Forces exerted during microneurosurgery: a cadaver study

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Abstract

Background A prerequisite for the successful design and use of robots in neurosurgery is knowledge of the forces exerted by surgeons during neurosurgical procedures. The aim of the present cadaver study was to measure the surgical instrument forces exerted during microneurosurgery.

Methods An experimental apparatus was set up consisting of a platform for human cadaver brains, a Leica microscope to provide illumination and magnification, and a Quanser 6 Degrees-Of-Freedom Telepresence System for tissue manipulation and force measurements.

Results The measured forces varied significantly depending on the region of the brain (P = 0.016) and the maneuver performed (P < 0.0001). Moreover, blunt arachnoid dissection was associated with greater force exertion than sharp dissection (0.22 N vs. 0.03 N; P = 0.001).

Conclusions The forces necessary to manipulate brain tissue were surprisingly low and varied depending on the anatomical structure being manipulated, and the maneuver performed. Knowledge of such forces could well increase the safety of microsurgery. © 2014 The Authors. The International Journal of Medical Robotics and Computer Assisted Surgery published by John Wiley & Sons, Ltd.

Keywords neurosurgery; microsurgery; robotics; force

Introduction

The evolution of neurosurgery has been towards increasingly precise, delicate and safe surgical technique. Surgical robotics, which has the ability to eliminate tremor, and scale movements, has the potential to greatly enhance surgical performance. A prerequisite for the successful design and use of such robots is knowledge of the surgical instrument forces exerted by surgeons during neurosurgical procedures. The advent of surgical robotics may in turn allow, for the first time, the forces exerted during neurosurgical procedures to be routinely recorded (1–4). The corollary is that expert performances might be analyzed to determine the optimal force ranges utilized when performing robot-assisted neurosurgical procedures, providing quantitative feedback to trainees to further their development, and allowing for the possibility of force limits to be set to improve surgical safety (4).

Despite an abundance of anecdotal data on the instrument forces exerted during neurosurgical procedures, there remains a lack of quantitative data in the field. To date, the majority of studies addressing the forces necessary to manipulate brain tissue are either non-penetrating indentation studies designed to estimate the elastic properties of the brain (5–9), or penetration studies designed to estimate the forces required for probe insertion (10–13).
Materials and methods

An experimental apparatus was set up consisting of a platform for brain specimens, a Leica microscope (Leica Microsystems GmbH, Wetzlar, Germany) to provide illumination and magnification, and a Quanser 6 Degrees-Of-Freedom (DOF) Telepresence System (Quanser Inc, Ontario, Canada) for tissue manipulation and force measurements (Figure 1). The robotic master–slave setup included a DENSO VP Series 6-Axis Articulated Robot and the control module (DENSO Robotics, Aichi, Japan), Gamma Multi-Axis ATI Force/Torque Sensor (ATI Industrial Automation, North Carolina, USA) equipped with a 16-bit Data Acquisition Board (National Instruments, Texas, USA) for force/torque measurements, and a High-Definition Haptic Device (HD) with the capability of providing 6 DOF force/torque feedback to the operator; this configuration allowed for continuous force feedback. The robot utilized an open-architecture interface with the QuaRC 2.2 (Quanser Real-time Control) Denso Robot block-set, alongside Simulink® (Mathworks, Massachusetts, USA), Matlab® (Mathworks, Massachusetts, USA) and Windows® (Microsoft, Washington, USA) force/torque sensor was located between the DENSO Robot’s end-effector and tool holder and measured 6 DOF force/torque with a capacity of 32 N and a resolution of 0.01 N. 

Two fresh brain specimens were utilized for the study (Body Donation Program, Department of Anatomy, University of Calgary, Alberta, Canada). Brains were removed from their respective cranial cavities and dural sacs, leaving the brain, arachnoid and pia. In each specimen, a neurosurgical trainee (HJM) was asked to incise the coagulated area, (2) the Mini-Blade was used to carry the incision to a length of approximately 30 mm, and (3) a No 6 Rhoton spatula dissector with a 1.1 mm tip was inserted to a depth of approximately 5 mm and used to retract the brain approximately 5 mm. These maneuvers were carried out in the cerebrum (gyrus rectus, middle frontal gyrus, inferior temporal gyrus), cerebellum (hemispheres, vermis) and brainstem (midbrain, pons, medulla); and each was repeated twice on each side of the brain, unless it was too technically difficult to do so. In addition, the forces required to perform a corpus callosotomy and perforate the floor of the third ventricle were also measured.

The Beaver Mini-Blade and No 6 Rhoton dissector were also used to perform sharp and blunt dissection of the Circle of Willis respectively. An observer (KZ) carefully took note of iatrogenic injury to neurovascular structures during dissection (such as injury to tearing of small perforators). In cases of uncertainty, we recorded injury as having occurred.

Force vector data were produced each 0.2 ms (5 kHz). A Matlab® program was developed and used to extract data each 10 ms (100 Hz) and to record it in an Excel spreadsheet, and force vectors were summed. Statistical software (SPSS 20.0.0; IBM, New York, USA) was then used to calculate the median, interquartile range and maximum forces during individual procedures. The Mann–Whitney U test was used to compare the surgical instrument forces exerted in each brain specimen, and on the left- and right-side of the brain. The Kruskal–Wallis test was used to compare the forces exerted when performing different procedures, and between different brain regions; if significance was demonstrated post hoc analysis was performed using the Mann–Whitney U test, with the Bonferroni correction. The Mann–Whitney U test was then used to compare the forces exerted when performing sharp and blunt dissection, and the maneuvers that resulted in iatrogenic injury against those that did not. The threshold for significance was set at 5%.

Results

In all, there was no significant difference in forces exerted between the two brain specimens, and between the left and right sides of the brains (P > 0.1). The median and interquartile ranges of forces exerted when performing different procedures in different brain regions are summarized in Table 1. The median force exerted when performing...
differently during microneurosurgery. The median, interquartile range, and maximum forces exerted when performing sharp and blunt arachnoid dissection around the Circle of Willis are summarized in Table 2 and Figure 3; maneuvers are stratified according to whether they did or didn’t result in iatrogenic injury. The median force exerted during blunt dissection (0.22 N) and sharp dissection (0.03 N) was significantly different (P = 0.001). When performing sharp dissection the median force during maneuvers in which iatrogenic injury occurred (0.28 N) and those in which it did not (0.02 N) was significantly different (P = 0.011). When performing blunt dissection the median force during maneuvers in which iatrogenic injury occurred (0.60 N) and those in which it did not (0.11 N) was also significantly different (P = 0.004).

Discussion

In this study the surgical instrument forces exerted during a number of robot-assisted procedures on fresh cadaver brains were successfully determined. The measured forces varied depending on the region of the brain and the maneuver performed. Significantly greater force was exerted when manipulating the brainstem (0.05 N) than the cerebellum (0.02 N; P = 0.022) or cerebrum (0.03 N; P = 0.013), and significantly less force was exerted when performing stab incisions (0.01 N) than carrying incisions (0.05 N; P < 0.0001) or retracting brain tissue (0.08 N; P < 0.0001). Moreover, blunt arachnoid dissection with a Rhoton No 6 dissector was associated with greater force exertion than sharp dissection with a Beaver Mini-Blade.

Existing literature on the forces exerted during neurosurgical procedures is sparse. Several studies have evaluated the mechanical properties of the brain itself through non-penetrating indentation experiments (5–9). As early as 1976, Walsh et al. measured the elastic response of brain tissue in dogs using a diaphragm-type pressure sensor mounted co-linear with a displacement transducer, and described a nonlinear response (5). Miller et al. conducted a study on an exposed porcine brain and reported that approximately 0.3 N was required for up to 4 mm of brain displacement, slightly greater than predicted by their hyper-viscoelastic constitutive model (7). Gefen et al. performed a similar non-penetrating indentation study on exposed porcine brains, comparing the forces required to deform brain tissue during in situ and in vitro experiments, and demonstrating that most of the brain’s mechanical properties are unaffected by perfusion pressure, and can therefore be examined in vivo (9). These findings are broadly comparable with those of the present study; we estimated that the median forces to retract brain tissue 5 mm varied from 0.03 N in the cerebrum to 0.18 N in the brainstem.

Alongside the aforementioned studies evaluating the mechanical properties of the brain, a number of studies have utilized penetration experiments to estimate the forces required to insert probes of various characteristics into neural tissue. Howard et al. measured the penetration forces on 2.5 mm spheres and the drag forces on a 3 mm ventricular catheter into a porcine brain advanced 20–30 mm deep into the brain tissue of patients undergoing temporal lobectomy, and reported forces of 0.08 N and 0.03 N respectively (11). Chen et al. measured the forces exerted when placing a 3 mm ventricular catheter into a porcine brain during validation of an agarose gel phantom, and reported a typical penetration force of less than 0.1 N (13). Sharp et al. addressed micrometer-scale penetration dynamics, assessing the influence of probe size and geometry, and also reported that low forces were required (10). When utilizing a 200 μm diameter flat punch probe, for example, a maximum force of 0.03 N was exerted. In the current study, the forces exerted to penetrate brain tissue were

Table 1. The median (interquartile range) of forces exerted (Newton) when performing simple procedures in different brain regions

| Region                        | Median (interquartile range) |
|-------------------------------|-----------------------------|
|                               | Stab Incision | Carrying Incision | Retraction |
| Cerebrum (n = 24)             |               |                  |            |
| Gyrus rectus (n = 8)          | -0.01 (0.00–0.03) | 0.02 (0.01–0.03) | 0.03 (0.03–0.05) |
| Inferior temporal gyrus (n = 8) | -0.01 (0.00–0.01) | 0.02 (0.00–0.03) | 0.07 (0.06–0.09) |
| Middle frontal gyrus (n = 8)  | -0.01 (0.00–0.01) | 0.15 (0.12–0.18) | 0.08 (0.06–0.10) |
| Cerebellum (n = 12)           |               |                  |            |
| Cerebellar hemisphere (n = 8) | 0.01 (0.00–0.01) | 0.03 (0.02–0.04) | 0.08 (0.02–0.13) |
| Cerebellar vermis (n = 4)     | 0.02 (0.01–0.02) | 0.12 (0.12–0.12) |            |
| Midbrain (n = 6)              | 0.01 (0.00–0.01) | 0.11 (0.04–0.26) | 0.15 (0.13–0.20) |
| Pons (n = 8)                  | -0.01 (0.00–0.01) | 0.05 (0.04–0.06) | 0.18 (0.12–0.21) |
| Medulla (n = 8)               | 0.01 (0.01–0.03) | 0.09 (0.06–0.16) | 0.09 (0.06–0.11) |
| Other (n = 8)                 |               |                  |            |
| Corpus callosum (n = 4)       | 0.01 (0.00–0.03) | 0.23 (0.09–0.43) | N.A.       |
| Perforating floor of third ventricle (n = 4) | <0.01 (0.00–0.01) | N.A.          | N.A.       |

N.A. = Not applicable.
very low, varying from <0.01 N to 0.02 N, although greater forces were required to extend the incision. We speculate that the very low forces observed in our study are the result of its distinct methodology; to better reflect standard operative neurosurgical practice the brain surface was coagulated with bipolar electrocautery prior to any maneuvers, and a sharp beaver mini-blade instrument used to incise the brain.

Cranial microsurgery, such as aneurysm clipping or tumor resection, is characterized by precise and delicate complex maneuvers such as dissection around critical neurovascular structures, rather than simple brain tissue retraction and penetration. To date, no previous studies have reported the forces actually exerted during such neurosurgical procedures. In other surgical disciplines, the forces exerted during, for example, laparoscopic cholecystectomy was reported to be approximately 17 N (14). In comparison, the instrument forces measured during sharp and blunt arachnoid dissection were an order of magnitude less, and with median forces typically less than 1 N.

**Limitations**

The present study has several limitations. First, although forces were measured carefully using an externally
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The present study suggests that the instrument forces exerted during microsurgical arachnoid dissection are relatively low, with median forces less than 1 N, and maximum forces less than 5 N. Nonetheless, in vivo forces are likely to vary depending on a number of factors including the patient’s particular brain characteristics, the nature of their pathology (such as tumor consistency), the experience of the operating surgeon, and the surgical procedure performed. In the future, widespread adoption of surgical robots into mainstream practice might allow for quantification of surgical forces on a routine basis, enhancing not only the precision, accuracy, and safety of cranial microsurgery, but also providing valuable feedback to neurosurgical trainees.

Acknowledgements

H.J. Marcus is supported by an NIHR Academic Clinical Fellowship, the Berkeley Travelling Fellowship and an Imperial College Wellcome Trust Clinical Fellowship.

Conflict of interest

The authors have stated explicitly that there are no conflicts of interest in connection with this article.

Funding

No specific funding.

Author contributions

HJM, KZ, LSG, FWY, SL, GZY and GRS were involved with the study conception and design. HJM, KZ, LSG, FWY and SL were involved with the acquisition of data. HJM, KZ, LSG, FWY, SL, GZY and GRS were involved with analysis and interpretation of data. HJM, KZ, LSG, FWY and SL were involved with drafting the manuscript. GZY and GSR were involved with critical revision of the manuscript.

Previous presentation

Interim findings of this study were presented at the Hamlyn Symposium on Medical Robotics 2013. Otherwise, the authors confirm no prior or duplicate publication or submission elsewhere of any part of this work.

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