the William Feindel Emeritus Professor in Neuro-Oncology at McGill University.

Correspondence: Inquiries to Hamed Azarnoush, PhD, Neurosurgical Simulation Research and Training Centre, Department of Neurology & Neurosurgery, Montreal Neurological Institute and Hospital, McGill University3801 University Street, Room E2.89, Montreal, Quebec, Canada, H3A 2B4; e-mail: hamed.azarnoush@mail.mcgill.ca

 1931-7204/$30.00 https://doi.org/10.1016/j.jsurg.2019.11.011

Tremor assessment has been carried out using multiple signal processing methods based on time domain analysis, time-frequency analysis, and frequency analysis.[3-7] Methods based on frequency analysis have been utilized in the majority of such studies.[3,5] VR simulators such as the NeuroTouch (now known as NeuroVR, CAE Healthcare, Montreal, Canada) platform have created opportunities to augment our understanding of the multiple psychomotor skills involved in neurosurgical expertise.[8-18]

The goal of this study was to use a VR simulator for the first time as a tool to assess tremor during tumor resection tasks and analyzing the results obtained from a "skilled" group of neurosurgeons and senior residents, and a "novice" group of junior residents and medical students. We investigated whether the skilled participants would display decreased physiological tremor in comparison with less skilled novice participants during VR tumor resection tasks. The tremor was measured from signals corresponding to instrument tip *x, y, z* coordinates, the instrument roll, pitch, yaw angles, and the instrument haptic force applied during tumor resection.

METHODS

Study Population

A total of 115 subjects participated in the study, including 16 board certified and practicing neurosurgeons, from 3 institutions, and 7 senior residents postgraduate year (PGY 4-6) who comprised the skilled group (total of 23 subjects) along with 8 junior residents (PGY 1-3) and 84 medical students from McGill University who comprised the less skilled novice group (total of 92 subjects). Participants had no previous experience with the NeuroTouch simulation platform. No financial or other compensation was offered for participation in the study and all participants signed an approved McGill University Health Centre consent form.

NeuroTouch

Tumor resections were performed using NeuroTouch platform with haptic feedback utilizing the simulated ultrasonic aspirator held in the dominant hand as shown in Figure 1(A).[12,16] The NeuroTouch VR simulator provided an adjustable armrest to stabilize hand position during the procedure. The bar was adjusted to maintain a 90° angle at elbow for all participants.

Simulation Scenarios

Participants were unaware of the study purpose and were instructed to resect each tumor with minimal removal of background tissue. Each of the 6 scenarios utilized in this study included 3 ellipsoidal tumors with either varying tactile or varying visual properties as shown in Figure 1(B). Young's modulus stiffness values of 3 kPa, 9 kPa, and 15 kPa were used for "soft,"

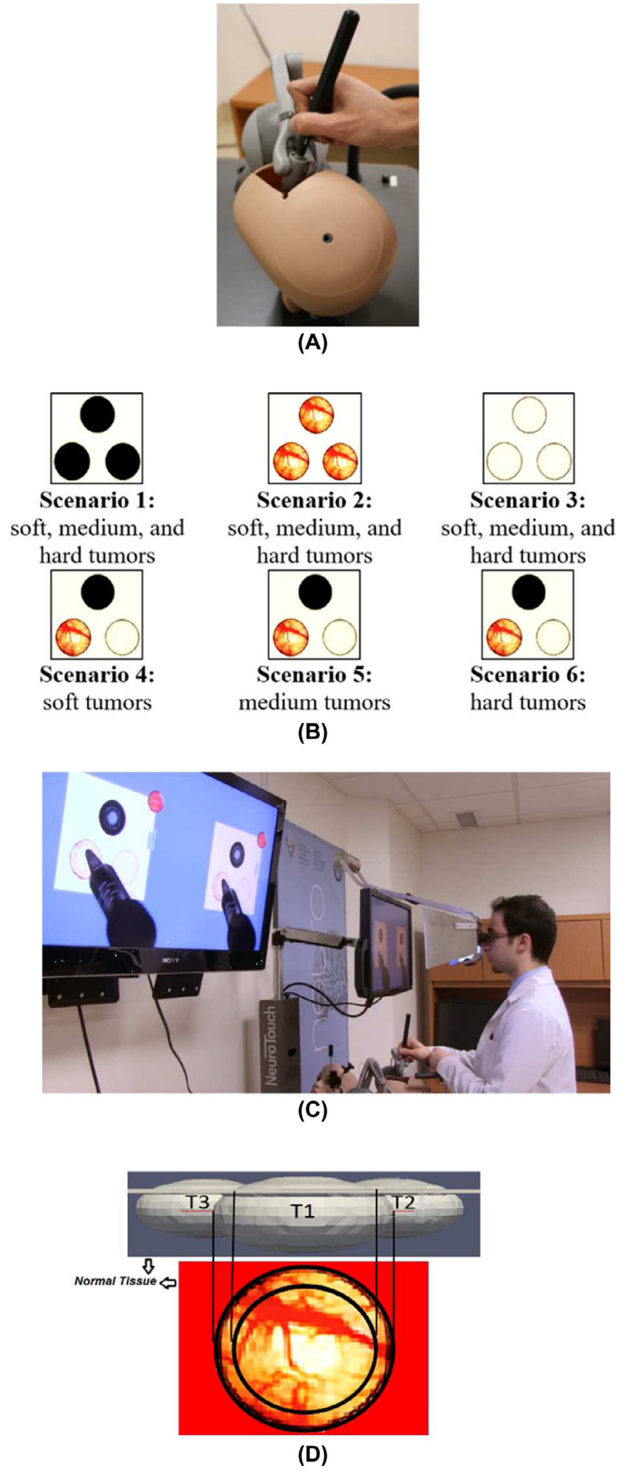

FIGURE 1. (A) The hand position of the operator holding the simulated ultrasonic aspirator, (B) The 6 simulated tumor scenarios with tumor color and sequence, and (C) Lateral view of the brain tumor geometry and ellipsoidal shape utilized in each scenario with part of the tumor buried underneath simulated "normal" tissue.

"medium," and "hard" tumors. Visually, tumors were simulated with black, glioma-like appearance, or white color. The background tissue, surrounding the tumor was white with the same Young's modulus as soft tumors (3 kPa). The black tumor scenario simulated malignant melanoma and was chosen to provide maximal color differential against the white "normal" tissue background, while the white tumor was chosen to provide minimal color differential. The glioma-like tumor provided an appearance similar to a glioma.[12] The glioma-like tumor was included in the study to also have a tumor with vascularized structure, different from the solid black and white appearance of the other 2 types of tumors. Young's modulus stiffness values of 3 kPa, 9 kPa, and 15 kPa were used for "soft," "medium," and "hard" tumors. Young's modulus values between 3 kPa and 15 kPa were chosen based on measured mechanical properties of multiple samples from 7 human brain tumors immediately after removal at operation.[16]

The simulated operative procedure utilized for these studies can be viewed in a previous publication.[12] To develop procedure familiarity operators resected a practice scenario but this data was not used. Three minutes were allowed for each tumor removal with a 1-minute rest time given between tumor resections to decrease fatigue. The trial involved 54 minutes of active tumor resection, 71 minutes in total. Figure 1(C) shows how a typical scenario is viewed by the subject. The 2 images on the auxiliary display are merged to provide a 3D view. Figure 1(D) provides a lateral view of the 3 tumors to visualize the 3D geometry of the tumors.

Applied Signals for Tremor Assessment

The NeuroTouch platform provides the capability to record various signals from the simulated ultrasonic aspirator during a tumor resection including instrument tip coordinates, i.e., x, y, and z, instrument orientation, i.e., roll, pitch, and yaw, and the simulated contact force between the virtual aspirator and the virtual tissues versus time.

Tremor Assessment Methods

Tremor in this study was considered as any involuntary, approximately rhythmic, and roughly sinusoidal movement of the simulated aspirator.[19] Therefore, signal processing methods based on time domain analysis, time-frequency analysis, and frequency analysis can be utilized for tremor assessment with frequency analysis being the most commonly employed.[3-7] Frequency analysis can be performed to specify the predominant tremor frequency by computing the power spectral density of the signal. This method has been previously used for tremor detection and to diagnose different disorders such as Parkinson's disease.[2,19-21] Physiological hand tremor lies in the band of 8 to 12 Hz, whereas voluntary movement would appear at lower frequencies.[7,22-24] Therefore, all our assessments have been performed within the 8 to 12 Hz bandwidth to capture the physiological hand tremor signal during the tumor resections studied. Since surgical instrument movements can either be translational or rotational, we have analyzed linear as well as angular acceleration signals to measure linear and rotational tremor, respectively.[20] In addition, analysis of force data enabled the investigation of the intraoperative effect of tremor on instrument manipulation during the procedures.[23]

The oscillation was considered as the sum of sinusoidal motions, each of which was specified independently by a frequency and an amplitude.[25] Welch's power spectral density estimate was used to assess tremor.[26] Welch method is performed by splitting the original signal into successive sequences, and averaging squared magnitude Discrete Fourier Transform of the signal sequences. Assuming that $\boldsymbol{x_m}$ is the $\boldsymbol{m}$-th sequence of the signal x, and $\boldsymbol{k}$ is the sequence number, then the Power spectral density (PSD) estimate, $\widehat{\boldsymbol{R}}_{\boldsymbol{x}}(\boldsymbol{k})$ is given by:[27]

$$\widehat{\boldsymbol{R}}_{\boldsymbol{x}}(\boldsymbol{k}) = \frac{1}{\boldsymbol{M}} \sum_{\boldsymbol{m}=0}^{\boldsymbol{M}-1} \left| \boldsymbol{DFT}_{\boldsymbol{k}}(\boldsymbol{x_m}) \right|^2$$

The amplitude of physiological hand tremor is defined as the amplitude of power spectral density in the 8 to 12 range which means larger power corresponds to higher tremor.[28] Therefore, we computed amplitude of PSD in 8 to 12 Hz band for the signal of interest.

Statistical Analysis of Group Tremors

The means of tremor amplitude for the skilled and novice group were obtained from the power spectral density method and were compared using 2-tailed t test ($\alpha = 0.05$) for each tumor type. The differences were considered significant for p values smaller than 0.05. Mean scores and standard error of mean for the skilled and the novice groups were used for comparison.

RESULTS

The results are provided for the skilled and novice groups during the resection of the 3 tactile subgroups, hard (H), medium (M), and soft (S) tumors along with the 3 visual subgroups, black (B), glioma-like (G), and white (W) tumors.

Figure 2(A) presents an example comparison of trajectories for tumor removal by an expert and a novice. The tool tip trajectory starts from a START button in the upper left side. The trajectory passes through the

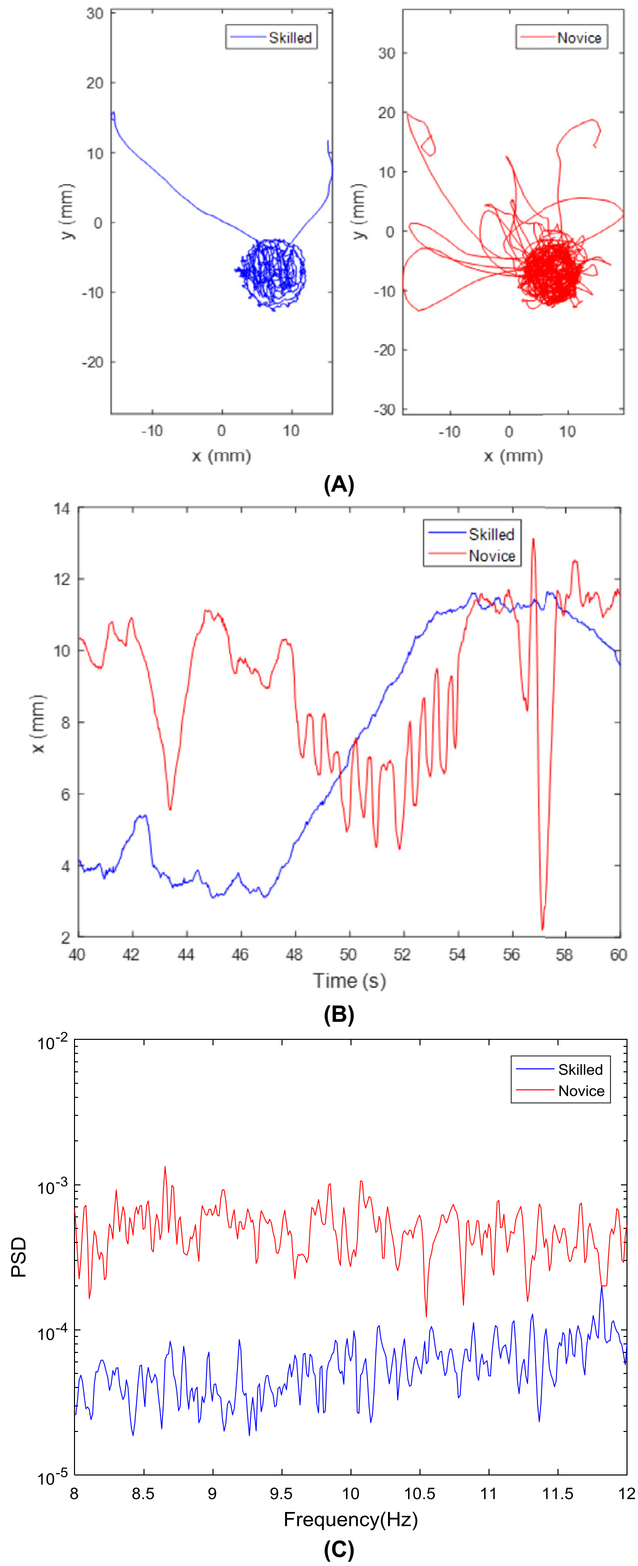

FIGURE 2. (A) Example of skilled and novice tool tip trajectories with oscillations evident in the novice trajectory, (B) Tool tip *x* coordinate of the skilled and novice trajectories for a magnified 40 to 60 second range with oscillations evident for the novice, and (C) Power spectral densities (PSD) of acceleration in the direction of the *x* axis for the skilled and novice participants in the 8 to 12 Hz bandwidth with PSD levels higher for the novice.

circular tumor region and ends at a STOP button in the upper right side. Considering the dense segment of the trajectory corresponding to motions of the tool tip in the tumor regions, it is difficult to compare tremor in this figure, while oscillations are evident in the novice tool maneuvers.

Figure 2(B) presents a magnified sample time interval of the *x* coordinate for these trajectories between 40 seconds and 60 seconds for both operators resecting the same tumor. As this figure shows there are more high frequency fluctuations in the signal obtained from novice in comparison to the one obtained from the skilled participant. These high frequency components can be quantified using PSD.

Figure 2(C) presents the PSD obtained from the skilled and novice participants demonstrating the differences seen in the 8 to 12 Hz range consistent with smaller physiological tremor in the skilled individual while operating. Sum of PSD in this frequency range could be considered as a measure of tremor, used in the subsequent analysis.

Group Analysis

Figure 3(A-C) demonstrates the spectral analysis of translational tremor in the *x, y*, and *z* directions for the 2 groups in each of the 6 tumor subgroups. Each subgroup, e.g., soft tumors, was analyzed across all scenarios. For example, for soft tumors we incorporated the results from all soft tumors, i.e., 6 soft tumors, including 1 tumor from each of the Scenarios 1, 2, 3, and 3 tumors from Scenario 4. The intensity level of tremor in the skilled group was less than that seen in the novice group for all coordinates but the differences were not statistically significant.

Figure 4(A-C) outlines the rotational tremor, in the roll, pitch, and yaw directions which show less tremor for the skilled group in comparison to the novice group. These differences were statistically significant for the roll and pitch directions. Table 1 and Table 2 provide statistical results for these directions.

Figure 5 demonstrates the results for the force signal analyzed for the 6 tumor subgroups. As Table 3 presents, the sum of power spectral density for force was significantly lower for the skilled group for all tumor subtypes studied.

DISCUSSION

The aim of this study is to introduce VR simulators as potential tools to assess tremor in neurosurgery.

Physiological tremor has not previously been used to differentiate skilled and novice groups performing VR tumor resection. The scenarios utilized in this study involved aspirator skills used in human tumor resections which are part of the surgical skill set of neurosurgeons

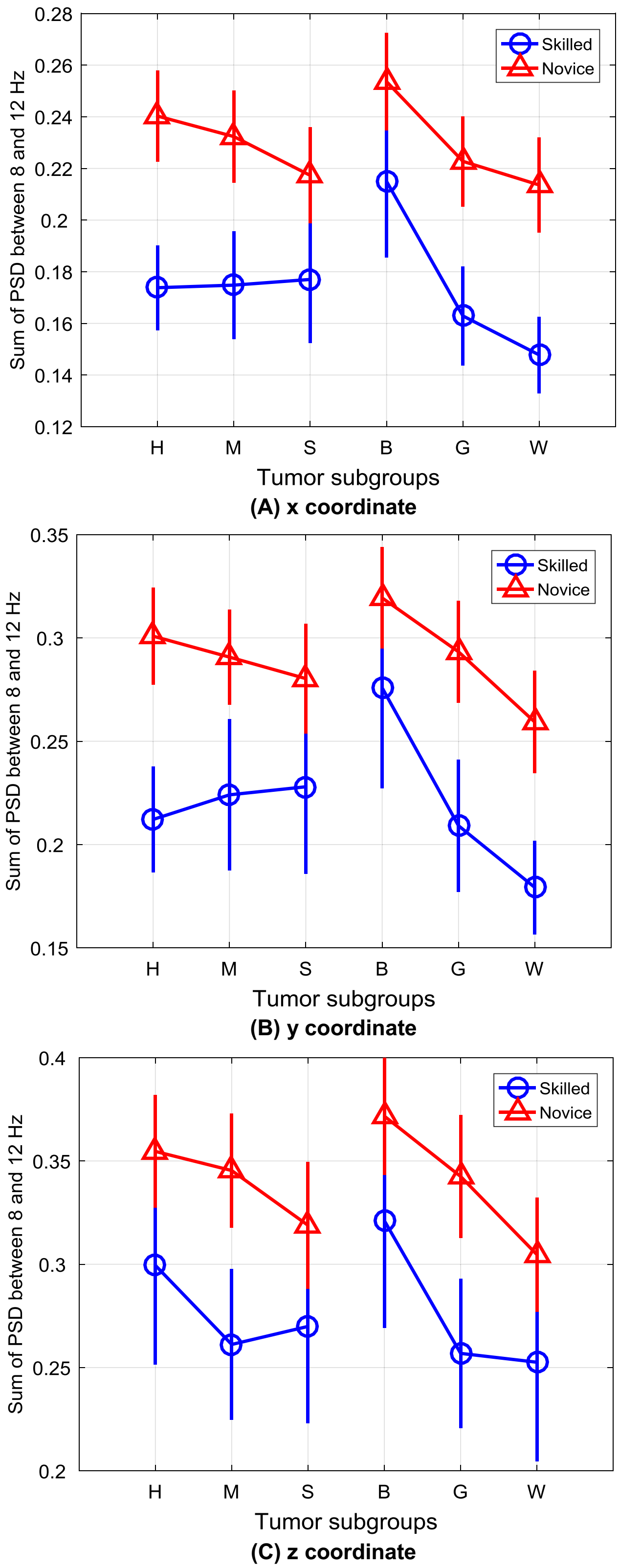

FIGURE 3. Sum of power spectral density (PSD) estimation of means ± SEM of linear acceleration for skilled ($n = 23$) and novice ($n = 92$) groups during the removal of 6 simulated tumor subgroups, obtained from (A) *x*, (B) *y*, and (C) *z* coordinates. SEM, standard error of mean.

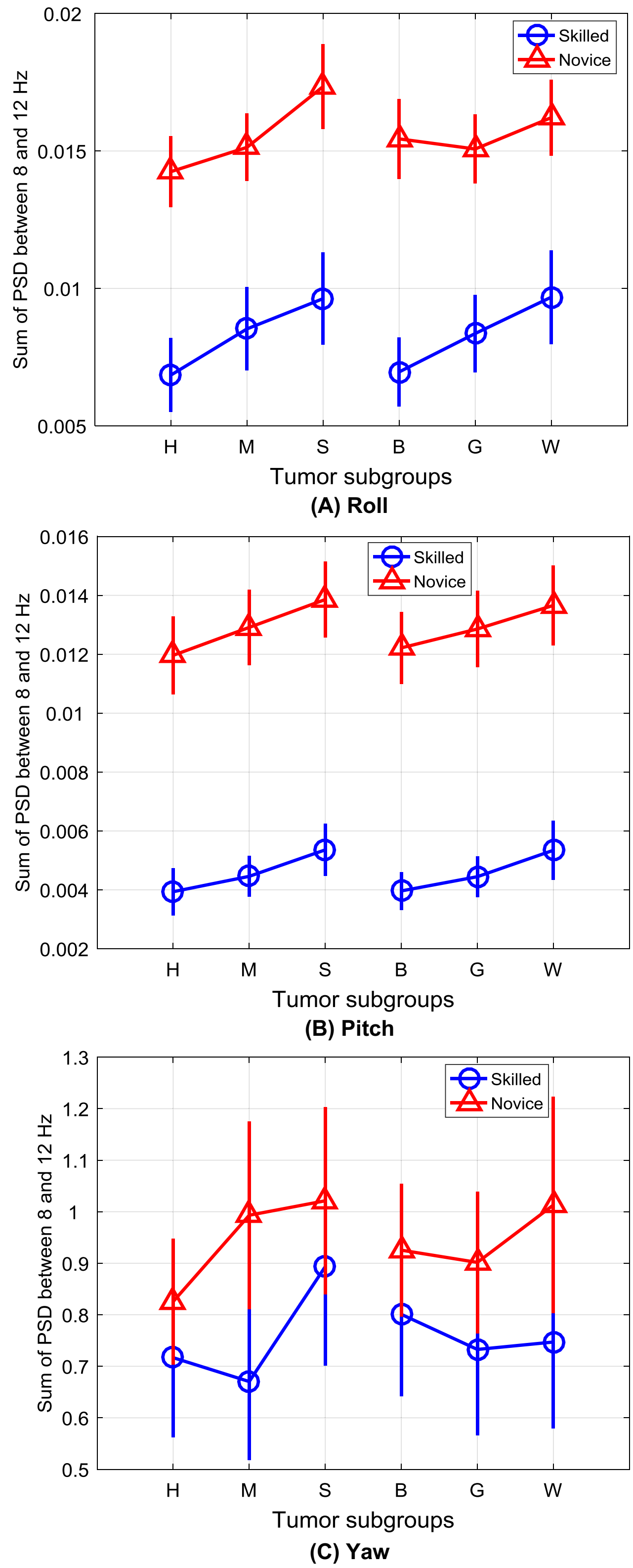

FIGURE 4. Sum of power spectral density (PSD) estimation of means ± SEM of angular acceleration for skilled ($n = 23$) and novice ($n = 92$) groups during the removal of 6 simulated tumor subgroups, obtained from (A) roll, (B) pitch, and (C) yaw signals. SEM, standard error of mean.

TABLE 1. *t* Test Results Based on the PSD Approach Applied to Roll Signal for 6 Simulated Tumor Subgroups: Hard Tumors, Medium Tumors, Soft Tumors, Black Tumors, Glioma Tumors, and White Tumors

Tumor Subgroup	Group	Mean ± SEM	p Value
Hard	Skilled (*n* = 23)	0.00068 ± 0.00129	0.005
	Novice (*n* = 92)	0.01425 ± 0.00124	
Medium	Skilled (*n* = 23)	0.00853 ± 0.00146	0.01
	Novice (*n* = 92)	0.01513 ± 0.00117	
Soft	Skilled (*n* = 23)	0.00963 ± 0.00162	0.01
	Novice (*n* = 92)	0.01735 ± 0.00148	
Black	Skilled (*n* = 23)	0.00696 ± 0.00120	0.004
	Novice (*n* = 92)	0.01544 ± 0.00139	
Glioma	Skilled (*n* = 23)	0.00836 ± 0.00135	0.01
	Novice (*n* = 92)	0.01507 ± 0.00120	
White	Skilled (*n* = 23)	0.00968 ± 0.00165	0.02
	Novice (*n* = 92)	0.01622 ± 0.00132	

SEM, standard error of mean.

and senior residents, but not yet acquired by all junior residents and medical students. We defined a skilled and a novice (less skilled) group based on the required technical skill set needed for the specific scenarios assessed.[3,29]

As shown in the results, the skilled group showed less tremor than the novice group in all cases. The difference between the PSD sums was statistically significant in 3 out of 7 signals. It is important to mention that the current study is more of an exploratory rather than a confirmatory study. From an expert performance viewpoint, we do not yet know whether experts have less tremor during surgery, and if they do is it less in all *x, y, z*, roll, pitch, yaw, and force signals or only for some of them. This study explored the tremor difference in these signals under the conditions of the simulated scenarios. Whether we could confirm the hypothesis that experts always and in all these signals have less tremor could be investigated more rigorously in the future:

1) From a hardware viewpoint, progress in the haptic technology could make tremor analysis more precise.

2) From a software viewpoint, improving the graphics and the mechanical models used for virtual tissues and tool-tissue interaction could improve the precision of tremor analysis.

3) Recruiting a large number of neurosurgeons for such studies is generally difficult. We had the opportunity to recruit 16 board certified and practicing neurosurgeons, who were from 3 institutions with different areas of expertise. These participants are felt to represent a

TABLE 2. *t* Test Results Based on the PSD Approach Applied to Pitch Signal for 6 Simulated Tumor Subgroups: Hard Tumors, Medium Tumors, Soft Tumors, Black Tumors, Glioma Tumors, and White Tumors

Tumor Subgroup	Group	Mean ± SEM	p Value
Hard	Skilled (*n* = 23)	0.00394 ± 0.00074	0.002
	Novice (*n* = 92)	0.01196 ± 0.00127	
Medium	Skilled (*n* = 23)	0.00446 ± 0.00064	0.001
	Novice (*n* = 92)	0.01291 ± 0.00122	
Soft	Skilled (*n* = 23)	0.00536 ± 0.00084	0.001
	Novice (*n* = 92)	0.01386 ± 0.00123	
Black	Skilled (*n* = 23)	0.00396 ± 0.00059	0.001
	Novice (*n* = 92)	0.01222 ± 0.00117	
Glioma	Skilled (*n* = 23)	0.00445 ± 0.00064	0.001
	Novice (*n* = 92)	0.01286 ± 0.00124	
White	Skilled (*n* = 23)	0.00534 ± 0.00095	0.002
	Novice (*n* = 92)	0.01366 ± 0.00130	

SEM, standard error of mean.

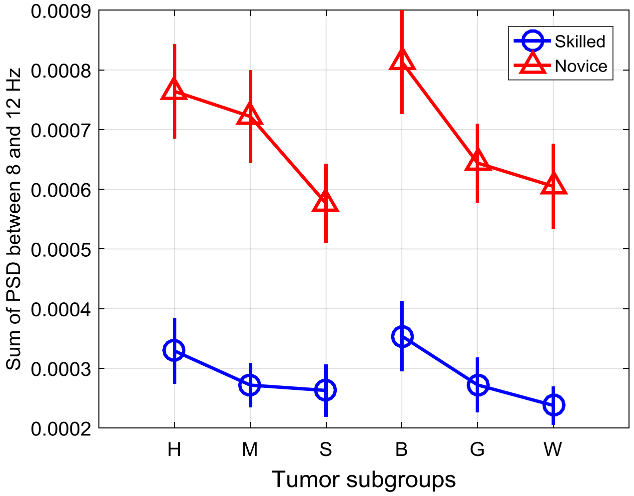

FIGURE 5. Sum of power spectral density (PSD) estimation of means ± SEM of force signal for skilled ($n = 23$) and novice ($n = 92$) groups during the removal of 6 simulated tumor subgroups. SEM, standard error of mean.

general neurosurgical population. Although having this number of neurosurgeons in similar studies is not usual, from a statistical analysis point of view a larger number of participants is desirable.

4) Simulation scenarios could be enriched. Patient tumor resections involve bimanual psychomotor skills with different instruments. Previous investigations have also demonstrated differences in ergonomics between right and left handed operators and this issue was not addressed in this study.[13] Multiple factors, including stress, fatigue, medications, and alcohol influence physiological tremor.[2] More realistic tumor scenarios with stressful simulated bleeding involving use of bimanual instruments in different tumor regions are being assessed. These studies may further define the influence of operative stress, hand ergonomics, and specific tumor features on tremor. Operative stress induced by simulated blood loss has significantly less detrimental impact on neurosurgeon's bimanual performance than that of resident groups.[14] The reasons the skilled group demonstrated decreased physiological tremor in our investigations may be related to their increased confidence in carrying out operative procedures with an ultrasonic aspirator which decreased their level of stress. This concept is supported by other studies in which physiological tremor was assessed during the suturing of silicone vessel replicas.[23,24] The scenarios defined in this study, were not designed to challenge the subjects in terms of the extent of tumor resection. Therefore, participants were able to resect the tumors to large extents which did not correlate with the tremor. Future work could study tremor in scenarios where the tumor resection task is more challenging, for example in presence of bleeding, where the scene could be filled up with blood, blocking the view for tumor resection. Our group has proposed a performance model for VR tumor resections encompassing human and task factors which are integrated into hand ergonomics resulting in safe and efficient procedures.[29] The present study suggests that decreasing physiological tremor may also be a component of the skill set of the expert neurosurgeon and needs to be incorporated into this model.

The focus of this paper was more on the investigation of tremor from an expert-novice point of view. The tremor could also be investigated from the tumor subgroup viewpoint. We did not observe trends that are consistent for both linear (x, y, and z) and angular (roll, pitch, and yaw) directions. We do observe a decreasing

TABLE 3. *t* Test Results Based on the PSD Approach Applied to Force Signal for 6 Simulated Tumor Subgroups: Hard Tumors, Medium Tumors, Soft Tumors, Black Tumors, Glioma Tumors, and White

Tumor Subgroup	Group	Mean ± SEM	p Value
Hard	Skilled ($n = 23$)	0.00033 ± 0.00002	0.01
	Novice ($n = 92$)	0.00076 ± 0.00003	
Medium	Skilled ($n = 23$)	0.00027 ± 0.00003	0.004
	Novice ($n = 92$)	0.00072 ± 0.00008	
Soft	Skilled ($n = 23$)	0.00026 ± 0.00004	0.02
	Novice ($n = 92$)	0.00058 ± 0.00006	
Black	Skilled ($n = 23$)	0.00035 ± 0.00006	0.02
	Novice ($n = 92$)	0.00081 ± 0.00008	
Glioma	Skilled ($n = 23$)	0.00024 ± 0.00004	0.005
	Novice ($n = 92$)	0.00060 ± 0.00006	
White	Skilled ($n = 23$)	0.00009 ± 0.00003	0.01
	Novice ($n = 92$)	0.00021 ± 0.00007	

SEM, standard error of mean.

trend from hard to medium to soft subgroups for force. Whether visual properties of tumors could affect tremor could be investigated further in future studies. Tactile properties could be related to the amount of effort, e.g., force, needed for tumor resection. Harder tumors require higher force amplitudes and this could increase tremors related to force, consistent with what has been observed.

CONCLUSION

We presented the first investigation of the application of a VR platform for the quantitation of physiological tremor during a tumor resection task. The importance of the proposed methodology lies in its potential educational application in resident training and helping to further define the psychomotor technical skills of the expert surgeon. In addition, the ability to measure physiological tremor, which we all possess, in a VR simulator may be particularly useful in surgical specialties which involve microsurgical techniques.

ACKNOWLEDGMENTS

We thank all the neurosurgeons, residents, and medical students from the Montreal Neurological Institute and Hospital and other institutions who participated in this study. We would also like to thank Drs GA AlZhrani, FE Alotaibi, AJ Sabbagh, K Bajunaid and SP Lajoie for their input and Robert DiRaddo, Group Leader, Simulation, Life Sciences Division, National Research Council of Canada at Boucherville and his team, including Denis Laroche, Valérie Pazos, Nusrat Choudhury and Linda Pecora for their support in the development of the scenarios used in these studies and all the members of the Simulation, Life Sciences Division, National Research Council of Canada.

REFERENCES

1. Elble RJ, Koller WC. Tremor. Baltimore: Johns Hopkins; 1990.
2. Lee HJ, Lee WW, Kim SK, et al. Tremor frequency characteristics in Parkinson's disease under resting-state and stress-state conditions. *J Neurol Sci*. 2016;362:272–277.
3. Burkhard PR, Langston JW, Tetrud JW. Voluntarily simulated tremor in normal subjects. *Neurophysiol Clin*. 2002;32:119–226.
4. Jeon H, Lee W, Park H, et al. Automatic classification of tremor severity in Parkinson's disease using a wearable device. *Sensors*. 2011;17:2067.
5. Narcisa V, Aguilar D, Nguyen DV, Campos L, Brodovsky J, White S, et al. Aquantitative assessment of tremor and ataxia in female FMR1 premutation carriers using CATSYS. *Curr Gerontol Geriatr Res*. 2011;146(5):629–635.
6. Timmer J, Häuler S, Lauk M, Lücking CH CH. Pathological tremors: deterministic chaos or nonlinear stochastic oscillators? *Chaos*. 2000;10:278–288.
7. Veluvolu KC, Ang WT. Estimation of physiological tremor from accelerometers for real-time applications. *Sensors*. 2011;11:3020–3036.
8. Alotaibi FE, ALZhrani GA, Bajunaid K, Winkler-Schwartz A, Azarnoush H, Mullah MA. Assessing neurosurgical psychomotor performance: role of virtual reality simulators, current and future potential. *SOJ Neurol*. 2015;2:1–7.
9. Alotaibi FE, AlZhrani GA, Mullah MA, et al. Assessing bimanual performance in brain tumor resection with NeuroTouch, a virtual reality simulator. *Oper Neurosurg*. 2015;11:89–98.
10. Alotaibi FE, AlZhrani GA, Sabbagh AJ, Azarnoush H, Winkler-Schwartz A, Del Maestro RF. Neurosurgical assessment of metrics including judgment and dexterity using the virtual reality simulator NeuroTouch (NAJD Metrics). *Surg Innov*. 2015;22:636–642.
11. AlZhrani G, Alotaibi F, Azarnoush H, et al. Proficiency performance benchmarks for removal of simulated brain tumors using a virtual reality simulator NeuroTouch. *J Surg Educ*. 2015;72:685–696.
12. Azarnoush H, Alzhrani G, Winkler-Schwartz A, et al. Neurosurgical virtual reality simulation metrics to assess psychomotor skills during brain tumor resection. *Int J Comput Assist Radiol Surg*. 2015;10:603–618.
13. Azarnoush H, Siar S, Sawaya R, et al. The force pyramid: a spatial analysis of force application during virtual reality brain tumor resection. *J Neurosurg*. 2016;127:171–181.
14. Bajunaid K, Mullah MA, Winkler-Schwartz A, et al. Impact of acute stress on psychomotor bimanual performance during a simulated tumor resection task. *J Neurosurg*. 2017;126:71–180.
15. Bugdadi A, Sawaya R, Olwi D, et al. Automaticity of force application during simulated brain tumor resection: testing the Fitts and Posner model. *J Surg Educ*. 2018;75:104–115.
16. Delorme S, Laroche D, DiRaddo R, Del Maestro RF. NeuroTouch: a physics-based virtual simulator for

cranial microneurosurgery training. *Neurosurgery*. 2012;71(suppl_1):32–42.

17. Sawaya R, Bugdadi A, Azarnoush H, et al. Virtual reality tumor resection: the force pyramid Approach. *Oper Neurosurg*. 2017;14:686–696.

18. Winkler-Schwartz A, Bajunaid K, Mullah MA, et al. Bimanual psychomotor performance in neurosurgical resident applicants assessed using NeuroTouch, a virtual reality simulator. *J Surg Educ*. 2016;73:942–953.

19. Heida T, Wentink EC, Marani E. Power spectral density analysis of physiological, rest and action tremor in Parkinson's disease patients treated with deep brain stimulation. *J Neuroeng Rehabil*. 2013;10:70.

20. Dai H, Zhang P, Lueth TC. Quantitative assessment of parkinsonian tremor based on an inertial measurement unit. *Sensors*. 2015;15:25055–25071.

21. Puschmann A, Wszolek ZK. Diagnosis and treatment of common forms of tremor. *Semin Neurol*. 2011;31:65–77.

22. Deuschl G, Raethjen J, Lindemann M, Krack P. The pathophysiology of tremor. *Muscle Nerve*. 2001;24:716–735.

23. Verrelli DI, Qian Y, Wilson MK, Wood J, Savage C. Intraoperative tremor in surgeons and trainees. *Interact Cardiovasc Thorac Surg*. 2016;23:410–415.

24. Verrelli DI, Qian Y, Wood J, Wilson MK. Measurement of tremor transmission during microsurgery. *Int J Med Robot*. 2016;12:585–597.

25. Kazemi H, Rappel JK, Poston T, Hai Lim B, Burdet E, Leong Teo C. Assessing suturing techniques using a virtual reality surgical simulator. *Microsurgery*. 2010;30:479–686.

26. Manzanera OM, Elting JW, van der Hoeven JH, Maurits NM. Tremor detection using parametric and nonparametric spectral estimation methods: A comparison with clinical assessment. *PloS one*. 2016;11: e0156822–e0156826.

27. Hayes MH. Statistical Digital Signal Processing and Modeling. John Wiley & Sons; 2009.

28. Gonenc B, Gehlbach P, Handa J, Taylor RH, Iordachita I. Motorized force-sensing micro-forceps with tremor cancelling and controlled micro-vibrations for easier membrane peeling. In: BioRob (2014 5th IEEE RAS & EMBS International Conference), IEEE; 2014:244–251.

29. Sawaya R, Alsideiri G, Bugdadi A, et al. Development of a performance model for virtual reality tumor resections. *JNS*. 2018;1:1–9. no. aop.