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Robotics in the neurosurgical treatment of glioma

Garnette R. Sutherland, Yaser Maddahi, Liu Shi Gan, Sanju Lama, Kourosh Zareinia

Project NeuroArm, Department of Clinical Neuroscience and The Hotchkiss Brain Institute, University of Calgary, 3280 Hospital Dr NW, Calgary, AB T2N 4Z6, Canada

E-mail: *Garnette Sutherland - garnette@ucalgary.ca; Yaser Maddahi - ymaddahi@ucalgary.ca; Liu Shi Gan - lsgan@ucalgary.ca; Sanju Lama - slama@ucalgary.ca; Kourosh Zareinia - kzareini@ucalgary.ca
*Corresponding author

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Abstract

Background: The treatment of glioma remains a significant challenge with high recurrence rates, morbidity, and mortality. Merging image guided robotic technology with microsurgery adds a new dimension as they relate to surgical ergonomics, patient safety, precision, and accuracy.

Methods: An image-guided robot, called neuroArm, has been integrated into the neurosurgical operating room, and used to augment the surgical treatment of glioma in 18 patients. A case study illustrates the specialized technical features of a teleoperated robotic system that could well enhance the performance of surgery. Furthermore, unique positional and force information of the bipolar forceps during surgery were recorded and analyzed.

Results: The workspace of the bipolar forceps in this robot-assisted glioma resection was found to be 25 × 50 × 50 mm. Maximum values of the force components were 1.37, 1.84, and 2.01 N along x, y, and z axes, respectively. The maximum total force was 2.45 N. The results indicate that the majority of the applied forces were less than 0.6 N.

Conclusion: Robotic surgical systems can potentially increase safety and performance of surgical operation via novel features such as virtual fixtures, augmented force feedback, and haptic high-force warning system. The case study using neuroArm robot to resect a glioma, for the first time, showed the positional information of surgeon's hand movement and tool-tissue interaction forces.

Key Words: Force feedback, glioma, haptic warning, intraoperative magnetic resonance imaging, robot-assisted microsurgery, virtual fixture

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INTRODUCTION

The complex nature of the brain possesses considerable challenges to neurosurgeons.[12,41] Choice between quality of life and loss of eloquent function compels highly skilled surgeons to make difficult decisions about the extent of resection in glioma surgery. An associated consequence of this approach is sub-optimal resection and relatively high tumor recurrence rates.[19,21] These tumors remain a challenge due to their highly aggressive and infiltrative nature.[40]

Treatment protocols for glioma vary based on the cell origin, composition, and tumor grade. For the majority, maximum resection of the tumor remains the initial step in the treatment regimen. Surgical intervention can be challenging due to lack of tumor margin demarcation, making it difficult for a surgeon to achieve complete resection without some degree of compromise to surrounding tissues and associated neurological deficit.[29,30] Furthermore, the process of mechanically dissecting the tumor brain interface may result in movement of glioma cells into the adjacent normal brain areas.[27,32]

Surgical resection of high-grade glioma is typically followed by adjuvant radiation and/or chemotherapy.[17,40] For low-grade glioma, gross total resection is the primary goal of surgical management as residual tumor cells are thought to increase the probability of tumor recurrence and malignant transformation.[5] For all gliomas, tumor recurrence is often associated with progression to a higher histologic grade and worse prognosis.[42]

Technologies that enhance tumor resection are important in achieving optimal outcome. Since the mid-1990s, intraoperative magnetic resonance imaging (iMRI) systems have been translated into the neurosurgical operative room to improve intraoperative lesion localization and resection control.[5,9,36] A recent randomized controlled trial has shown that the use of iMRI increases the extent of resection in patients with high-grade glioma.[31] As the acquisition of intraoperative images disrupts the rhythm of surgery, the technique has been primarily used to assess the extent of resection, rather than to guide surgery as it is being performed. But what if surgeons had a new way to operate? If only they could somehow operate inside an MR system during the actual imaging, seeing the image of the brain in real time. Toward this end, investigators at the University of Calgary, Calgary, Alberta, Canada together with Macdonald Dettwiler and Associates, Brampton, Ontario, Canada developed an MR compatible image-guided robot called neuroArm.[8,34-37] The inclusion of robotics, together with iMRI in glioma surgery is expected to enhance patient outcome by maximizing the extent of resection while preserving eloquent brain regions and associated fiber tracts.[3,18]

This report provides an insight into challenges related to robot-assisted surgery, potential benefits of robotics, position and force data obtained from a neuroArm procedure for glioma, and ongoing advances that can be used in robotic systems to improve safety and performance. For the first time, positional information of surgeon's hand movement and tool-tissue interaction forces are reported. The position and force ranges of the robotic arm have been quantified, which may be used as a reference for further training purposes in robot-assisted glioma surgery, and for design and development of new surgical tools.

Glioma Surgery improved by robotics

Surgical robots provide surgeons the benefit of features such as tremor filters and motion scaling to enhance surgical performance. The neuroArm's sensory immersive workstation allows the surgeon to interact with imaging data without interrupting the rhythm of surgery. The workstation comprising of haptic hand-controllers, three dimensional (3D) MRI display with tool overlay, a stereoscopic view of the operative field and a virtual image of the manipulators relative to the patient. An additional monitor includes images from the surgical site including the manipulators and operating team. To date, the system has been used in 56 cases, primarily for central nervous system (CNS) neoplasia and cavernous angioma [Table 1].

Navigating narrow surgical corridors

A distinct advantage of using a robot in neurosurgery is that the precision and accuracy of machine technology is combined with the executive capacity of the human brain (a teleoperated robotic system with the surgeon in the loop).[33-35] With improvements in lesion localization together with microsurgical technique, surgical corridors have become narrower, pushing surgeons toward the limits of their inherent ability. A robot with sub-millimeter precision and accuracy provides a viable solution to this challenge. Furthermore, electronic highways can be created establishing no-go zones such that increased resistance is encountered as the tools approach the boundaries [Figure 1]. Such an achievement reflects integration of aerospace technology with surgery toward improving patient safety.

The neuroArm includes a specialized tremor filter, developed in software, that enables smooth displacement of robotic arms. At the workstation, the surgeon uses hand-controllers to manipulate the robotic arms. A low-pass filter is applied to the command signals so that high frequency components representative of physiological tremor (>6 Hz) can be filtered.[26] The system allows the surgeon to adjust the cut-off frequency of the filter so that different settings can be adjusted for different surgeons depending on frequency of the tremor in their hands. Moreover, it can be adjusted with different settings for

Table 1: Neuroarm patient group characteristics (*n*=55)

Patient group	Number and sex	Age in years (range, mean±SD)
Low-grade glioma	4 F, 8 M	18-62, 43±14
High-grade glioma	3 F, 3 M	39-65, 54±11
Meningioma	18 F, 9 M	21-74, 50±15
Cavernous angioma	4 M	20-72, 47±25
Schwannoma	2 F	49-69, 59±14
Dermoid	1 M	55
Metastatic carcinoma	1 F	61
Brain abscess	1 F	43
Medulloblastoma	1 F	30
Glomus jugulare tumor	1 M	68

F: Female, M: Male, SD: Standard deviation

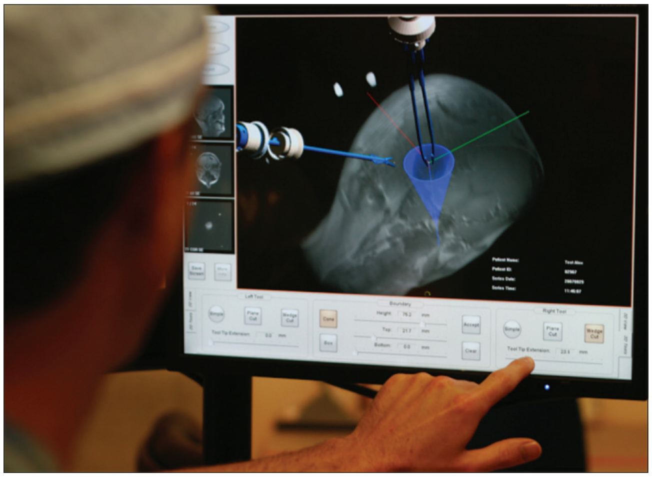

Figure 1: Electronic highways for tool placement creating no-go zones thereby improving the safety of surgery

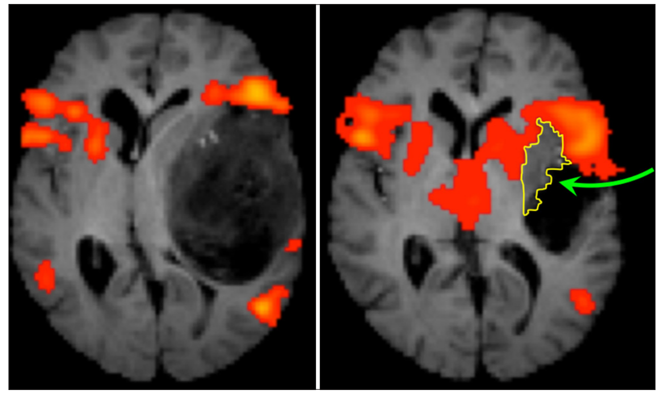

Figure 2: Left: Preoperative T1 MR image, Right: Postoperative T1 MR image, with superimposed speech cortex and its connections to the thalamus, using a noun–verb task-based fMRI. Green arrow shows how an articulated tool could access residual tumor (within the yellow margin)

left or right hand. At Foothills Hospital, in Calgary, this frequency was set at 2 Hz for both hands and was found to include all components of intentional movements of the surgeon during microsurgery. The tremor filter capability helps surgeon achieve a more steady and precise movement as compared with conventional surgery.[39]

Another feature of neuroArm that helps the surgeon maneuver surgical tools attached to the end-effector of the robot more precisely is motion scaling.[25] Motion scaling allows for small movements at the hand-controller to be scaled down to even finer movements. For example, a scaling factor of 10:1 allows for robot manipulator movement of only 0.1 mm when the hand-controllers are moved by 1 mm. Each surgeon can adjust this scaling factor based on the demand for each patient and surgery. This feature enables surgeons to perform surgical procedures and reach targets with the level of accuracy and control that would not otherwise be feasible because of the size of surgical corridor, size of the target, or simply natural limitation of human hand.

Brain shift

Brain shift during surgery makes surgical navigation based on preoperative images invalid. This issue is usually in part managed by the experience of the surgeon. In those units that possess iMRI systems, new images can be acquired during surgery to assess the extent of tumor resection and to re-register the navigation system. In many cases, as illustrated in Figure 2, residual tumor is left for fear of injuring eloquent brain. Notwithstanding significant challenges, this problem could be rectified by providing robotic surgical tools not limited by the line of sight while able to bend around corners, for example, a snake-like mechanism, during functional MRI in an awake patient.[43] As imaging and microsurgery could be performed at the same time using an MR compatible robotic system, the tool-tip could be well positioned for resection of residual tumor adjacent to speech cortex and its connections.

Surgeon fatigue

As shown on the left panel of Figure 3, in conventional surgery, the surgeon may have to work in an awkward posture, sometimes for hours, to achieve access to surgical corridor during the performance of surgery. This may result in surgeon fatigue and could correlate to unintended errors. In robot-assisted neurosurgery, the surgeon is located at a workstation, which provides a more ergonomic environment [Figure 3, top right]. This minimizes surgeon fatigue, which could correlate to better performance.[10] In conventional operating rooms, surgeons need to glance away from the surgical site to review imaging information displayed on monitors that often interrupts the rhythm of surgery. The robotic workstation allows the surgeon to link imaging information and other sensory inputs more effectively than conventional surgery.[33] Furthermore, haptic hand-controllers at the workstation provide the sense of touch and at the same time, the forces of tool-tissue interaction. The force-scaling feature of neuroArm offers a unique ability for surgeons to alter or scale the sense of touch if so desired. For example, by scaling the force up, fine tissues can be felt firmer, and scaling the remote forces down could make hard objects such as bone, feel softer. This ability is dependent on and complemented by the fidelity and positioning of force sensors relative to the surgical tool, and the design and bandwidth of the haptic hand-controller.

Other benefits of robotic surgery

Image-guided robotic surgery provides a platform for case documentation, safety, and education. These will become increasingly integrated into neurosurgical practice as advances in technology, machine control, and computer processing occur.[6]

Collecting data for case rehearsal and training

A surgical robotic system can record positional and force data during surgery, which is not possible in conventional surgery. This recorded data can be used for quality

Figure 3: Top left: Surgeon's posture in conventional surgery, top right: Surgeon at the robot workstation, bottom: NeuroArm robot operating in conjunction with the surgical assistant in the operating room; inset: NeuroArm tools within the surgical corridor

assurance and case rehearsal. Case rehearsal in a virtual reality simulator may be of a particular value in making a novice surgeon's initial experience with robotic surgery safer, less stressful and more efficient.

Positional and force data collected during robotic surgery can also contribute to the development of surgical simulators. A simulator that provides touch sensation via haptic hand controllers, allows surgeons to practice surgery with or without a robotic platform, thus acquiring experience in a fail-safe environment. In any haptic hand-controller, the force feedback to be generated by the haptic device actuators first needs to be computed in software based on the physical properties of the tissue models. The computed force is sent as command signals to the actuators of the hand-controllers. Intraoperative force and positional data, acquired during robotic procedures, can be used to define the mechanical properties of virtual tissue models and assist in development of realistic tissue deformation and tool-tissue interaction in the virtual environment.[23]

Technical methods to increase safety

Implementing the concept of virtual fixture

The concept of virtual fixtures is a technique that could greatly improve safety during robot-assisted surgery. Virtual fixtures could be defined in software to assist the surgeon performing a tele-manipulation task. Such a feature can limit the position or force to guide surgery while tasks are being performed.[1] Furthermore, constraints to a surgeon's hand movements can be posed by virtual fixtures when moving along desired paths in the surgical corridor increasing the safety of surgery.[1,38] These can guide surgeon's hand and navigate surgical tools to the target.[24] Unwanted movements can be redirected to prevent damage to the healthy tissue through the definition of virtual walls or no-go zones.[20] Not only can the virtual fixtures help the surgeon operate safer, but also faster.[2]

Virtual fixtures were employed by Rosenberg for a teleoperation task and found to improve operator performance by up to 70%.[28] Investigators have also shown that by applying various levels of guidance in a path following task that complete guidance offers the best performance.[16] Stability of virtual fixtures has been analyzed to avoid vibrations of manipulators.[2] In general, the use of virtual fixtures is popular because (i) they do not have any mass or mechanical constraints, (ii) they do not require maintenance, (iii) they can be easily designed, developed, customized and modified based on the surgical corridor for a specific patient, (iv) the stiffness and other characteristics of the fixture can be changed easily, and (v) any desirable dynamics can be defined in software such as frictionless plains, viscose environment, course or fine textures, different inertia or mass properties, or compliant surfaces.

With respect to robot-assisted glioma surgery, brain shift during the operation, for example, invalidates the navigation technology based on preoperative images.[7,11,13] Although 3D reconstruction of fiber tracts provides an excellent pictorial representation of the otherwise not visible fiber pathways and direction within the white matter, there still exists uncertainty as compared with a real-time verification of such pathways.[22] For instance, the increase of safety using virtual fixtures is extremely important to decrease the margin of error for a fiber tract representation in diffusion tensor imaging (DTI) and real time. In such an application, the use of a no-go zone Virtual Fixture can benefit the surgeon to maintain the tip of surgical tool out of a predefined region inside the narrow surgical corridor.

Technically, a no-go zone has no effect on the robot when its end-effector is out of the defined no-go zone. Therefore, the surgeon can guide the robot end-effector as long as the surgical tool is not going to penetrate into the no-go zone, that is, the corridor virtual wall. Figure 4 shows a simple no-go zone virtual fixture defined at the slave site of the image-guided computer-assisted neuroArm surgical system[34] to avoid the surgical robot penetrating into no-go zones when an undesirable command is issued (e.g. unwanted hand movement). As observed, a cylindrical no-go zone has been defined that does not allow the bipolar forceps to move out of the defined cylinder. Figure 5 illustrates the no-go zone virtual fixture and some probable linkage configurations for the tele-manipulator in order to have no penetration into no-go zones.

Implementing the concept of augmentation force

The virtual fixture helps the operator keep the surgical tool in a safe zone during surgery. They are normally

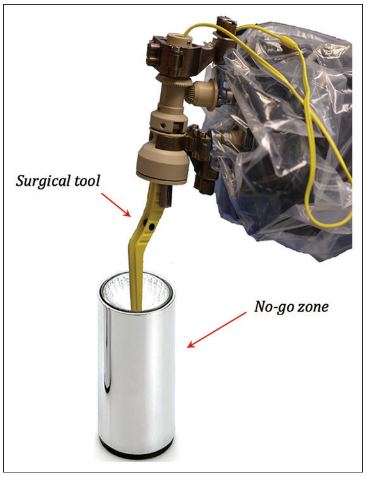

Figure 4: A cylindrical no-go zone defined to maintain the bipolar forceps within the virtual cylinder, restricting any penetration beyond that virtual wall. The no-go zone is defined according to the shape of the surgical corridor geometry required to conduct the surgery

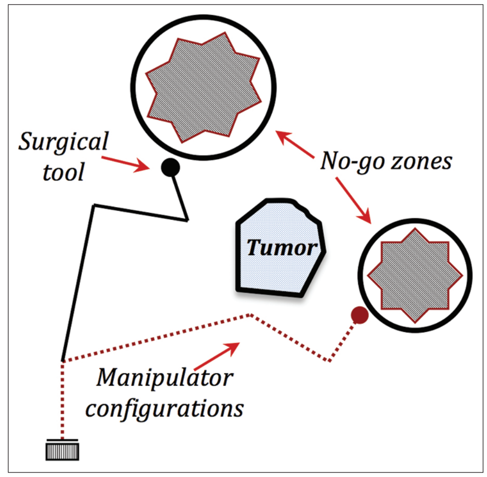

Figure 5: Example of a no-go zone virtual fixture (shown as circular solid lines) and robot positional configuration. Several no-go zones can be defined for a surgical task. The region of interest, in which the robot performs surgery, is shown with dotted area. Dashed areas are critical structures in brain, for example, speech cortex and motor cortex

defined at the sensory immersive workstation-haptic hand-controller, maintaining the surgeon's hand in a safe zone; thus, the surgical tool, at the slave manipulator, stays within the anticipated safe zone. This allows the surgeon to move the hand-controller implement faster when desired while relying on the fact that the patient would be safe in the presence of the virtual fixture.[4] As a result, the slave manipulator could potentially lag due to latency in the actuation control system.[15] When the information from either master or slave site is not adequate, having an additional level of control on the robot allows the surgeon to conduct robot-assisted surgery with more confidence. In other words, since the virtual fixture does not have any influence on robot side, it cannot effectively compensate for errors of the surgical tool. Therefore, even if the surgeon moves within the workspace defined as no-go zone virtual fixture (see cylinder in Figure 4), an accurate position tracking of the slave manipulator cannot be guaranteed. A solution to reduce position error at the slave end-effector is to add an augmentation force to the virtual fixture force.[15] The augmentation force signals the surgeon to slow down the haptic implement (hand) motion when the position error becomes larger than the accuracy expected from the controller at the slave end-effector. The direction of this force should be opposite to the surgeon's hand instantaneous velocity. By pulling the surgeons' hand back, this force allows the surgeon to realize position error at the slave site, and reduce the hand's motion speed. In combined virtual fixture and augmentation arrangement, the virtual fixture force keeps the surgeon's hand inside the desirable zone. The augmentation force, in contrast, guides the surgeon to adjust the pace of their hand movement when position error is observed at the salve end-effector more than that predefined.

Haptic warning system

While performing surgery, application of excessive force to nontargeted structures in the brain might cause unintended damage to healthy brain tissues. In robot-assisted neurosurgery, forces of tool-tissue interaction can be measured and relayed to the surgeon's workstation. In neuroArm, each robotic arm is equipped with two titanium Nano17 force sensors (ATI Technologies Inc.) to measure these forces in real-time [Figure 6]. Table 2 lists important parameters of the titanium Nano17 force sensor. While no-go zone virtual fixtures, as mentioned earlier, can reduce the risk of damage to healthy tissues, it might be an inadequate technique in procedures that physically isolate the target anatomy from adjacent structures. In such cases, instead of limiting the robot in physical space in terms of position and orientation, a warning system that provides notifications (when interaction forces exceed safe level of forces) would be helpful. Incorporating such a warning system is possible only if the safe level of forces for each type of tissue and structure in the brain are known. This data can be obtained from recorded data during robotic cases. Incorporating such a notification system was shown to help operators avoid unintentional tissue puncture, and improve operator's awareness about applied force.[14]

Clinical case study

Experimental setup

NeuroArm[34,37] can be used for both image-guided stereotaxy and microsurgery. The system consisted of two MR compatible robotic manipulators mounted on a mobile base [Figure 7], a main system controller together with a sensory immersive workstation that includes haptic hand-controllers and 3D monitors [Figure 3, right panel]. Information between the slave manipulator and the master haptic hand-controllers is transmitted through the main system controller. For this case, two custom designed neurosurgical tools were attached. A bipolar forceps was inserted into the right and a suction tool into the left end-effector [Figure 7]. This section reports the positional and force measurements of the bipolar forces attached to the right manipulator.

An Omega 7 haptic device provides 7 degrees of freedom (DOFs) positional sensing and 4 DOFs force feedback. The haptic device implement covers the natural range of motion of the human hand pivoting around the wrist, and is compatible with bi-manual teleoperation console design. The haptic device, comprised of a parallel mechanism, has the capability of producing force up to 12 N, and a grasping force feedback up to 8 N. During teleoperation of neuroArm, the surgeon who is located at the workstation uses hand-controllers to command the neuroArm manipulators. As a safety feature, the foot pedals have to remain engaged to allow the robot to move. Haptic capability of the hand-controllers allows the surgeon to experience the tool-tissue interaction remotely.

Test procedure

The results are taken from a robot-assisted glioma surgical operation performed by neuroArm. Total duration of robot-assisted surgery, excluding craniotomy and wound closue was about 33 min. The surgical tasks were a combination of manipulation, coagulation and pick and place motions of cotton strips.

RESULTS

Figure 8 depicts position components of the manipulator end-effector holding the bipolar forceps recorded over 100-s period of surgery. As observed, the bipolar forceps at the end-effector was shown to travel 9.8, 11.1, and 11.8 mm along *x*, *y*, and *z* axes. Figure 9 illustrates the measured force by the force sensor located at the neuroArm manipulator [see arrows in Figure 6].

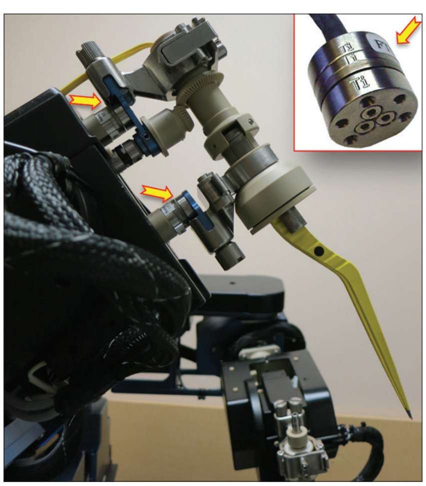

Figure 6: Titanium Nano17 force sensor used in neuroArm (arrows)

Results of the glioma case in four dimensions

The workspace of the bipolar forceps over 2000-s of surgery is shown in Figure 10. As seen, the workspace that was used in the performance of this robot-assisted glioma resection was 25 × 50 × 50 mm in the *x*, *y*, and *z* directions. The mean values (+SD) of the measured interaction forces between the bipolar forceps and the tissue, together with concurrent position of the forceps are listed in Table 3. Maximum values of the force components were 1.37, 1.84, and 2.01 N along *x*, *y*, and *z* axes, respectively. A maximum total force of 2.45 N was observed during 2000-s period of surgery. The total force was calculated using $F = \sqrt{F_x^2 + F_y^2 + F_z^2}$. The mean and standard deviation values of the forces indicate that 95% of the applied forces were less than 0.6 N.

Table 2: Characteristics of the titanium Nano17 force sensors

Variable	Nano17 titanium
Resolution	0.149 gram-force
Max threshold	8 N
Weight	10.1 g
Diameter	17 mm
Height	15 mm
Torque overload	±1.0 Nm

Table 3: Position and interaction force of the bipolar forceps over 2000-s period of surgery

Variable	Mean value±SD
Position mm	11±9
	41±19
	39±8
Force N	0.1±0.1
	0.2±0.2
	0.3±0.2
	0.3±0.3

SD: Standard deviation

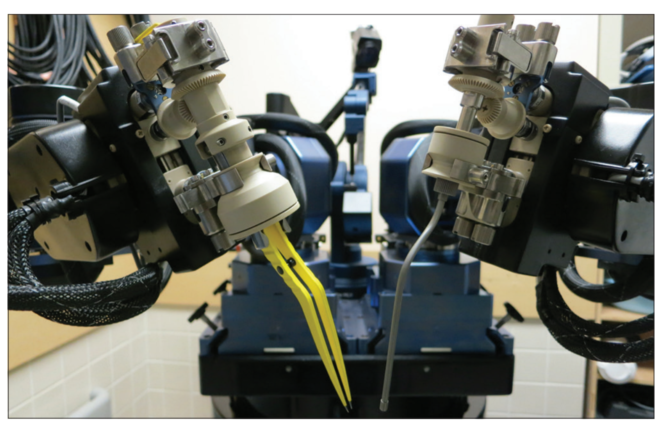

Figure 7: The neuroArm robotic arms with bipolar forceps on the right and suction tool on the left arm

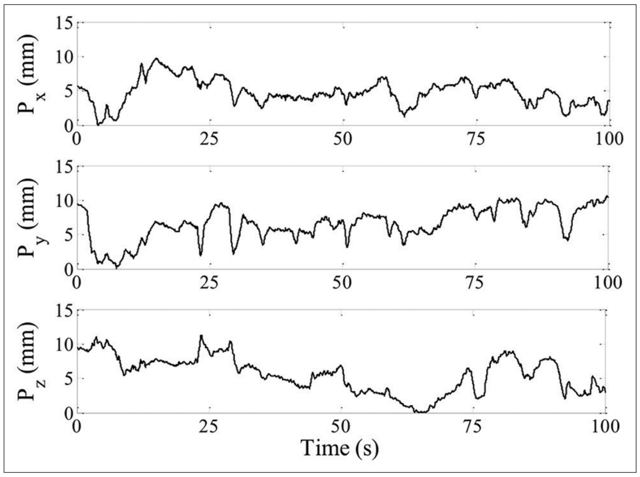

Figure 8: Position components of the bipolar forceps located at the end-effectors of the right neuroArm manipulator

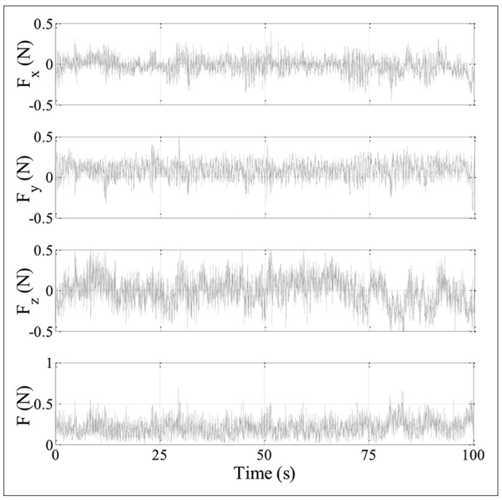

Figure 9: Force measured by the force sensor for the trajectory given in Figure 8

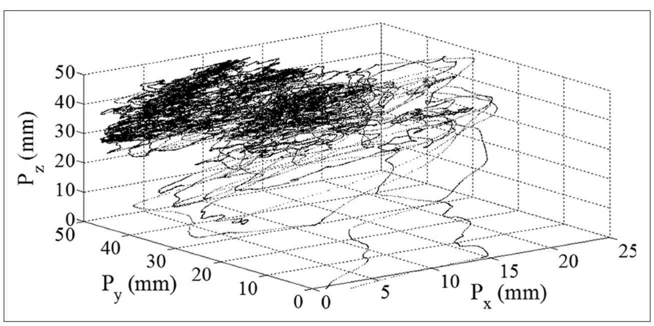

Figure 10: 3D reconstruction of the bipolar forceps position. As seen, during the chosen time period, the end-effectors has moved by 25, 50, and 50 mm along *x*, y, and z axes, respectively

CONCLUSIONS

This report addresses the importance of continuing the translation of robotic technology into neurosurgery. Robotic surgical systems provide an advantage when surgical corridors are narrow, brain shift is inevitable and or when conventional surgery demands for an ergonomic posture for the surgeon. Unique solutions to increasing safety and performance of the operation were exemplified. In particular the use of virtual fixtures, using augmented force feedback to reduce the possible positional errors, and the addition of a haptic high-force warning system. The case study using neuroArm robot to resect a glioma, for the first time, showed the positional information of surgeon's hand movement and tool-tissue interaction forces. The mean values of these interactive forces were much less than 1N in *x*, *y*, or *z* directions. The position and force ranges of the robotic arm were quantified, and may be use to reference training in robot-assisted glioma surgery.

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