Role of Hand Ergonomics in Virtual Reality Brain Tumor Resections

Robin Sawaya, BSc

Integrated Program in Neuroscience

McGill University, Montreal

May 2017

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science in the Integrated Program in Neuroscience

TABLE OF CONTENTS

Abstract v

Résumé vii

Acknowledgements ix

Preface and Contribution of Authors xi

Abbreviations 12

Thesis Introduction 13

Background 16

    Surgical Education 16

    Surgical Simulation 19

    NeuroVR 22

    Haptic Feedback 23

    Force Pyramid 25

    Hand Ergonomics 26

Studies 28

    Rationale for Study 1 28

    Study 1 29

        Abstract 30

        Introduction 31

        Methods 32

        Results 35

        Discussion 39

Conclusion 44

Rationale for Study 2 45

Study 2 46

Abstract 47

Introduction 48

Methods 49

Results 51

Discussion 52

Conclusion 56

Thesis Conclusions 58

References 61

Appendix 72

Tables 72

Table 1 72

Figures 73

Figure 1 73

Figure 2 74

Figure 3 75

Figure 4 76

Figure 5 77

Figure 6 78

Figure 7 80

Figure 8 81

Figure 9 82

Figure 10 83

Figure 11 84

Figure 12 85

Figure 13 86

Figure 14 87

Figure 15 88

ABSTRACT

Background: The NeuroVR virtual reality neurosurgical simulation platform has been used to analyze the bimanual psychomotor performance of neurosurgeons, residents and medical students. Previous metrics developed by our group have focused on safety, force use, and bimanual performance. A new metric, the force pyramid, was created to study the spatial distribution of forces applied during simulated tumor resections.

Hypothesis: Hand ergonomics play an important role in the magnitude and spatial distribution of forces applied during simulated neurosurgical tumor resections.

Objectives: First, to explore the role of the dominant, non-dominant and bimanual force pyramids in assessing the spatial distribution of forces applied during virtual reality tumor resections. Second to define the influence of hand ergonomics on the relationship between force applied, time expended, and tumor volume removed.

Methods: Data from trials in which neurosurgeon, resident and medical student groups resected simulated tumors were assessed. The force pyramid methodology was used to determine the spatial distribution of force applied, time expended, and tumor volume removed. To assess ergonomics, spatial information was partitioned into four tumor quadrants (Q1-Q4) each requiring a defined hand position to carry out the procedure.

Results: The force pyramid analyses show that the highest forces form a crescent in Q4 for the dominant right hand and a peak at the center for the non-dominant left hand. The bimanual pyramids show an equal ratio of dominant and non-dominant forces for neurosurgeons and increased non-dominant forces for resident groups. Neurosurgeons distinctly adapt their performance to Q2 and Q4 and for each unit of force applied, neurosurgeons and residents remove more volume in Q2 and less in Q4.

Conclusion: Hand ergonomics play a critical role in force application and tissue removal during surgical performance and help define expertise in the removal of simulated brain tumors. The new NeuroVR metrics assessed in this study allow for a more comprehensive evaluation of trainee psychomotor performance and provides detailed feedback on their technical skills.

RÉSUMÉ

Contexte : La plateforme de réalité virtuelle en neurochirurgie NeuroTouch/NeuroVR a été utilisée dans l'analyse de la performance psychomotrice bi-manuelle de neurochirurgiens, de résidents, et d'étudiants en médecine. Les indicateurs précédemment développés par notre groupe se sont principalement portés sur la sûreté, l'utilisation de la force, et la performance bi-manuelle. Un nouvel indicateur, la *force pyramid*, a été créé afin d'étudier la distribution spatiale des forces utilisées pendant la résection de tumeurs cérébrales virtuelles.

Hypothèse : L'ergonomie de la main joue un rôle important dans l'ampleur et la distribution spatiale des forces utilisées pendant les résections de tumeurs cérébrales virtuelles.

Objectifs : En premier, examiner le rôle des *force pyramids* dominantes, non-dominantes, et bi-manuelles dans l'évaluation de la distribution spatiale des forces utilisées pendant les résections de tumeurs cérébrales virtuelles. En second, définir l'influence de l'ergonomie de la main sur le rapport entre les forces utilisées, le temps dépensé, et le volume de tumeur retiré.

Méthodes : Les données de neurochirurgiens, de résidents, et d'étudiants en médecine ayant réséqué des tumeurs cérébrales virtuelles ont été évaluées. La méthodologie de la *force pyramid* a été utilisée afin de déterminer la distribution spatiale des forces appliquées, du temps dépensé, et du volume de tumeur retiré. L'évaluation de l'ergonomie s'est faite en divisant l'information spatiale en quatre quadrants tumoraux (Q1- Q4), chacun exigeant une position de la main particulière pour effectuer la chirurgie.

Résultats : Les *force pyramids* montrent que les forces les plus élevées forment un croissant à Q4 pour la main droite (dominante), et un pic au centre pour la main gauche (non-dominante). La pyramide bi-manuelle montre un rapport égal entre les forces dominantes et non-dominantes chez les neurochirurgiens, et des forces non-dominantes plus élevées chez les résidents. Les neurochirurgiens adaptent leur comportement à Q2 et Q4 et, pour chaque unité de force utilisée, les neurochirurgiens et les résidents retirent un plus grand volume tumoral à Q2 par rapport à Q4.

Conclusion : L'ergonomie de la main joue un rôle crucial dans l'utilisation de la force et l'extraction de tissus pendant les opérations chirurgicales, et aide à définir le niveau d'expertise pour la résection de tumeurs cérébrales simulées. Les nouveaux indicateurs du NeuroVR évalués dans cette étude permettent une examination plus complète de la performance psychomotrice des résidents et fournissent des informations détaillées au sujet de leurs habiletés techniques.

ACKNOWLEDGEMENTS

The work presented in this thesis would not have been possible without the unwavering support and supervision of Dr. Rolando Del Maestro. Beyond being the director of the Neurosurgical Simulation Research and Training Centre, Dr. Del Maestro has been a wonderful mentor, and the two years spent working with him have been full of new experiences. I would like to thank him for this once-in-a-lifetime opportunity, for the advice and guidance, and for the passion he has instilled in me. It has been an honor.

My time at the lab would have been quite different without the delightful presence of Dr. Abdulgadir Bugdadi. I am grateful for our friendship and the fruitful and interesting conversations we have had over the past two years; it has been a great pleasure working together. His generosity and hard-work will lead him far, and I wish him the best with his neurosurgical residency in Paris.

I would also like to thank Dr. Ghusn Alsidieri and Dr. Alexander Winkler-Schwartz for their help with my work, especially for the interesting discussions and insight. I wish them both great success with their graduate studies and their residency training.

And to everyone who has been part of the lab during my time here, thank you for making the centre a great place for exchanging ideas and for camaraderie. With you, the work of the Neurosurgical Simulation Research and Training Centre is making its way around the world.

I would also like to acknowledge the support of Denis Laroche and Dr. Carlo Santaguida, who graciously accepted to be members of my Thesis Advisory Committee and who have provided invaluable feedback in putting this thesis together.

Thank you to the Di Giovanni Foundation, who has helped fund this lab for over 10 years, and to the Christian Geada Brain Tumour Research Studentship, which I was honored to receive in September 2016, for supporting our work.

To all my friends and colleagues throughout the Integrated Program in Neuroscience and the Graduate Student Association for Neuroscience, who have made my graduate studies an enjoyable and enriching experience, thank you.

Finally, to my parents, whose unbounded love and presence by my side has more impact on my work than they can imagine, thank you for teaching me, for supporting me, for motivating me, for everything. With you, I am embarking on my next adventure. “Love is my father and mother”, Khalil Gibran.

PREFACE AND CONTRIBUTION OF AUTHORS

The thesis is structured in a manuscript-based manner. The bimanual pyramid paper is under review of the Operative Neurosurgery editorial board. The ergonomics paper is in preparation to be submitted.

These studies build on work completed by previous students at the Neurosurgical Simulation Research and Training Centre.

Dr. Hamed Azarnoush initially created the force pyramid methodology and the first study on the subject was led by him.

Dr. Fahad Alotaibi investigated on the role of tumor characteristics on neurosurgical bimanual performance. The bimanual force pyramid study used the dataset that had been collected during these studies.

Dr. Khalid Bajunaid led a study on the effects of stress on psychomotor performance whose dataset was used to carry out the second project.

Dr. Abdulrahman Sabbagh worked in collaboration with the National Research Council to develop the virtual reality simulation scenarios used by participants in our studies.

Dr. Abdulgadir Bugdadi, Dr. Ghusn Alsidieri, Dr. Alexander Winkler-Schwartz, and Dr. Gmaan AlZhrani contributed to the elaboration of the experimental designs and to the interpretation of the results.

ABBREVIATIONS

AE: adverse events

OR: operating room

CB: computer-based

VR: virtual reality

Q1-Q4: quadrant 1 – quadrant 4

THESIS INTRODUCTION

Over the past decades, restriction in resident training hours, reports on surgical errors, and pressure to optimize costs have motivated educators to change their approach on postgraduate medical training. While still inspiring, the efficacy of the old Halstedian way of “see one, do one, teach one” is being reassessed as the optimal method of surgical teaching in dealing with the new realities of the surgical field. To remedy the situation, many accreditation organizations have developed new competency-based curricula focused on trainees achieving specific milestones using objective assessment and continual feedback.

Educators have recognized simulation as a powerful tool in training students and surgeons, and are recommending its greater integration in the new curricula. From cadavers, to animal models, including mannequins or the laparoscopic box, all surgeons and trainees today are familiar with a wide array of medical simulations. However, the simulation world is now evolving to include sophisticated computer-based platforms.

The NeuroVR (formerly NeuroTouch) virtual reality simulator focuses on neurosurgical procedures such as tumor resections. Its main property is the ability to provide users with haptic feedback: a feature that allows participants to receive tactile information on the simulated tissues and to manipulate them in a realistic way. While the necessity of haptic feedback in simulations and robot-assisted devices is agreed upon, most studies have seen its integration to platforms as an end, rather than a mean to assess the forces applied by surgeons. Haptic devices, such as the ones used in the NeuroVR, provide critical sensory feedback to participants and a wealth of information on the forces used that can be used in assessment and in the creation of performance benchmarks.

Several studies from the Neurosurgical Simulation Research and Training Centre have developed metrics to infer psychomotor skills from the force data obtained using the NeuroVR. Force use has been shown to vary between groups based on their level of expertise (AlZhrani et al., 2015; Alotaibi et al., 2015; Bajunaid et al., 2017). These measures, however, have been limited in their ability to assess force application and hand ergonomics during the resection of complex tumors. Established in a pilot study, the new force pyramid concept seems to be a promising addition to the performance metrics, as it can provide a large spectrum of information, including the spatial distribution of force applied by the participant during a simulated procedure (Azarnoush et al., 2015).

The studies carried out for this project make use of the force pyramid concept to investigate the spatial distribution of forces applied during simulated brain tumor resections to more closely evaluate psychomotor skills of trainees and neurosurgeons. In addition, the relationship between force applied, time expended, and tumor volume removed will be assessed to contextualize the technical skills of the various groups studied.

The hypothesis tested in these studies is that hand ergonomics affect the spatial distribution and magnitude of forces applied during virtual reality brain tumor resections, and play a critical role in the safety, quality, and efficiency of the simulated neurosurgical procedures. Assessing this hypothesis involved two objectives:

1. The first aim is to further expand the force pyramid analysis to both dominant and non-dominant hands. The data obtained will allow for the creation of a bimanual force pyramid to include the distribution of all forces applied during a virtual neurosurgical procedure.
2. The second aim is to assess the relationship between force applied, time expended, and tumor volume removed as a holistic approach to understand technical skills.

For each of these aims, the effect of expertise, handedness, and various tumor characteristics (colour, stiffness, border complexity) on hand ergonomics and the metrics will be evaluated.

The assessment of the role of hand ergonomics is essential in our understanding of bimanual psychomotor skills in neurosurgery. These studies will allow future trainees to receive accurate and detailed feedback on their surgical performance which may allow them to achieve competency at earlier stages of their training and increase their level of expertise. Ultimately, patients will benefit from surgeons acquiring expert skills at an earlier time during their training and career, to carry out procedures safely and efficiently.

BACKGROUND

Surgical Education

Historically, and for centuries, students interested in pursuing surgical training learned their craft through apprenticeships alongside a master surgeon (Hamdorf & Hall, 2000; Schlich, 2015). In 1890, John Hopkins Hospital's chief surgeon William Stewart Halsted established the first residency program for surgical education (Schlich, 2015). Following the "see one, do one, teach one" precept, his goal was for residents to acquire skills gradually until they achieved competency (Kotsis & Chung, 2013). Since Halsted's introduction of the residency program over a century ago, needs and expectations as well as technologies and techniques have evolved dramatically driving the surgical field towards reform. Reports on surgical errors (Baker et al., 2004; Stone & Bernstein, 2007; Anderson et al., 2013), restriction of weekly training hours (Blum et al., 2011; Kavic, 2011; Greenberg, 2013), and increased pressure to optimize costs (Sutherland et al., 2006; Delorme et al., 2012; Alaraj et al., 2013) have prompted accreditation organizations and medical schools to review their residency programs and curricula.

Following the 2000 report "To Err is Human" (Donaldson et al.), the movement for increased patient safety gained momentum. Over the next years, various reports on adverse events (AEs) demonstrated high preventability in surgical errors. A recent review study on surgical AEs concluded that potentially preventable AEs occurred in 5.2% of the surgical cases studied, with 3.6% leading to fatal consequences and 10.4% to severe injuries (Anderson et al., 2013). In neurosurgery, 87.1% of studied cases had an error, 27.8% of which were due to technical mistakes. However, most strikingly, 78.5% of those errors were considered highly preventable (Stone & Bernstein, 2007). A more detailed analysis shows that 65% of technical errors are due to manual performance, 49% of which cause permanent disability and 16% death (Regenbogen et al., 2007).

A similar report showed that 55% of consequential errors in laparoscopic surgery were due to technical errors where the surgical trainees applied too much force with their instrument (Tang et al., 2005). A large portion of these AEs may be due to the inherent learning curve technical skills acquisition which applies to both residents and expert surgeons (Bernstein et al., 2003).

Taken together, these AEs can be quite costly, both to the affected individuals and to society (Cobb et al., 2015). It is estimated that medical injuries in the United States lead to an extra 2.4 million days of hospitalization and 9.3 billion dollars in annual added costs (Zhan & Miller, 2003). In a similar study on surgical AEs, 36 patients who were victims of an error cost an extra 1.7 million dollars to the hospital for with a mortality rate of 55% (Couch et al., 1981). These studies reveal that there exists room for improvement in surgical training, to reduce the number of surgical errors, for the benefit of both patients and society.

Following the 1984 case of Libby Zion in the United States (Asch & Parker, 1988) and subsequent reports on operative fatigue, the Accreditation Council for Graduate Medical Education (ACGME) issued recommendations to restrict weekly training hours (Damadi et al., 2007). Since the early 2000s, countries worldwide have adopted a similar stance creating a discrepancy between the new guidelines and the established training programs (Woodrow et al., 2006). These new measures ultimately reduced the number of opportunities for resident to practice their skills with little to no improvements in patient care (Barry Issenberg et al., 2005; Sutherland et al., 2006; Damadi et al., 2007; Connors et al., 2008; Ahmed et al., 2014). However, some claim that increased resident wellbeing can ameliorate overall performance (Romanchuk, 2004; Durkin et al., 2007). Additionally, certain routine interventions for common diseases, that allowed residents to practice their technical skills on straightforward procedures, have either become less common or are now treated in minimally- or non-invasive ways (Murayama et al., 1999; Kavic, 2011). It is therefore imperative for current surgical residency programs to compose with these new realities and adapt.

Today's North American neurosurgical residents usually complete their residency in six or seven years, having spent an average of 26,320 hours in training (Cobb et al., 2015). During their residency, trainees rotate through various subspecialties to achieve learning objectives. After their training, they are required to pass examinations to be granted the certification and be deemed 'competent' (Bullock et al., 2014; Snell et al., 2014). While the evaluation of learned concepts may be objective, assessment of technical skills is highly subjective and is left to the judgment of surgical educators who simply observe trainees during their residency (Ota et al., 1995). However, medical educators have been critical of this approach and the vague definition of 'competence', and have called for thorough reform of the postgraduate medical curricula (Ota et al., 1995; Frank et al., 2010; Holmboe et al., 2010). The proposed changes would include a shift to a competency-based training model that puts greater emphasis on learned abilities with clear and achievable goals (Frank et al., 2010). Rather than training neurosurgeons to pass their exams, the competency-based model would ensure that all trainees reach predefined milestones. The Canadian Royal College of Physicians and Surgeons (CRCPS) has listed several changes needed to adjust to the new era: identification of core competencies, clear learning plans, personalized training and progress tracking and objective assessment and feedback ('Competence by Design', 2017). The organization has committed, through its new competency-based curricula, to provide trainees with "frequent assessment and meaningful feedback" as well as "well-defined learning paths and clarity around the competencies needed" ('Benefits of Competence by Design', 2017).

Given the proposed changes medical education, and a desire of residents to receive greater feedback (Aoun et al., 2012), new tools will be required. Likely, the new competency-based changes in residency training would benefit from a greater integration of simulation training. Various studies have suggested that the inclusion of simulation could in fact improve the overall quality of surgical education (Hamdorf & Hall, 2000; McNatt & Smith, 2001; Stienen et al., 2016).

Surgical Simulation

The first use of simulation in surgical education dates to 600 B.C. In a foundational text of Ayurvedic medicine, Indian physician Sushruta declares that “A pupil, otherwise well read, but uninitiated into the practice (of medicine or surgery) is not competent to take in hand the medical or Surgical treatment of a disease” and recommends practicing various surgical procedures on items such as watermelons, dead animals, or limbs of a doll (Bhishagratna, 1963; Menon & Haberman, 1969; Dwivedi & Dwivedi, 2007). Throughout history, other medical professionals have resorted to simulation to practice their skills: in 1759, Mme du Coudray toured France with her “Machine”, a mannequin composed of the pelvis of a woman and a model infant, to teach midwives the art of delivery (Gelbart, 1998); in the late 1800s, French surgeon Alexis Carrel invented the “triangulated vascular repair technique” by practicing embroidery on paper with fine needles (Rooney, 2012); in the late 1900s, William Steward Halsted himself practiced on animals to develop experimental surgical techniques while his student, Harvey Cushing, reportedly used cadavers to hone his skills for the removal of trigeminal ganglia (Schlich, 2015). In 1958, nearly two centuries after Madame du Coudray’s “Machine”, Asmund Laerdal, a Norwegian toy maker, started working on a mannequin for practicing CPR and mouth-to-mouth breathing, he named “Resuci-Anne” (Rosen, 2008; Rehder et al., 2016). To this day, Resusci-Anne mannequins are used worldwide to teach CPR techniques.

Modern simulation evolved with the technologies that emerged during the digital revolution and was largely inspired by the success of simulation in the aviation industry (Baker et al., 2008; Rosen, 2013). In the late 1960s, Sim One made its debut as the first computer-controlled simulator for anaesthesiology. Its creators, Denson and Abrahamson describe it as a six feet tall patient with a heartbeat, normal breathing and the capacity to blink (Denson & Abrahamson, 1969). Over the next decades, various simulators would appear, with varying amounts of success (Rosen, 2013). Among those, the MISTELS simulator for laparoscopic skills would prove to be the most successful (Fried et al., 2004; Rosen, 2013). With its adoption by the Society of American Gastrointestinal and Endoscopic Surgeons and the validation of the Fundamental of Laparoscopic Surgery curriculum developed for the MISTELS, it has become the gold standard for laparoscopic training (Satava, 2008).

High-fidelity computer-based (CB) and virtual reality (VR) simulators present numerous advantages for medical trainees, residents, and surgeons compared to classical simulation models such as animals and cadavers (Hamdorf & Hall, 2000; Coelho et al., 2014). Unlike animal models or cadavers, high-fidelity simulation can represent tissues as operators will commonly encounter them during surgical procedures (Gilbody et al., 2011; Scalese & Hatala, 2013; Gan et al., 2015). Furthermore, a common drawback of traditional models is their limited availability and reusability (Coelho et al., 2014). A review paper by Barry Issenberg et al. has classified key characteristics of high-fidelity simulations in the medical field in order of importance (2005). The authors found that a large portion of papers reviewed noted two main advantages of high-fidelity simulators: 1) their use in providing objective feedback, and 2) their ability in allowing users to practice repetitively. High-fidelity simulation thus excels by allowing trainees to rehearse procedures *ad infinitum*. This repetition is essential in developing automated psychomotor skills that allow trainees to focus on other situational aspects of the operation (Dagi, 2013). Additionally, CB and VR simulations permit the rehearsal of infrequent cases and complications, therefore increasing chances surgeons will be prepared when these situations occur (Rall & Dieckmann, 2005).

Simulations may also improve patient safety and outcomes. By introducing simulation workshops into the surgical curricula, educators would partially shift the skill acquisition period to simulated models, consequently decreasing associated risks to patient (Satava, 2008). This change would also offer the opportunity for students to learn from mistakes and to focus on specific aspects of their skills (Dagi, 2013). Ultimately, CB and VR simulations would allow researchers to study both the causes of human error, and the reaction of trainees to those mistakes (Rall & Dieckmann, 2005). Care and patient safety should always be a priority (Sirimanna & Aggarwal, 2013), and simulation is thought to promote a “safety culture” that could be transferred to operating rooms (ORs) (Bernstein et al., 2003; Rall & Dieckmann, 2005).

The OR presents many obstacles in the accurate task analysis and assessment of a trainee’s abilities (Rall & Dieckmann, 2005; Sirimanna & Aggarwal, 2013). One of the main advantages of CB and VR simulations are their ability to provide users with objective feedback without the need to be under constant supervision of a trained surgeon (Hamdorf & Hall, 2000; Coelho et al., 2014). The combination of assessment and feedback, is thought to help promote the acquisition, development and refinement of psychomotor and cognitive technical skills (Satava, 2008; Sirimanna & Aggarwal, 2013; Coelho et al., 2014), and to reduce the rate of decay of acquired skills (Issenberg et al., 2005). Finally, the creation of accurate assessment tools would allow to evaluate proficiency and set expert benchmarks that trainees will be expected to reach (Dagi, 2013).

Because of its inherent ‘hands-on’ approach, simulation allows learners to better integrate knowledge compared to traditional lecture courses (Pasquale, 2013). While some studies claim that simulation training still needs to achieve desired patient outcomes (Rosen, 2013) and that more proof is needed to show that CB simulation is superior to standard or video simulation (Sutherland et al., 2006), other research suggests that it indeed improves results in the OR (Seymour et al., 2002; Lehmann et al., 2005; Palter et al., 2011). Further work is warranted to clearly demonstrate the translation of skills acquired during simulation training to the OR. It is generally agreed upon, however, that simulation technology is not currently meant to replace traditional learning methods, but to complement it (Issenberg et al., 2005).

NeuroVR

The NeuroVR (formerly NeuroTouch) is a virtual reality simulation platform developed by the National Research Council (NRC) of Canada in collaboration with universities across Canada to aid in the assessment and training of residents' technical skills on a wide variety of craniotomy-based procedures (Alotaibi et al., 2015; Alotaibi et al., 2015; AlZhrani et al., 2015; Azarnoush et al., 2015; Azarnoush et al., 2016; Bajunaid et al., 2016; Choudhury et al., 2013; Delorme et al., 2012; Gélinas-Phaneuf et al., 2014; Rosseau et al., 2013; Varshney et al., 2014; Varshney et al., 2014; Winkler-Schwartz et al., 2016). It uses physics-based finite element tissue models to simulate tissue deformation and dissection as well as bleeding and blood accumulation (Clarke et al., 2012; Delorme et al., 2012). The simulator features a microscope and surgical tools (e.g. ultrasonic aspirator, suction tool, bipolar coagulator, microscissors, etc.) to be used on various neurosurgical tasks. The simulators' realism relies on its stereoscopic vision showing tissue deformation in the operating field, and haptic feedback which allows the user to correctly perceive and manipulate tissues. A library of various surgical procedures (or scenarios) are available for training purposes, including tumor resection (Choudhury et al., 2013).

The simulator has undergone various validation studies (Gélinas-Phaneuf et al., 2014; Alotaibi et al., 2015; Azarnoush et al., 2015). Although face and content validity have been demonstrated, construct validity has required more extensive research, with initial work establishing the basic framework to quantify operator performance (Azarnoush et al., 2015). Metrics used to measure the proper execution of the virtual procedures were categorized into three tiers: tier 1, tier 2, and tier 3. Each tier analyzed select aspects of the intervention: tier 1assessed safety and quality, tier 2 assessed force application, and tier 3 assessed spatial distribution of force (Alotaibi et al., 2015; Azarnoush et al., 2015). Another tier, advanced tier 2 (or tier 2a), was added to analyze bimanual performance (Alotaibi et al., 2015). Following studies showing differences between medical students, residents, and neurosurgeons, performance benchmarks were established (AlZhrani et al., 2015). Subsequent research proved construct validity with the introduction of stress factors (Bajunaid et al., 2017) or by comparing and scoring neurosurgical resident applicants (Winkler-Schwartz et al., 2016).

Haptic Feedback

Throughout these studies, it became apparent that force metrics are essential in the accurate assessment of participant performance (Alotaibi et al., 2015; AlZhrani et al., 2015). This observation is due primarily to the capacity of the NeuroVR to provide users with realistic tactile experience, by using the Phantom Omni haptic devices that transmit forces to the user (Delorme et al., 2012). "Haptic feedback is defined as the combination of sensory input through the tactile receptors of skins and the kinesthetic receptors in the muscles, tendons, and joints" (Owens & Taekman, 2013). This tactile output allows users of simulators, such as the NeuroVR, to interact with and manipulate simulated tissues in a more realistic way (Rall & Dieckmann, 2005). The ability to sense the mechanical properties of the operated tissues can reveal critical information to the surgeon, whether it is about the underlying structures or to distinguish different tissue types (De Lorenzo et al., 2011). This is especially important to expert surgeons as they have been shown to more efficiently discriminate between tissues with force alone compared to vision alone (Moradi Dalvand et al., 2014).

The importance of realism or 'high-fidelity' has been the subject of extensive research aiming to link simulator fidelity to skill acquisition. In aviation, it has been established that while low-fidelity simulators may be useful for early skill acquisition, high-fidelity simulators are much better predictors of real-life performance (Noble, 2002). In the surgical field, Ericsson and Charness (2014) outline that to properly assess expertise, the simulated environment must closely imitate the real task.

The introduction of robotic systems into the OR, improving the efficiency of various surgical procedures, demonstrated the importance of haptic feedback in maintaining surgeons' performance (Wagner et al., 2007). While visual and auditory feedback are simple to translate, adequate tactile stimulation has been a limiting factor, both in robot-assisted systems and in surgical simulation (Maddahi et al., 2015). Initial studies looking at the effect of haptic feedback on surgical procedures noted significant differences in force application between operations carried out with the added tactile response and those executed without (Bethea et al., 2004; Tholey et al., 2005; Rodrigues, et al., 2014). Additionally, a study by Wagner et al. (2007) showed that inaccurate force feedback led to increased force application by the operator and therefore to a significantly greater number of errors. Finally, studies by a group in Calgary established force metrics and showed that maximum forces used by a controlled robotic arm on cadaveric brains varied between 1 to 3 Newtons (Maddahi et al., 2015; Maddahi et al., 2016).

Several metrics, belonging to the tier 2 category, have been developed to evaluate the forces applied by participants on the NeuroVR: the maximum force applied (MFA) shows the peak force used by an operator, while the sum of forces applied (SFU) calculates the total forces used during the simulated procedure (Azarnoush et al., 2015; Alotaibi et al., 2015). Although these metrics have allowed psychomotor skill characterization of various groups (Alotaibi et al., 2015; AlZhrani et al., 2015; Bajunaid et al., 2017), their scope is limited. While the MFA can be useful in determining force restraint in groups, it represents an instantaneous force applied that may be related to a sudden inadvertent movement. The SFU considers all forces used, however, the values obtained can only be compared in procedures of similar durations. Metrics such as "average force applied" and "median force applied" may provide more insight but much like the other metrics, they evaluate the overall forces used and consider neither temporal nor spatial distribution.

Force Pyramid

The concept of the force pyramid first emerged in a pilot study by Azarnoush et al. (2015), which involved the development of a visual representation of the spatial distribution of forces applied. The xy plane of the figure represented the operating field, while the z axis showed peaks whose height was proportional to the force applied at each position. The force pyramid potentially allows one to distinguish certain areas that are subject to increased force and may provide insight into regions of the tumor that require advanced psychomotor skills to resect. Its name was derived from an initial hypothesis that operators would apply greater forces at the centre of the tumor, where it is safe to do so without any risk of damaging surrounding structures.

The initial study conducted using the new metric assessed medical students, residents, and neurosurgeons on a series of 18 tumors with different stiffness and colour characteristics. All participants were required to remove each tumor using only a surgical aspirator held in the dominant hand. The force pyramid showed that all groups used most of their highest forces in the lower right quadrant of the tumor. When separating right-handed and left-handed participants, an interesting difference was observed where left-handed exerted their highest forces on the lower left quadrant of the tumor. The group comparison revealed that neurosurgeons generally used less force than residents, who in turn used less force than medical students. Tumor characteristics had an additional effect on the performance of all groups: hard and black tumors, in contrast with soft and white tumors, showed greater forces overall. The work therefore validated the force pyramid as a metric that can distinguish novices from experts and that can reveal the effects of tumor characteristics on surgical performance. Finally, the study raised the issue of hand ergonomics and of its role in the spatial distribution of forces used during these virtual reality brain tumour resections.

Hand Ergonomics

The hand is used extensively by humans to interact with the world. With its three degrees of freedom, flexion and extension, radial and ulnar deviation, and rotation, the wrist allows us to perform a wide variety of tasks with ease and precision (Palmer et al., 1985). Hand and wrist ergonomics, the study of interactions between humans and the tools they use, have therefore been of great interest to various fields. Improving the efficiency of systems in place and adapting human performance depend on proper assessment of these ergonomic parameters (Berguer, 1998).

Hand and wrist ergonomics have been primarily studied in the context of carpal tunnel syndrome. Many studies have characterized the biomechanics of the wrist and have established safe carpal tunnel pressure thresholds beyond which nerve impairment can occur. Wrist deviation from normal slowly increase carpal tunnel pressure, and pressures above 30 mmHg have been shown to lead to changes in neuronal conduction amplitude, and when sustained, to edema and demyelination in animals (Keir et al., 2007). A link therefore exists between hand-wrist ergonomics and corresponding deficits in normal sensory and motor nerve function (Gelberman et al., 1983; Luchetti et al., 1990; Keir et al., 1998).

An ergonomics study of pianists' hand revealed that wrist mobility influenced their performance while playing and had a positive correlation with their perceived success. The mobility of the joint affected their tempo, and the evenness of their musical piece (Lee, 1990). In the surgical field, hand ergonomics became a topic of interest with the introduction of laparoscopic surgery. Studies have observed that the tools needed to carry out the procedure cause excessive flexion of the wrist which, when in a non-neutral position, increases carpal tunnel pressure and subsequent fatigue and therefore affecting surgical performance (Berguer, 1997; Berguer et al., 1998; Berguer; 1999; Hanna et al., 2001). It is all the more important to evaluate ergonomics in the context of surgery due to the high level of precision and concentration required from surgeons and trainees. When performing such tasks, Visser et al. have observed increased contraction of muscles leading to reduced wrist mobility, which allows the individual to better control their movements (2004).

The work presented in this thesis will therefore use the force pyramid as a tool to evaluate hand ergonomics during virtual reality brain tumor resections. A proper assessment of hand and wrist positions during these procedures and the observation of their effects on surgical performance will allow us to better understand expertise and behaviors learned during residency training.

RATIONALE: STUDY 1

This first project will expand on the force pyramid concept and introduce two new types of pyramids: the non-dominant force pyramid and the bimanual force pyramid. Like the dominant force pyramid, the non-dominant force pyramid is a visual representation of the spatial distribution of forces applied with the non-dominant hand (e.g. the suction tool or other instruments). The bimanual force pyramid aims to combine both dominant and non-dominant force pyramids to display all forces applied in the operating field during a simulated procedure.

STUDY 1

Virtual Reality Tumor Resection: The Force Pyramid Approach

Robin Sawaya, BSc, Abdulgadir Bugdadi, MD, MSc, Hamed Azarnoush, PhD, Alexander Winkler-Schwartz, MD, Fahad E. Alotaibi MD, MSc, Khalid Bajunaid, MD, MSc, Gmaan A. AlZhrani, MD, MA, Ghusn Alsideiri, MD, Abdulrahman J. Sabbagh, MBCHB, FRCSC, Rolando F. Del Maestro, MD, PhD

ABSTRACT

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, non-dominant hand, and bimanual force pyramids during resection of virtual reality brain tumors.

Objective: This study addresses four questions: Do ergonomics and handedness influence force pyramid structure? What are the differences between dominant and non-dominant 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 non-dominant hand, 6 neurosurgeons and 14 residents resected 8 different tumors using the NeuroVR virtual reality neurosurgical simulation platform. 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. Non-dominant 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.

INTRODUCTION

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 (Wagner et al., 2007). 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 resection of simulated tumors using the NeuroVR virtual reality simulation platform (Alotaibi et al., 2015; Alotaibi et al., 2015; AlZhrani et al., 2015; Azarnoush et al., 2015; Azarnoush et al., 2016; Bajunaid et al., 2016; Choudhury et al., 2013; Delorme et al., 2012; Gélinas-Phaneuf et al., 2014; Rosseau et al., 2013; Varshney et al., 2014; Varshney et al., 2014; Winkler-Schwartz et al., 2016). These metrics have allowed us to explore ‘expert’ (neurosurgeon) and ‘novice’ (senior, junior resident and medical student) operative behaviour (Alotaibi et al., 2015; Alotaibi et al., 2015; AlZhrani et al., 2015; Azarnoush et al., 2015; Azarnoush et al., 2016; Bajunaid et al., 2016; Gélinas-Phaneuf et al., 2014; Winkler-Schwartz et al., 2016). Dominant hand ergonomics play a role in determining location and magnitude of force application (Azarnoush et al., 2016). However, dexterity varies significantly between dominant and non-dominant hands, and fine muscle control of the non-dominant hand is a learned skill requiring significant practice (Gélinas-Phaneuf et al., 2013; Khabbaz et al., 2016). 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 non-dominant hand to control bleeding. This allowed the generation of force pyramids for both dominant and non-dominant 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', operator-specific force pyramid structures continually modulated by education and experience.

This study was designed to answer four questions: 1) Do ergonomics and handedness influence the force pyramid structure? 2) What are the differences between dominant and non-dominant hand force pyramids? 3) What is the spatial distribution of forces amongst 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, PGY1-3 and 7 seniors, PGY 4-6) participated. All had previously enrolled in a simulation trials and were familiar with the NeuroVR (Azarnoush et al., 2015; Azarnoush et al., 2016). All signed a consent form approved by the institute's ethics review board before taking part.

NeuroTouch/NeuroVR Simulator

The previously described NeuroTouch (now known as NeuroVR) virtual reality simulation platform was used in this study (Alotaibi et al., 2015; Alotaibi et al., 2015; AlZhrani et al., 2015; Azarnoush et al., 2015; Azarnoush et al., 2016; Bajunaid et al., 2016; Choudhury et al., 2013; Delorme et al., 2012; Gélinas-Phaneuf et al., 2014; Rosseau et al., 2013; Varshney et al., 2014; Varshney et al., 2014; Winkler-Schwartz et al., 2016). The procedures were performed with an aspirator in the dominant hand to resect the tumor and a sucker in the non-dominant hand to control bleeding (Figure 1A). Instrument intensities were controlled at constant values (Alotaibi et al., 2015).

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 two 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 kPa), border complexity and color characteristics (Figure 1B). Table 1 shows the tumor characteristics and tumor sequences presented to participants (Alotaibi et al., 2015).

Resection was carried out in a predefined sequence (Table 1, left to right). Participants were given a sufficient 3 minutes to resect each tumor (Alotaibi et al., 2015). 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) (Alotaibi et al., 2015; Alotaibi et al., 2015; Azarnoush et al., 2016). To assess intratumoral spatial distribution of forces applied, the top view of the tumors was divided into 4 quadrants (Q1 to Q4, counter-clockwise from the top-right quadrant) (Figure 1C) (Azarnoush et al., 2016).

Spatial Analysis

Position and force application data were recorded for each instrument. Position data was fitted to a 0.5 mm three-dimensional grid from its original scattered distribution (Figure 2A and B). Forces associated with the same position were averaged. The force data was then summed along the z-axis (depth of the tumor) to obtain the total forces applied at each position on the xy-plane of the scenario (tumor and surrounding tissue), as previously described (Figure 2C) (Azarnoush et al., 2016). A force pyramid was created for each tumor resected, for the dominant and non-dominant hand (Figure 2D). The bimanual pyramids were generated by addition of dominant and non-dominant pyramids at corresponding xy position. Average force pyramids for each group and tumor characteristic were obtained by averaging the forces at corresponding xy positions. All force pyramids were similarly scaled and coloured using a standardized scale ranging from 0 Newtons (dark blue) to 0.2 Newtons (dark red). Figures representing highest forces areas were created by locating forces above 70% of the maximum force applied, as previously described (Azarnoush et al., 2016).

Time and adjusted force distributions

Two additional pyramids types were created to control for time spent at each tumor position. 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 (IBM Corporation) software. Due to small sample sizes, the distribution data was analyzed using non-parametric tests.

The Mann-Whitney U test was used to compare right and left-handed participants, with p-values < 0.05 indicating significance. The Kruskall-Wallis test, followed by Dunn's test for non-parametric pairwise comparison, was used to compare the four quadrants of participants, with p-values < 0.05 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, 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 ($p=.01$) (Azarnoush et al., 2016). Due to those differences, left-handed participants were excluded from subsequent analyses.

Force Pyramids of Right-handed Participants

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

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 (Azarnoush et al., 2016). 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 non-dominant central peak, seen in all groups. For residents, the predominant central peak is due to the higher forces applied by the non-dominant 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

Non-dominant, 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 (non-dominant $p=.92$, dominant $p=.88$, bimanual $p=.99$).

The non-dominant 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 non-dominant 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 non-dominant 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 difficulty of resection, this would suggest that Q4 presents the greatest challenge to right-handed individuals with Q1 and Q3 being intermediate and Q2 being the least difficult.

Force Thresholds

Neurosurgeons applied lower average forces (0.12 ± 0.04 N) with the non-dominant hand followed by senior (0.13 ± 0.03 N) and junior residents (0.14 ± 0.04 N). Comparing average force thresholds for each group shows that neurosurgeons applied greater force with the dominant hand (0.15 ± 0.02 N) followed by junior (0.14 ± 0.03 N) and senior residents (0.12 ± 0.02 N) respectively. A comparison of dominant to non-dominant hand threshold ratios shows that non-dominant thresholds predominately contributed to bimanual pyramids of resident groups while neurosurgeons' bimanual pyramids consisted of dominant and non-dominant values in equal proportion.

Tumor Characteristics

Figures 7, 8, and 9 compare the tops views for groups resecting hard and soft, black and glioma-like, distinct and indistinct tumors, respectively.

In figure 7, neurosurgeons and senior residents applied lower forces with the dominant hand in tumors with 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 show that residents applied more force with the non-dominant hand while neurosurgeons contributed with both hands equally.

In figure 8, all groups applied higher forces with the non-dominant hand when removing black tumors. With the dominant hand, neurosurgeons confined their highest forces in Q4 for both colors, while residents scattered these forces. Bimanual pyramids illustrate that the non-dominant hand contributed the highest forces for black tumors in all groups, while the dominant hand was the main responsible for glioma-like tumors for neurosurgeons.

In figure 9, each group applied higher forces to remove hard tumors with the dominant hand, consistent with our previous studies (Azarnoush et al., 2016). Neurosurgeons confined their highest forces in Q4 for both tumor types while residents distributed these forces more broadly. All groups had difficulty at the tumor-normal tissue interface of soft tumors, with larger crescent areas involving R2 and R3 for resident groups. The bimanual pyramids show a greater contribution of the non-dominant hand to the highest forces in hard tumors and of the dominant hand for soft tumors.

DISCUSSION

Summary

We have applied novel force pyramid methodology to create and quantify dominant, non-dominant, and bimanual pyramids to assess the role of handedness and document differences between neurosurgeon and resident groups (Azarnoush et al., 2015; Azarnoush et al., 2016). The multiple bleeding sources in the present scenario improved realism but necessitated the use of a suction tool in the non-dominant hand allowing the creation of non-dominant and bimanual force pyramids. This study is unique in conceptualizing the bimanual force pyramid, derived from the NeuroVR virtual reality platform, 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 non-dominant and bimanual force pyramids of right and left-handed operators. The quantitative analyses corroborated our qualitative observations, demonstrating significant differences in force distribution between the dominant force pyramids of right and left-handed participants. The ergonomic factor of operator hand position during tumor resection is hypothesized to be responsible for these findings (Azarnoush et al., 2016). 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, then internally rotating and further flexing the wrist to resect the lesion at the Q4 tumor-normal tissue interface in region R2. Left-handed and ambidextrous individuals first begin wrist flexion to remove Q4 tumor and then rotate and further flex their wrist to complete tumor resection in Q3. 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 (Azarnoush et al., 2016). 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.

Non-dominant 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 (Bajunaid et al., 2016). The novel bimanual force pyramid combines the central peak generated by the non-dominant 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 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 (e.g. Q4 tumor-normal tissue interface for right-handed students, Q3 for left-handed participants) at increased risk of damage.

Quadrant Force Distribution and Ergonomics

For all groups, significantly less force was used with the dominant hand in Q2 compared to Q4. If dominant hand force distribution relates to ease of resection, our data would indicate that Q2 is the easiest quadrant to resect for right-handed participants using the aspirator, while Q4 is the most difficult. Q1 and Q3 quadrant resection require forces midway between those employed to resect tumor in Q2 and Q4. This data is best explained by the ergonomics of the dominant hand at each quadrant, with Q2 requiring minimal wrist flexion and internal rotation, Q1 and Q3 slightly more, and Q4 requiring maximal flexion and rotation. Studies focused on defining the ergonomics that provide the best dominant and non-dominant hand positions, instrument orientation and human interactive factors to maximize safe tumor resection are needed.

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 non-dominant hand on the left side of the tumor. Since no significant differences are seen in the time-adjusted force distribution of the non-dominant 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 non-dominant hand to the total forces employed by residents, while neurosurgeons' dominant and non-dominant 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 behaviour enhanced by experience gained after residency.

Forces Applied and Thresholds

In a previous study on force pyramids, our group showed that neurosurgeons used significantly less force than medical students and resident groups (Azarnoush et al., 2016). In the present study, however, neurosurgeons used higher forces than the resident groups assessed. The more complex scenario requiring more extensive bimanual technical expertise might explain this difference (Gélinas-Phaneuf et al., 2014; Holloway et al., 2015; Khabbaz et al., 2016). Although neurosurgeons and residents had participated in our previous studies, neurosurgeons may have more efficiently used their prior knowledge of virtual reality and clinical experience to adjust their psychomotor behavior for this more difficult trial. Wagner et al. discussed an efficiency-force trade-off in which experts may use higher forces necessary to remove a greater amount of tumor in a shorter amount of time, while novices are more hesitant with their forces or have not yet learned to use forces appropriately (Wagner et al., 2007). The bimanual force pyramid thresholds also provide information on the ratio of the dominant and non-dominant pyramids. Resident bimanual pyramids thresholds are principally dependent on the higher relative force of their non-dominant hand. Neurosurgeons forces, although higher, tend to be similar for both hands possibly due to their ability to better control forces using their non-dominant hand (Bethea et al., 2004).

Tumor Characteristics

The present study corroborates our results on dominant force pyramids and provides additional insight into non-dominant and bimanual forces used in the resection of simulated tumors (Alotaibi et al., 2015; Azarnoush et al., 2016). Despite altering the stiffness, border distinction, and color of tumors, non-dominant hand pyramids demonstrate that the highest forces are concentrated in the central tumor region. The bimanual pyramids of these various tumors emphasize the contribution of the non-dominant hand to the total forces employed by residents. Neurosurgeon bimanual pyramids, however, show that the dominant and non-dominant hands are equally responsible for the total forces. This data would suggest that 'experts' have learned to distribute forces uniformly between their two hands when using multiple instruments, a behaviour enhanced by experience gained after residency. Our results are consistent with the concept of the 'surgical fingerprint' that, where operators evolve specific dominant, non-dominant and bimanual force pyramid structures that are continually fine-tuned by experience and deliberate practice.

Strengths and Limitations

Our results are consistent with the concept of the 'surgical fingerprint' that operators evolve unique dominant, non-dominant 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 (Rosseau et al., 2013; Varshney et al., 2014; Varshney et al., 2014; Thawani et al., 2016). 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. Finally, video recordings of the tumor resection and hand positions during the procedure will be included in future studies, which should allow us to further understand the complex relationship between hand ergonomics and bimanual performance. Further studies of the effect of simulators such as the NeuroVR on patient outcomes are needed (Azarnoush et al., 2015; Gélinas-Phaneuf et al., 2013; Kirkman et al., 2014).

CONCLUSION

The innovative force pyramid approach to virtual reality tumor resection provides spatial distribution and quantitation 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.

RATIONALE: STUDY 2

This second project will delve deeper into the effect of ergonomics theorized in the previous studies. Only one type of tumor is analyzed and medical students are included as a naïve population to understand how technical skills are acquired and how expertise affects various metrics. To the study of forces applied will be added the spatial distribution of time expended and tumor volume removed. Including these measures will allow us to gain a better understanding of the relationship between those variables and clarify their link to hand ergonomics.

STUDY 2

Effect of hand ergonomics on performance metrics in virtual reality brain tumor resections

Robin Sawaya, BSc, Ghusn Alsidieri, MD, Abdulgadir Bugdadi, MD, MSc, Alexander Winkler-Schwartz, MD, Khalid Bajunaid, MD, MSc, Abdulrahman J. Sabbagh, MBCHB, FRCSC, Rolando Del Maestro, MD, PhD

ABSTRACT

Background: Previous work from our centre has shown that hand ergonomics play an important role in surgical psychomotor performance during virtual reality brain tumor resections. Studies on the matter indicate that wrist mobility can affect movements and efficiency. In this study, we use previous analyses of spatial distribution with new metrics to elucidate the relationship between ergonomics and the surgical fingerprint.

Objective: This study aims to answer three questions: How much time does each group spend in specific tumor areas? How are time, force, and tumor volume removed distributed amongst the four quadrants of the tumor? How do hand ergonomics affect the relationship between tumor volume removed and force applied?

Methods: Neurosurgeons, residents, and medical students were tasked to resect tumors using a simulated aspirator in the dominant hand on the NeuroVR virtual reality neurosurgical simulation platform. The spatial distribution of force applied, time expended, and tumor volume removed were analyzed for each group.

Results: There were significant differences between Q2 and Q4 for the forces applied, and significant differences between right-hand-side and left-hand-side quadrants for time expended and tumor volume removed. Differences between Q2 and Q4 were emphasized in measures of force applied and tumor volume removed per second. Similar differences between quadrants were observed in tumor of tissue removed per unit of force used.

Conclusion: The results indicated the critical role of hand ergonomics in surgical performance. Assessment and training of students may allow them to better control their movements to carry out procedures safely and efficiently.

INTRODUCTION

Research from our group has explored the effect of hand position and ergonomics on the spatial distribution of force application during virtual reality simulated brain tumor resections (Azarnoush et al., 2016). A new metric, the force pyramid, was developed to compare groups with different levels of expertise and handedness (Azarnoush et al., 2015). Our previous study examined differences between the dominant hand using a surgical aspirator and the non-dominant hand using a suction tool. The results distinguished critical regions of the tumor that required participants to adapt their behavior to complete the task. The spatial distribution analysis of forces applied has therefore provided us with a greater understanding of the complex bimanual performance of various groups.

The NeuroVR virtual reality neurosurgical simulation platform has allowed us to assess the surgical performance of 'expert' and 'novice' participants carrying out simulated brain tumor resections (Alotaibi et al., 2015; Alotaibi et al., 2015; AlZhrani et al., 2015; Azarnoush et al., 2015; Azarnoush et al., 2016; Bajunaid et al., 2016; Gélinas-Phaneuf et al., 2014; Winkler-Schwartz et al., 2016). The performance of neurosurgeon, resident, and medical student groups has been evaluated using a series of metrics developed by our group. These metrics, organized into tiers, focus on psychomotor skills such as safety, quality, efficiency, and bimanual dexterity. While these measures are very informative, their scope is limited in assessing the spatial distribution of force application.

With the recent creation of the force pyramid, we have been able to assess hand position and ergonomics and the resulting spatial distribution of force. However, the relation of force application to other measures of surgical performance remains unclear. This work therefore aims to further expand the spatial distribution analysis to other variables such as time expended and tumor volume removed.

In this study, we investigate the effects of hand ergonomics on time expended, force applied, and tumor volume removed. The work presented addresses the following three questions: 1) How much time does each group spend in specific tumor and non-tumor areas? 2) How are time, force, and tumor volume removed distributed amongst the four quadrants? 3) How do hand ergonomics affect the relationship between tumor volume removed and force applied?

METHODS

Subjects

Six neurosurgeons, 6 senior residents (PGY 4-6), 6 junior residents (PGY 1-3) and 6 medical students participated in this study. Left-handed participants (one senior resident and one medical student) were removed from subsequent analyses. Everyone signed a consent form approved by McGill's Ethics Review Board before taking part in the study.

Study design

The data used in the following analyses was collected in a previous study that assessed the effects of stress on surgical performance (Bajunaid et al., 2016). Participants were instructed to resect a series of six ellipsoidal tumors, identical in colour and stiffness. To induce stress, the fourth tumor would bleed uncontrollably, unbeknownst to the participant. The tumors were categorized into 4 groups: tumor 1 was considered a practice trial, tumors 2 and 3 as 'pre-stress', tumor 4 as 'stress' and tumors 5 and 6 as 'post-stress'. Based on the previous study's categorization, only the 'pre-stress' tumors (tumors 2 and 3) are analyzed in this work. Time, force, and volume data were averaged for each participant and subsequently analyzed as one.

The simulated brain tumor resections were performed on the NeuroVR virtual reality simulator platform. To perform the tumor resection, participants used an aspirator in the dominant hand for tumor removal, and a sucker in the non-dominant hand to control bleeding. Participants were allowed 2 minutes to carry out the procedure on each tumor.

Data analyses

The data analyzed in this project included the position of the dominant-hand instrument in space and the time expended in seconds (s), force applied in Newtons (N), and tumor tissue removed in cubic centimeters (cc) corresponding to each position. All analyses were performed using MATLAB (MathWorks Inc.).

The surgical field was separated into three areas (Figure 10): all components that do not involve the tumor (A), the tumor above the surface of the brain (B), the tumor below the surface of the brain (C). Because of its critical location adjacent to surrounding normal tissue, only area C was considered in subsequent analyses.

The tumor was further partitioned into 4 equal quadrants starting from the top-right quadrant Q1 and going counter-clockwise to Q4 (Figure 1C). For each tumor resection, the total time spent, total forces used, and total tumor volume removed were calculated per quadrant.

Statistical analyses

Statistical analyses were conducted using JMP statistical software (SAS Institute). A non-parametric approach using the Kruskal-Wallis test, followed by Dunn's test for pairwise comparisons was chosen due to the small sample sizes. P-values below 0.05 were considered significant. Error bar show the standard error (SE).

RESULTS

Time expended per tumor area

The time expended per tumor area was only significant between neurosurgeons and medical students in area A (Figure 11). No significant differences were observed between participant groups in areas B and C. However, a trend shows neurosurgeons spending more time within area C and less time in areas A and B, compared to residents and medical students.

Considering the proportion of time spent within critical tumor area C was not significantly different between groups, only data from area C was considered in subsequent analyses.

Quadrants

The total time expended per quadrant (Figure 12) shows significant differences between Q1 and Q3 for neurosurgeons ($p=.026$) and senior residents ($p=.020$). All groups appear to spend less time in Q2 and Q3 and more in Q1 and Q4. The total force applied per quadrant (Figure 12) was significantly different between Q2 and Q4 for neurosurgeons ($p=.004$); as seen in our previous study (Azarnoush et al., 2016). Resident groups distributed their forces in a similar fashion. The total tumor volume removed per quadrant (Figure 12) shows a significant difference between Q1 and Q3 for neurosurgeons ($p=.012$).

The average force used per second (Figure 13) shows a significant difference between Q2 and Q4 for neurosurgeons ($p=.004$), similar trends for residents, and no observable change for medical students. The average tumor volume removed per second (Figure 13) shows a significant difference between Q2 and Q4 for junior residents ($p=.037$), similar trends for neurosurgeons and senior residents, and no observable change for medical students.

The average tumor volume removed per unit of force (Figure 14) shows a significant difference between Q2 and Q4 for neurosurgeons (p=.002) and junior residents (p=.042). A similar trend appears for senior residents, while medical students remain constant with a much lower value.

Ellipses

Since the most significant differences were observed between Q2 and Q4 for quadrants, these quadrants were selected for our qualitative analysis of each group's adaptive capacity. The average force used per second was plotted against the average tumor volume removed per second for each group and the 95% coverage ellipse for each quadrant or shell was outlined (Figure 15). The ellipses for Q2 and Q4 segregated into two distinct groups for neurosurgeons, overlapped to a small extent for residents, and overlapped completely for medical students.

Groups

Significant differences were observed for the tumor volume removed between neurosurgeons and junior residents in Q2 (p=.046) and Q3 (p=.040), and between neurosurgeons and medical students in Q2 (p=.019) and Q3 (p=.019).

DISCUSSION

Summary

This study furthers our understanding of the effect of hand position and ergonomics on surgical performance. Time expended, forces applied, and tumor volume removed were analyzed per tumor quadrant. The results corroborated our previous findings (Azarnoush et al., 2016) and emphasized the role of expertise in psychomotor performance. Neurosurgeons have developed and posses a higher capacity to adapt their hand position and ergonomics to perform tumor resections with increased efficiency.

Quadrants

In previous studies, our group had shown significant differences between Q2 and Q4 in the amount of force applied (Azarnoush et al., 2016). Those results were hypothesized to be due to the specific hand ergonomics needed to resect the tumor in each quadrant. The dominant wrist is in a neutral position when resecting tumor in Q2, but flexed and internally rotated while in Q4. This sub-optimal wrist flexion has been shown to reduce individuals' ability to correctly perceive force feedback and to subsequently modulate the forces used (Gelberman et al., 1983; Luchetti et al., 1990; Keir et al., 1998).

The spatial distribution of force observed in this study corroborated our previous results. The findings also indicated a tendency towards increased time expended and tumor volume removed for the right-hand-side tumor quadrants (Q1 and Q4). The non-neutral hand position and flexed wrist may lead right-handed participants to spend more time in the right-hand-side tumor quadrants, perhaps due to the difficulty of the task and to the higher demand for precision in these tumor regions (Visser et al., 2004).

The mean force applied and mean tumor volume removed measures emphasize the differences in hand position and ergonomics between Q2 and Q4 for forces applied, and between right and left-hand-side quadrants for tumor volume removed. The increased capacity to remove tumor per second in left-hand-side tumor quadrants is best explained by the neutral, and thus optimal, position of the wrist which permits ample and fast instrument movements. The analysis of the tumor volume removed per force applied further highlights differences between Q2 and Q4.

Neurosurgeons and residents remove a larger tumor volume for each Newton used in Q2 compared to Q4. For the latter quadrant, sub-optimal hand ergonomics decrease the ability of participants to efficiently remove and equivalent amount of tumor tissue per Newton applied.

Comparing neurosurgeon and resident groups to the medical student group suggests that experience has taught participants in the former groups to adapt their manual behavior when moving from one operative quadrant to another. Novice behavior, such as that of medical students, does not change throughout the procedure. These results imply an adaptation phenomenon (exemplified by this capacity to adjust hand ergonomics) that is a learned skill. The 95% confidence ellipses further emphasize the differences between experts (neurosurgeons) and the novices (residents and medical students) in their capacity to adapt their surgical behavior to the location of the tumor resection. For quadrants Q2 and Q4, there are distinct mean forces associated with distinct mean tumor volumes removed. The two discrete ellipses observed for the neurosurgeon group clearly differentiate the forces applied and the tumor volumes removed when operating in these fundamentally different quadrants. Interestingly, the ellipses overlap completely for medical students, and begin to separate for junior and senior residents indicating a progression of skill acquisition.

Hand ergonomics

The overall results confirm the significant role of hand and wrist ergonomics in the surgical performance of neurosurgeons, residents, and medical students assessed. Increasing expertise correlates with a greater capacity for neurosurgeons to adapt their ergonomics to use the wrist and hand's full range of motion to carry out the procedure. The differences observed between Q2 and Q4 are an indicator of this behavior.

Ergonomics, the study of interactions between humans and various tools, can be used to optimize systems and influence behavior (Berguer, 1998). A study on pianists showed that the tempo and evenness of their musical performance was directly correlated with wrist mobility (Lee, 1990). In laparoscopic surgery, ergonomics studies have shown that procedures involving excessive wrist flexion results in increased fatigue and decreased overall performance (Berguer, 1997; Berguer et al., 1998; Berguer, 1999).

Previous studies on hand and wrist ergonomics may provide some insight to help explain the differences in surgical performance between quadrants Q2 and Q4. Flexion of the wrist and increased muscle activity, secondary to increased cognitive stress and a need for precision, leads to decreased wrist mobility which may adversely impact performance. A study by Visser et al. (2004) showed that the greater concentration needed to perform exact and calculated movements were correlated with increased muscle contraction in participants performing a computer task with a mouse. The higher muscle activity allowed to control unwanted movements but also led users to apply higher forces with their fingers on the mouse. This might provide an explanation for the location of highest forces in Q4, at the tumor-normal tissue interface, where precision is crucial to avoid damaging the surrounding normal tissue. In the same study, it was shown that precision also required participants to reduce the speed of their movements when closer to the target. In future studies, it may be useful to investigate quadrant differences in surgical aspirator speed.

Other studies have observed increased times to complete tasks with reduced wrist mobility (Adams et al., 2003). These effects are further compounded by the fact that wrist positions that deviate from a neutral position may affect both sensory and motor nerve function (Gelberman et al., 1983; Luchetti et al., 1990; Keir et al., 1998). Our results are consistent with the concept that sub-optimal wrist ergonomics involved in the resection of tumor in Q4 may increase muscle activity and rigidity, which reduces wrist mobility and compromises sensory feedback and motor control which result in decreased movement speeds, longer task times, increased forces applied, and therefore decreased efficiency.

Limitations

A number of limitations are associated with the work presented above. The NeuroVR virtual reality neurosurgical platform, although continually improving, does not represent complex situations encountered in the operating room. Future studies need to integrate a more realistic tumor shapes to assess psychomotor performance in complicated cases. The two-minute time allotment, although sufficient for most participants, only represents a small portion of the time involved in a tumor resection. Although our results show significant differences between groups, the small sample size and the similar university of all participants makes it difficult to extend our results to other study populations. These concerns are being addressed in work that has gathered a greater sample size, with participants from multiple institutes that were asked to resect an irregularly-shaped tumor.

Finally, throughout this study, wrist ergonomics have been inferred from their effects on the various metrics studied. Future work needs to directly assess that information, either by analyzing the instrument orientation (angle), or using specialized gloves that determine hand position (Lemos et al., 2017).

CONCLUSION

Hand ergonomics play an important role in psychomotor performance and affect the previously suggested surgical fingerprint concept (Azarnoush et al., 2016). Explicit measures of ergonomics are needed to better understand its effects on various metrics, both on the neurosurgical simulation platform and in the operating room. The results may aid future trainees to gain awareness of their movements at an earlier stage and enhance their dexterity to carry out procedures safely and efficiently.

THESIS CONCLUSIONS

Summary

This thesis contains two complementary projects that attempt to elucidate complex psychomotor skills through the study of hand ergonomics and its resulting effects on surgical performance.

The first project makes use of the force pyramid metric to analyze the spatial distribution of forces applied with the dominant and the non-dominant hand of neurosurgeon and resident groups. The bimanual pyramid was created to represent all forces applied during a virtual reality brain tumour resection. Results identified different force pyramid structures: a force crescent located in the lower-right quadrant for the dominant hand, and a force peak located the centre of the simulated tumor for the non-dominant hand. These results indicated the effect of ergonomics on the spatial distribution of force, where wrist flexion and rotation play a critical role on location and magnitude of forces.

The second project was carried out to further elucidate the influence of hand and wrist ergonomics on the spatial distribution of forces applied, time expended and tumor volume removed. Our results indicate differences between the top-left (Q2) and lower-right (Q4) quadrants, secondary to the fundamentally different hand and wrist ergonomics needed to carry out the procedure in these two tumor locations. The work proposes a link between wrist flexion, reduced wrist mobility and decreased sensory and motor nerve function. The sub-optimal wrist ergonomics result in longer task times, increased force application, decreased movement speeds, and decreased surgical efficiency.

Future directions

As previously mentioned these studies have two main limitations: their small sample sizes, and the limited realism of the tumors. Another project is currently underway that will address these issues. A new scenario presents participants with a complex tumor model with an irregular shape that is embedded in the normal brain tissue. The project has collected data from over a dozen participants for each group (neurosurgeons, senior residents, junior residents, and medical students), which presents a significant improvement and advantage for future analyses.

Accordingly, new metrics will need to be developed to better address the question of ergonomics and to adapt to new datasets. In the work presented here, the effect of ergonomics was implied through the spatial distribution of time expended, forces applied, and tumor volume removed. Future work would benefit from assessing other indirect measures such as instrument speed, and more direct ones such as instrument orientation in space. Quaternion information is currently available in our studied datasets and can provide information on instrument rotation and angle which can be more accurate surrogates for hand position and ergonomics.

Finally, the force pyramid concept will need to be generalized to be applied to non-symmetrical tumors. A 'force heatmap' could be an alternative that allows the visual representation of force magnitude in a three-dimensional tumor model. More complex calculations will be required to carry out these analyses.

Conclusion

The development of the force pyramid has improved our understanding of bimanual psychomotor performance. Its generalization to study the spatial distribution of other measures has furthered our analysis of hand ergonomics in the context of surgical performance. These results reinforce the concept of the existence of a ‘surgical fingerprint’, a concept unique to each surgeon and resident that is continually modulated with knowledge, skill and experience.

In time, our observations will provide residents with ways to accurately assess their skills and with tools to improve them. With the incoming changes to the neurosurgical curriculum, the NeuroVR is a promising platform that will benefit trainees and surgeons alike, by allowing them to safely increase their competency level and ultimately to maintain their expertise. Patients will benefit from more expertise in both trainees and surgeons, who will be able to carry out procedures more safely and with increased efficiently.

REFERENCES

Benefits of Competence by Design. (2017). Retrieved from http://www.royalcollege.ca/rcsite/cbd/rationale/benefits-cbd-e

Competence by Design: The rationale for change. (2017). Retrieved from http://www.royalcollege.ca/rcsite/cbd/rationale-for-change-e

Adams, B. D., Grosland, N. M., Murphy, D. M., & McCullough, M. (2003). Impact of impaired wrist motion on hand and upper-extremity performance. *The Journal of Hand Surgery, 28*(6), 898-903.

Ahmed, N., Devitt, K. S., Keshet, I., Spicer, J., Imrie, K., Feldman, L., . . . Rutka, J. (2014). A Systematic Review of the Effects of Resident Duty Hour Restrictions in Surgery: Impact on Resident Wellness, Training, and Patient Outcomes. *Annals of surgery, 259*(6), 1041-1053. doi:10.1097/sla.0000000000000595

Alaraj, A., Tobin, M. K., Birk, D. M., & Charbel, F. T. (2013). Simulation in neurosurgery and neurosurgical procedures *The Comprehensive Textbook of Healthcare Simulation* (pp. 415-423): Springer.

Alotaibi, F. E., AlZhrani, G. A., Mullah, M. A., Sabbagh, A. J., Azarnoush, H., Winkler-Schwartz, A., & Del Maestro, R. F. (2015). Assessing bimanual performance in brain tumor resection with NeuroTouch, a virtual reality simulator. *Neurosurgery, 11 Suppl 2*, 89-98; discussion 98. doi:10.1227/NEU.0000000000000631

Alotaibi, F. E., AlZhrani, G. A., Sabbagh, A. J., Azarnoush, H., Winkler-Schwartz, A., & Del Maestro, R. F. (2015). Neurosurgical Assessment of Metrics Including Judgment and Dexterity Using the Virtual Reality Simulator NeuroTouch (NAJD Metrics). *Surg Innov, 22*(6), 636-642. doi:10.1177/1553350615579729

AlZhrani, G., Alotaibi, F., Azarnoush, H., Winkler-Schwartz, A., Sabbagh, A., Bajunaid, K., . . . Del Maestro, R. F. (2015). Proficiency performance benchmarks for removal of simulated brain tumors using a virtual reality simulator NeuroTouch. *J Surg Educ, 72*(4), 685-696. doi:10.1016/j.jsurg.2014.12.014

Anderson, O., Davis, R., Hanna, G. B., & Vincent, C. A. (2013). Surgical adverse events: a systematic review. *Am J Surg, 206*(2), 253-262. doi:10.1016/j.amjsurg.2012.11.009

Aoun, S. G., El Ahmadieh, T. Y., Yip, B. K., Batjer, H. H., & Bendok, B. R. (2012). Attending feedback after surgery: an under-utilized force in surgical education. *Neurosurgery, 71*(4), N15-16. doi:10.1227/01.neu.0000419709.17781.8a

Asch, D. A., & Parker, R. M. (1988). The Libby Zion case. One step forward or two steps backward? *N Engl J Med, 318*(12), 771-775. doi:10.1056/NEJM198803243181209

Azarnoush, H., Alzhrani, G., Winkler-Schwartz, A., Alotaibi, F., Gelinas-Phaneuf, N., Pazos, V., . . . Del Maestro, R. F. (2015). Neurosurgical virtual reality simulation metrics to assess psychomotor skills during brain tumor resection. *Int J Comput Assist Radiol Surg, 10*(5), 603-618. doi:10.1007/s11548-014-1091-z

Azarnoush, H., Siar, S., Sawaya, R., Zhrani, G. A., Winkler-Schwartz, A., Alotaibi, F. E., . . . Del Maestro, R. F. (2016). The force pyramid: a spatial analysis of force application during virtual reality brain tumor resection. *J Neurosurg*, 1-11. doi:10.3171/2016.7.JNS16322

Bajunaid, K., Mullah, M. A., Winkler-Schwartz, A., Alotaibi, F. E., Fares, J., Baggiani, M., . . . Del Maestro, R. F. (2017). Impact of acute stress on psychomotor bimanual performance during a simulated tumor resection task. *J Neurosurg, 126*(1), 71-80. doi:10.3171/2015.5.JNS15558

Baker, G. R., Norton, P. G., Flintoft, V., Blais, R., Brown, A., Cox, J., . . . Tamblyn, R. (2004). The Canadian Adverse Events Study: the incidence of adverse events among hospital patients in Canada. *CMAJ, 170*(11), 1678-1686.

Barry Issenberg, S., McGaghie, W. C., Petrusa, E. R., Lee Gordon, D., & Scalese, R. J. (2005). Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review. *Medical Teacher, 27*(1), 10-28. doi:10.1080/01421590500046924

Berguer, R. (1997). The application of ergonomics in the work environment of general surgeons. *Rev Environ Health, 12*(2), 99-106.

Berguer, R. (1998). Surgical technology and the ergonomics of laparoscopic instruments. *Surgical Endoscopy, 12*(5), 458-462. doi:10.1007/s004649900705

Berguer, R., Forkey, D. L., & Smith, W. D. (1999). Ergonomic problems associated with laparoscopic surgery. *Surgical Endoscopy, 13*(5), 466-468. doi:10.1007/pl00009635

Bernstein, M., Hebert, P. C., & Etchells, E. (2003). Patient Safety in Neurosurgery: Detection of Errors, Prevention of Errors, and Disclosure of Errors. *Neurosurgery Quarterly, 13*(2), 125-137.

Bethea, B. T., Okamura, A. M., Kitagawa, M., Fitton, T. P., Cattaneo, S. M., Gott, V. L., . . . Yuh, D. D. (2004). Application of haptic feedback to robotic surgery. *J Laparoendosc Adv Surg Tech A, 14*(3), 191-195. doi:10.1089/1092642041255441

Bhishagratna, K. K. (1963). An English translation of the Sushruta Samhita based on the original Sanskrit text, with a full and comprehensive introduction, additional texts, different readings, notes, comparative views, index, glossary and plates.

Blum, A. B., Shea, S., Czeisler, C. A., Landrigan, C. P., & Leape, L. (2011). Implementing the 2009 Institute of Medicine recommendations on resident physician work hours, supervision, and safety. *Nat Sci Sleep, 3*, 47-85. doi:10.2147/NSS.S19649

Bullock, G., Allen, T., Chapin, J., Cole, G., Harris, K. A., Hodder, R., . . . Frank, J. R. (2014). Assessment *Competence by Design: Reshaping Canadian Medical Education* (pp. 106-117): Royal College of Physicians and Surgeons of Canada.

Choudhury, N., Gelinas-Phaneuf, N., Delorme, S., & Del Maestro, R. (2013). Fundamentals of neurosurgery: virtual reality tasks for training and evaluation of technical skills. *World Neurosurg, 80*(5), e9-19. doi:10.1016/j.wneu.2012.08.022

Clarke, D. B., D'Arcy, R. C. N., Delorme, S., Laroche, D., Godin, G., Hajra, S. G., . . . DiRaddo, R. (2013). Virtual Reality Simulator. *Surgical Innovation, 20*(2), 190-197. doi:doi:10.1177/1553350612451354

Cobb, M. I., Taekman, J. M., Zomorodi, A. R., Gonzalez, L. F., & Turner, D. A. (2015). Simulation in Neurosurgery-A Brief Review and Commentary. *World Neurosurg*. doi:10.1016/j.wneu.2015.11.068

Coelho, G., Zanon, N., & Warf, B. (2014). The role of simulation in neurosurgery. *Childs Nerv Syst, 30*(12), 1997-2000. doi:10.1007/s00381-014-2548-7

Connors, R. C., Doty, J. R., Bull, D. A., May, H. T., Fullerton, D. A., & Robbins, R. C. (2009). Effect of work-hour restriction on operative experience in cardiothoracic surgical residency training. *The Journal of Thoracic and Cardiovascular Surgery, 137*(3), 710-713. doi:https://doi.org/10.1016/j.jtcvs.2008.11.038

Couch, N. P., Tilney, N. L., Rayner, A. A., & Moore, F. D. (1981). The high cost of low-frequency events: the anatomy and economics of surgical mishaps. *N Engl J Med, 304*(11), 634-637. doi:10.1056/NEJM198103123041103

Dagi, T. F. (2013). Commentary: the roles and future of simulation in neurosurgery. *Neurosurgery, 73 Suppl 1*, 4-5. doi:10.1227/NEU.0000000000000055

Damadi, A., Davis, A. T., Saxe, A., & Apelgren, K. (2007). ACGME duty-hour restrictions decrease resident operative volume: a 5-year comparison at an ACGME-accredited university general surgery residency. *J Surg Educ, 64*(5), 256-259. doi:10.1016/j.jsurg.2007.07.008

De Lorenzo, D., De Momi, E., Dyagilev, I., Manganelli, R., Formaglio, A., Prattichizzo, D., . . . Ferrigno, G. (2011). Force feedback in a piezoelectric linear actuator for neurosurgery. *Int J Med Robot, 7*(3), 268-275. doi:10.1002/rcs.391

Delorme, S., Laroche, D., DiRaddo, R., & Del Maestro, R. F. (2012). NeuroTouch: a physics-based virtual simulator for cranial microneurosurgery training. *Neurosurgery, 71*(1 Suppl Operative), 32-42. doi:10.1227/NEU.0b013e318249c744

Denson, J. S., & Abrahamson, S. (1969). A computer-controlled patient simulator. *JAMA, 208*(3), 504-508.

Donaldson, M. S., Corrigan, J. M., & Kohn, L. T. (2000). *To err is human: building a safer health system* (Vol. 6): National Academies Press.

Durkin, E. T., McDonald, R., Munoz, A., & Mahvi, D. (2008). The Impact of Work Hour Restrictions on Surgical Resident Education. *Journal of Surgical Education, 65*(1), 54-60. doi:https://doi.org/10.1016/j.jsurg.2007.08.008

Dwivedi, G., & Dwivedi, S. (2007). Sushruta-the clinician-teacher par excellence. *Indian Journal of Chest Diseases and Allied Sciences, 49*(4), 243.

Ericsson, K. A., & Charness, N. (1994). Expert performance: Its structure and acquisition. *American psychologist, 49*(8), 725.

Frank, J. R., Snell, L. S., Cate, O. T., Holmboe, E. S., Carraccio, C., Swing, S. R., . . . Harris, K. A. (2010). Competency-based medical education: theory to practice. *Med Teach, 32*(8), 638-645. doi:10.3109/0142159X.2010.501190

Fried, G. M., Feldman, L. S., Vassiliou, M. C., Fraser, S. A., Stanbridge, D., Ghitulescu, G., & Andrew, C. G. (2004). Proving the value of simulation in laparoscopic surgery. *Annals of surgery, 240*(3), 518-528.

Gan, L. S., Zareinia, K., Lama, S., Maddahi, Y., Yang, F. W., & Sutherland, G. R. (2015). Quantification of forces during a neurosurgical procedure: A pilot study. *World neurosurgery, 84*(2), 537-548.

Gelbart, N. R. (1998). *The king's midwife: a history and mystery of Madame du Coudray*: Univ of California Press.

Gelberman, R. H., Szabo, R. M., Williamson, R. V., Hargens, A. R., Yaru, N. C., & Minteer-convery, M. A. (1983). Tissue pressure threshold for peripheral nerve viability. *Clinical orthopaedics and related research, 178*, 285-291.

Gelinas-Phaneuf, N., Choudhury, N., Al-Habib, A. R., Cabral, A., Nadeau, E., Mora, V., . . . Del Maestro, R. F. (2014). Assessing performance in brain tumor resection using a novel virtual reality simulator. *Int J Comput Assist Radiol Surg, 9*(1), 1-9. doi:10.1007/s11548-013-0905-8

Gelinas-Phaneuf, N., & Del Maestro, R. F. (2013). Surgical expertise in neurosurgery: integrating theory into practice. *Neurosurgery, 73 Suppl 1*, 30-38. doi:10.1227/NEU.0000000000000115

Gilbody, J., Prasthofer, A. W., Ho, K., & Costa, M. L. (2011). The use and effectiveness of cadaveric workshops in higher surgical training: a systematic review. *Ann R Coll Surg Engl, 93*(5), 347-352. doi:10.1308/147870811X582954

Greenberg, W. E. (2013). Changes in residency training over the past quarter-century: reflections of a longtime program director. *Acad Psychiatry, 37*(4), 223-228. doi:10.1176/appi.ap.12110190

Hamdorf, J. M., & Hall, J. C. (2000). Acquiring surgical skills. *Br J Surg, 87*(1), 28-37. doi:10.1046/j.1365-2168.2000.01327.x

Hanna, G. B., Elamass, M., & Cuschieri, A. (2001). Ergonomics of Hand-Assisted Laparoscopic Surgery. *Seminars in Laparoscopic Surgery, 8*(2), 92-95. doi:doi:10.1177/155335060100800202

Holloway, T., Lorsch, Z. S., Chary, M. A., Sobotka, S., Moore, M. M., Costa, A. B., . . . Bederson, J. (2015). Operator experience determines performance in a simulated computer-based brain tumor resection task. *Int J Comput Assist Radiol Surg, 10*(11), 1853-1862. doi:10.1007/s11548-015-1160-y

Holmboe, E. S., Sherbino, J., Long, D. M., Swing, S. R., & Frank, J. R. (2010). The role of assessment in competency-based medical education. *Med Teach, 32*(8), 676-682. doi:10.3109/0142159X.2010.500704

Kavic, M. S. (2011). Teaching and training surgery to the next generation of surgeons. *JSLS, 15*(3), 279-281. doi:10.4293/108680811X13125733356675

Keir, P. J., Bach, J. M., Hudes, M., & Rempel, D. M. (2007). Guidelines for Wrist Posture Based on Carpal Tunnel Pressure Thresholds. *Human Factors, 49*(1), 88-99. doi:doi:10.1518/001872007779598127

Keir, P. J., Bach, J. M., & Rempel, D. M. (1998). Effects of finger posture on carpal tunnel pressure during wrist motion. *The Journal of Hand Surgery, 23*(6), 1004-1009. doi:http://dx.doi.org/10.1016/S0363-5023(98)80007-5

Khabbaz, F. H., Goldenberg, A., & Drake, J. (2016). Force Discrimination Ability of the Human Hand near Absolute Threshold for the Design of Force Feedback Systems in Teleoperations. *Presence: teleoperators and virtual environments, 25*(1), 47-60. doi:10.1162/PRES_a_00245

Kirkman, M. A., Ahmed, M., Albert, A. F., Wilson, M. H., Nandi, D., & Sevdalis, N. (2014). The use of simulation in neurosurgical education and training. A systematic review. *J Neurosurg, 121*(2), 228-246. doi:10.3171/2014.5.JNS131766

Kotsis, S. V., & Chung, K. C. (2013). Application of the "see one, do one, teach one" concept in surgical training. *Plast Reconstr Surg, 131*(5), 1194-1201. doi:10.1097/PRS.0b013e318287a0b3

Lee, S.-H. (1990). Pianists' hand ergonomics and touch control. *Med Probl Perform Art, 5*(2), 72-78.

Lehmann, K. S., Ritz, J. P., Maass, H., Çakmak, H. K., Kuehnapfel, U. G., Germer, C. T., . . . Buhr, H. J. (2005). A prospective randomized study to test the transfer of basic psychomotor skills from virtual reality to physical reality in a comparable training setting. *Annals of surgery, 241*(3), 442-449.

Lemos, J., Hernandez, A., & Soto-Romero, G. (2017). An Instrumented Glove to Assess Manual Dexterity in Simulation-Based Neurosurgical Education. *Sensors, 17*(5), 988.

Luchetti, R., Schoenhuber, R., Alfarano, M., Deluca, S., De Cicco, G., & Landi, A. (1990). Carpal tunnel syndrome: correlations between pressure measurement and intraoperative electrophysiological nerve study. *Muscle & nerve, 13*(12), 1164-1168.

Maddahi, Y., Gan, L. S., Zareinia, K., Lama, S., Sepehri, N., & Sutherland, G. R. (2015). Quantifying workspace and forces of surgical dissection during robot-assisted neurosurgery. *Int J Med Robot*. doi:10.1002/rcs.1679

Maddahi, Y., Ghasemloonia, A., Zareinia, K., Sepehri, N., & Sutherland, G. R. (2016). Quantifying force and positional frequency bands in neurosurgical tasks. *Journal of robotic surgery, 10*(2), 97-102.

McNatt, S. S., & Smith, C. D. (2001). A computer-based laparoscopic skills assessment device differentiates experienced from novice laparoscopic surgeons. *Surg Endosc, 15*(10), 1085-1089. doi:10.1007/s004640080022

Menon, I. A., & Haberman, H. F. (1969). Dermatological writings of ancient India. *Med Hist, 13*(4), 387-392.

Moradi Dalvand, M., Shirinzadeh, B., Nahavandi, S., & Smith, J. (2014). Effects of realistic force feedback in a robotic assisted minimally invasive surgery system. *Minim Invasive Ther Allied Technol, 23*(3), 127-135. doi:10.3109/13645706.2013.867886

Murayama, Y., Vinuela, F., Duckwiler, G. R., Gobin, Y. P., & Guglielmi, G. (1999). Embolization of incidental cerebral aneurysms by using the Guglielmi detachable coil system. *J Neurosurg, 90*(2), 207-214. doi:10.3171/jns.1999.90.2.0207

Noble, C. (2002). The relationship between fidelity and learning in aviation training and assessment. *Journal of Air Transportation, 7*(3), 33-54.

Ota, D., Loftin, B., Saito, T., Lea, R., & Keller, J. (1995). Virtual reality in surgical education. *Computers in Biology and Medicine, 25*(2), 127-137. doi:http://dx.doi.org/10.1016/0010-4825(94)00009-F

Owens, R., & Taekman, J. M. (2013). Virtual reality, haptic simulators, and virtual environments *The comprehensive textbook of healthcare simulation* (pp. 233-253): Springer.

Palmer, A. K., Werner, F. W., Murphy, D., & Glisson, R. (1985). Functional wrist motion: a biomechanical study. *J Hand Surg Am, 10*(1), 39-46.

Palter, V. N., Grantcharov, T., Harvey, A., & MacRae, H. M. (2011). Ex vivo technical skills training transfers to the operating room and enhances cognitive learning: a randomized controlled trial. *Annals of surgery, 253*(5), 886-889.

Pasquale, S. J. (2013). Education and learning theory *The comprehensive textbook of healthcare simulation* (pp. 51-55): Springer.

Rall, M., & Dieckmann, P. (2005). Simulation and patient safety: The use of simulation to enhance patient safety on a systems level. *Current Anaesthesia & Critical Care, 16*(5), 273-281.

Regenbogen, S. E., Greenberg, C. C., Studdert, D. M., Lipsitz, S. R., Zinner, M. J., & Gawande, A. A. (2007). Patterns of technical error among surgical malpractice claims: an analysis of strategies to prevent injury to surgical patients. *Ann Surg, 246*(5), 705-711. doi:10.1097/SLA.0b013e31815865f8

Rehder, R., Abd-El-Barr, M., Hooten, K., Weinstock, P., Madsen, J. R., & Cohen, A. R. (2016). The role of simulation in neurosurgery. *Childs Nerv Syst, 32*(1), 43-54. doi:10.1007/s00381-015-2923-z

Rodrigues, S. P., Horeman, T., Sam, P., Dankelman, J., van den Dobbelsteen, J. J., & Jansen, F. W. (2014). Influence of visual force feedback on tissue handling in minimally invasive surgery. *Br J Surg, 101*(13), 1766-1773. doi:10.1002/bjs.9669

Romanchuk, K. (2004). The Effect of Limiting Residents' Work Hours on Their Surgical Training: A Canadian Perspective. *Academic Medicine, 79*(5), 384-385.

Rooney, A. (2012). *The History of Medicine*: Rosen Publishing Group, Incorporated.

Rosen, K. (2013). The history of simulation *The comprehensive textbook of healthcare simulation* (pp. 5-49): Springer.

Rosen, K. R. (2008). The history of medical simulation. *J Crit Care, 23*(2), 157-166. doi:10.1016/j.jcrc.2007.12.004

Rosseau, G., Bailes, J., del Maestro, R., Cabral, A., Choudhury, N., Comas, O., . . . Diraddo, R. (2013). The development of a virtual simulator for training neurosurgeons to perform and perfect endoscopic endonasal transsphenoidal surgery. *Neurosurgery, 73 Suppl 1*, 85-93. doi:10.1227/NEU.0000000000000112

Satava, R. M. (2008). Historical review of surgical simulation--a personal perspective. *World J Surg, 32*(2), 141-148. doi:10.1007/s00268-007-9374-y

Scalese, R. J., & Hatala, R. (2013). Competency assessment *The Comprehensive Textbook of Healthcare Simulation* (pp. 135-160): Springer.

Schlich, T. (2015). 'The Days of Brilliancy are Past': Skill, Styles and the Changing Rules of Surgical Performance, ca. 1820-1920. *Med Hist, 59*(3), 379-403. doi:10.1017/mdh.2015.26

Seymour, N. E., Gallagher, A. G., Roman, S. A., O'Brien, M. K., Bansal, V. K., Andersen, D. K., & Satava, R. M. (2002). Virtual reality training improves operating room performance:

results of a randomized, double-blinded study. *Ann Surg, 236*. doi:10.1097/00000658-200210000-00008

Sirimanna, P. V., & Aggarwal, R. (2013). Patient Safety *The Comprehensive Textbook of Healthcare Simulation* (pp. 111-120): Springer.

Snell, L., Frank, J. R., Stoneham, G., Rossi, S. D., Fletcher, W., Gillis, K., . . . Harris, K. A. (2014). Competency-based Medical Education *Competence by Design: Reshaping Canadian Medical Education* (pp. 99-105): Royal College of Physicians and Surgeons of Canada.

Stienen, M. N., Netuka, D., Demetriades, A. K., Ringel, F., Gautschi, O. P., Gempt, J., . . . Schaller, K. (2016). Residency program trainee-satisfaction correlate with results of the European board examination in neurosurgery. *Acta neurochirurgica, 158*(10), 1823-1830.

Stone, S., & Bernstein, M. (2007). Prospective error recording in surgery: an analysis of 1108 elective neurosurgical cases. *Neurosurgery, 60*(6), 1075-1080; discussion 1080-1072. doi:10.1227/01.NEU.0000255466.22387.15

Sutherland, L. M., Middleton, P. F., Anthony, A., Hamdorf, J., Cregan, P., Scott, D., & Maddern, G. J. (2006). Surgical simulation: a systematic review. *Ann Surg, 243*(3), 291-300. doi:10.1097/01.sla.0000200839.93965.26

Tang, B., Hanna, G. B., & Cuschieri, A. (2005). Analysis of errors enacted by surgical trainees during skills training courses. *Surgery, 138*(1), 14-20. doi:10.1016/j.surg.2005.02.014

Thawani, J. P., Ramayya, A. G., Abdullah, K. G., Hudgins, E., Vaughan, K., Piazza, M., . . . Sean Grady, M. (2016). Resident simulation training in endoscopic endonasal surgery utilizing haptic feedback technology. *J Clin Neurosci, 34*, 112-116. doi:10.1016/j.jocn.2016.05.036

Tholey, G., Desai, J. P., & Castellanos, A. E. (2005). Force feedback plays a significant role in minimally invasive surgery: results and analysis. *Ann Surg, 241*(1), 102-109.

Varshney, R., Frenkiel, S., Nguyen, L. H., Young, M., Del Maestro, R., Zeitouni, A., . . . Tewfik, M. A. (2014). The McGill simulator for endoscopic sinus surgery (MSESS): a validation study. *J Otolaryngol Head Neck Surg, 43*(1), 40. doi:10.1186/s40463-014-0040-8

Varshney, R., Frenkiel, S., Nguyen, L. H., Young, M., Del Maestro, R., Zeitouni, A., . . . National Research Council, C. (2014). Development of the McGill simulator for endoscopic sinus surgery: a new high-fidelity virtual reality simulator for endoscopic sinus surgery. *Am J Rhinol Allergy, 28*(4), 330-334. doi:10.2500/ajra.2014.28.4046

Visser, B., De Looze, M. P., De Graaff, M. P., & Van Dieën, J. H. (2004). Effects of precision demands and mental pressure on muscle activation and hand forces in computer mouse tasks. *Ergonomics, 47*(2), 202-217. doi:10.1080/00140130310001617967

Wagner, C. R., Stylopoulos, N., Jackson, P. G., & Howe, R. D. (2007). The benefit of force feedback in surgery: Examination of blunt dissection. *Presence: teleoperators and virtual environments, 16*(3), 252-262.

Winkler-Schwartz, A., Bajunaid, K., Mullah, M. A., Marwa, I., Alotaibi, F. E., Fares, J., . . . Del Maestro, R. F. (2016). Bimanual Psychomotor Performance in Neurosurgical Resident Applicants Assessed Using NeuroTouch, a Virtual Reality Simulator. *J Surg Educ, 73*(6), 942-953. doi:10.1016/j.jsurg.2016.04.013

Woodrow, S. I., Segouin, C., Armbruster, J., Hamstra, S. J., & Hodges, B. (2006). Duty Hours Reforms in the United States, France, and Canada: Is It Time to Refocus Our Attention on Education? *Academic Medicine, 81*(12), 1045-1051. doi:10.1097/01.acm.0000246751.27480.55

Zhan, C., & Miller, M. R. (2003). Excess length of stay, charges, and mortality attributable to medical injuries during hospitalization. *JAMA, 290*(14), 1868-1874. doi:10.1001/jama.290.14.1868

APPENDIX

TABLES

Scenario	1		2		3		4	
Tumor	A	B	A	B	A	B	A	B
Colour	Black				Glioma-like			
Border	Distinct		Indistinct		Distinct		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)

Table 1 – Tumor sequence and characteristics

FIGURES

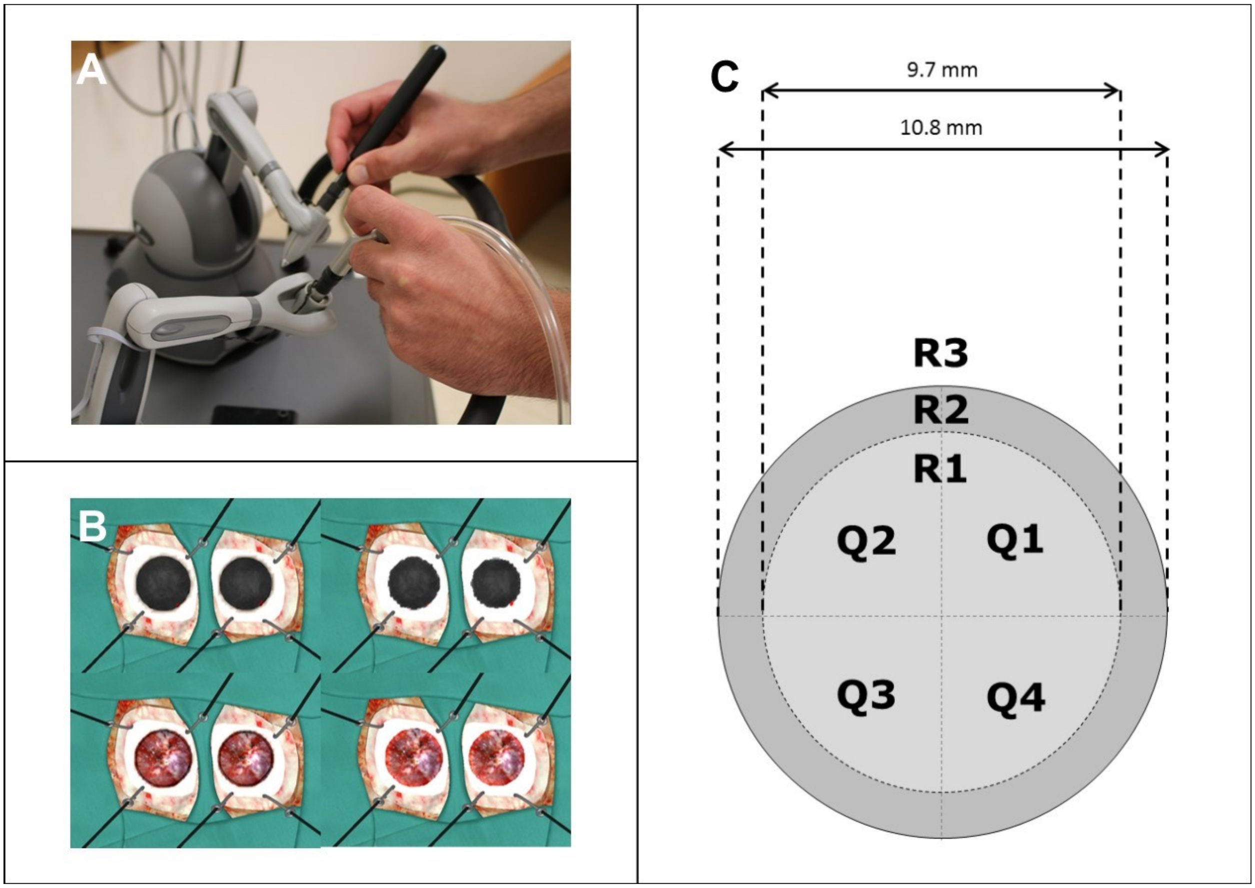

Figure 1. A: Right-handed operator's hand positions holding a simulated ultrasonic aspirator in the dominant hand and a simulated sucker in the non-dominant hand.

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: 3D view of an ellipsoidal tumor outlining the R1, R2 and R3 regions with top view of the regions of tumors divided into quadrants Q1-Q4.

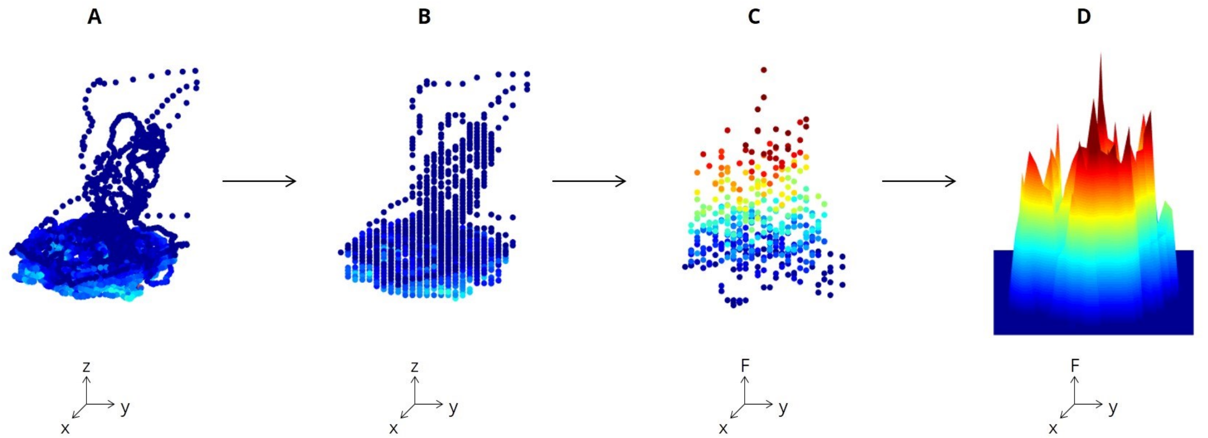

Figure 2. A: Scatter plot of the position data in three dimensions with colours corresponding to the force applied (0 N in dark blue to 0.2 N in dark red).

B: Position data fitted to a three-dimensional 0.5 mm grid with colours corresponding to the force applied.

C: Initial force pyramid following the summation of points along the z-axis for each xy position with colours corresponding to the force applied.

D: Similar to C, a surface is added to enhance visualization of the figure.

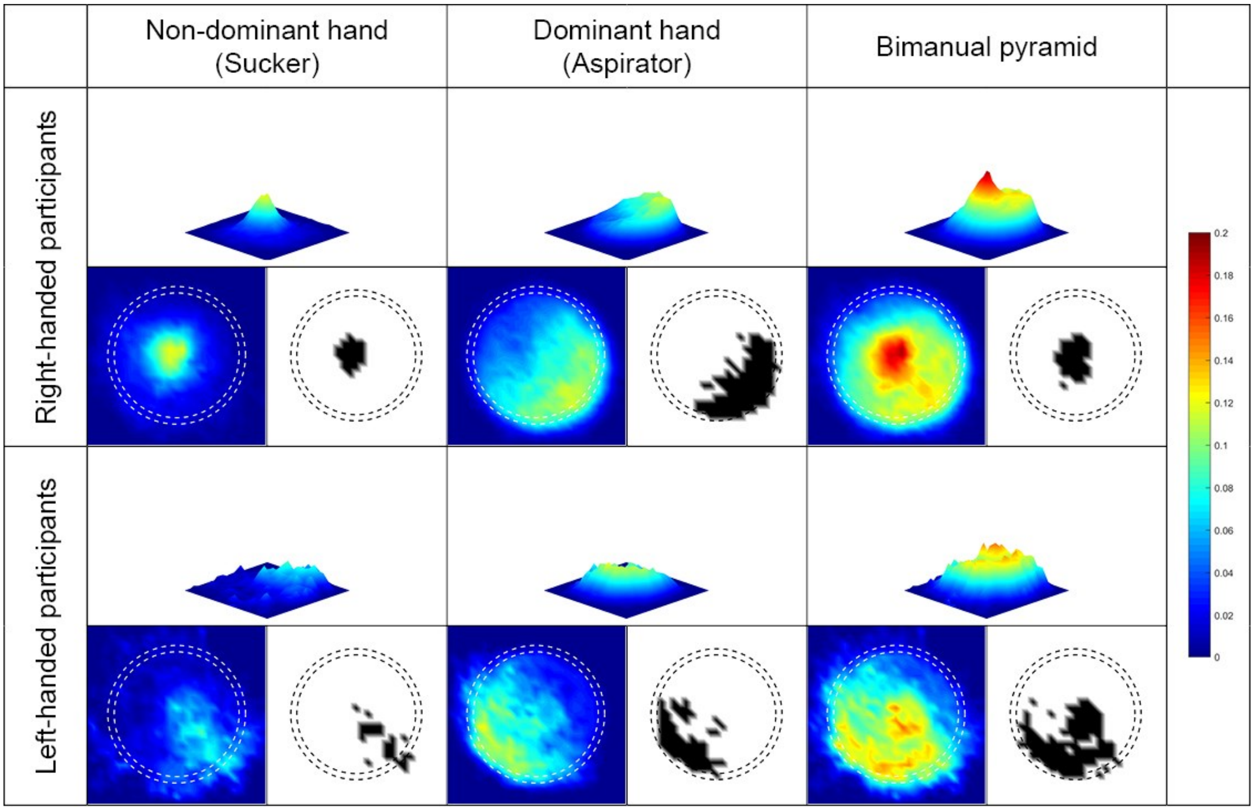

Figure 3. Non-dominant, dominant, and bimanual force pyramids (3D and top views) for the all right handed (n= 17) and left handed (n=3) participants. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for all 8 tumors.

The highest forces for non-dominant 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.

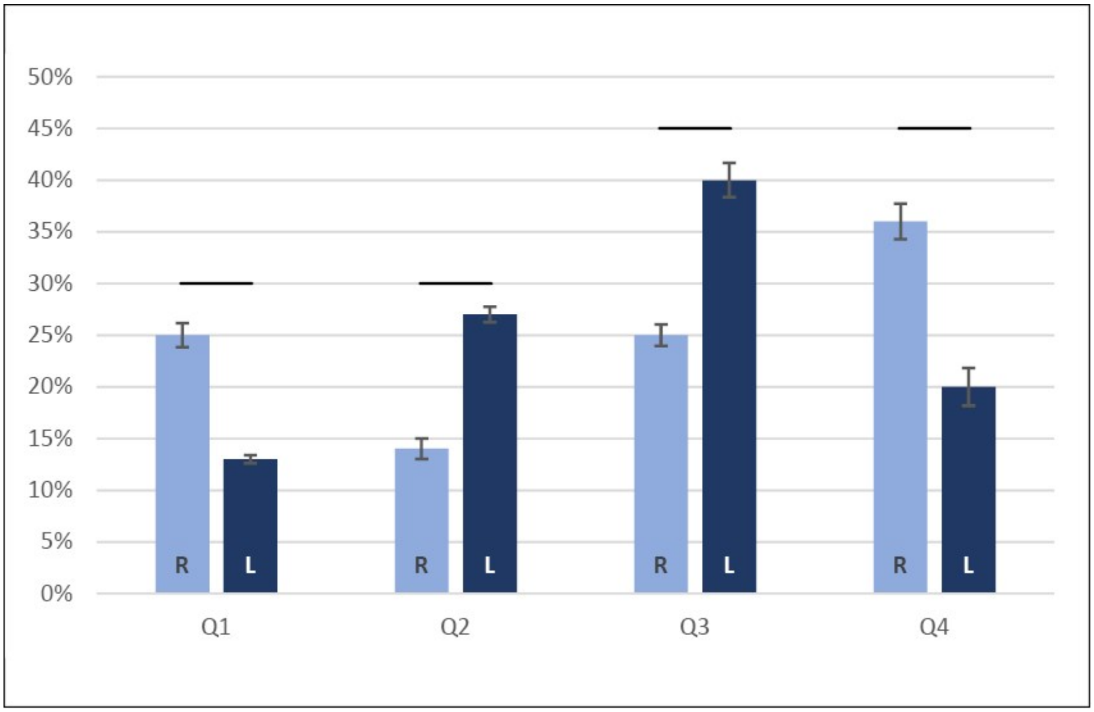

Figure 4. Force distribution per quadrant (in percent ± SEM) for right (labelled "R", n=17) and left (labelled "L", n=3) handed groups. Lines indicate quadrants that are significantly different ($p<0.05$).

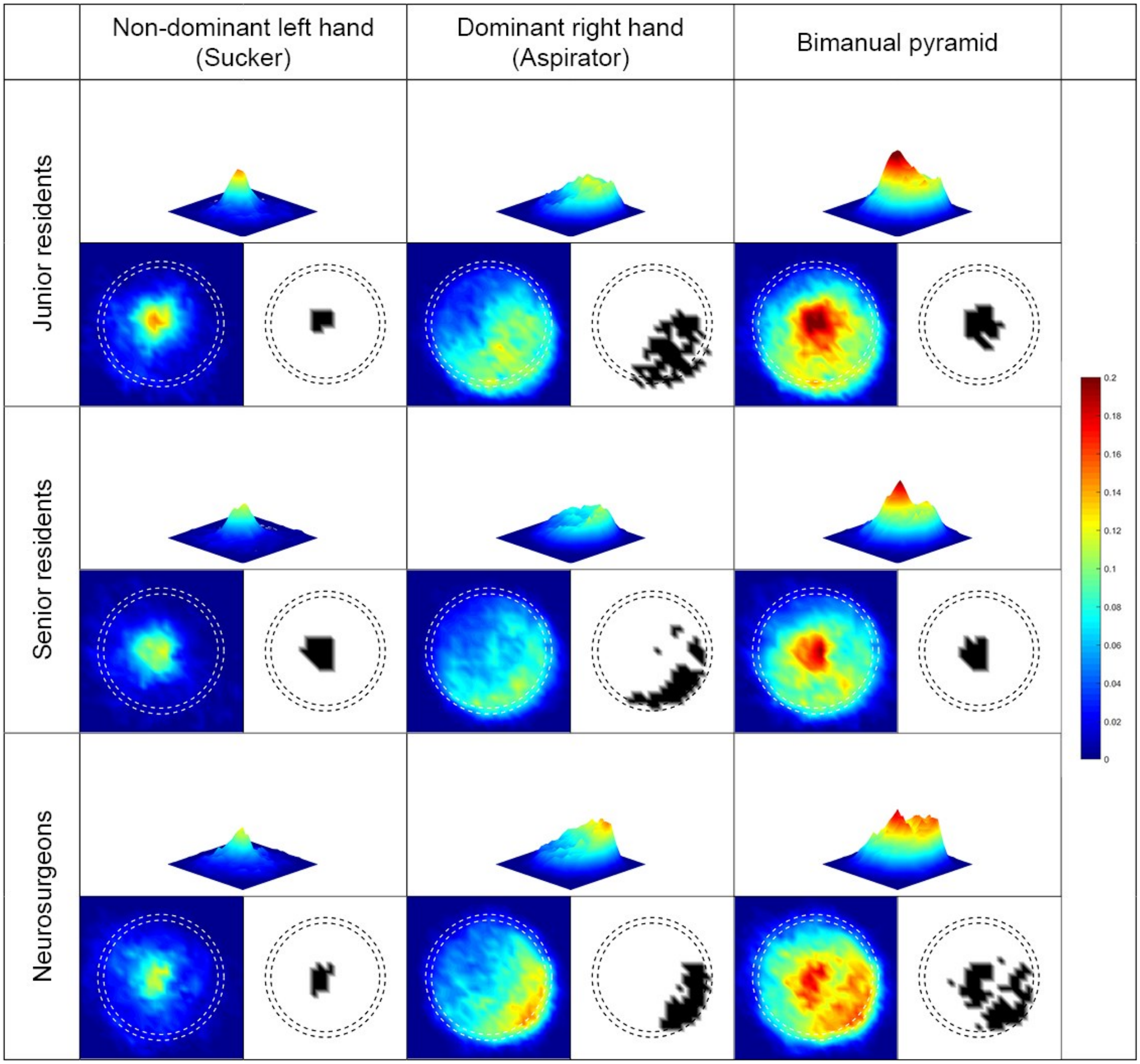

Figure 5. Right-handed non-dominant, dominant and bimanual force pyramids (3D and top views) for junior resident (n=5), senior resident (n=6), and neurosurgeon (n=6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for all 8 tumors.

The highest forces for non-dominant force pyramids are located predominantly at the center for all group. 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 left outlines the colors corresponding to different forces in Newtons.

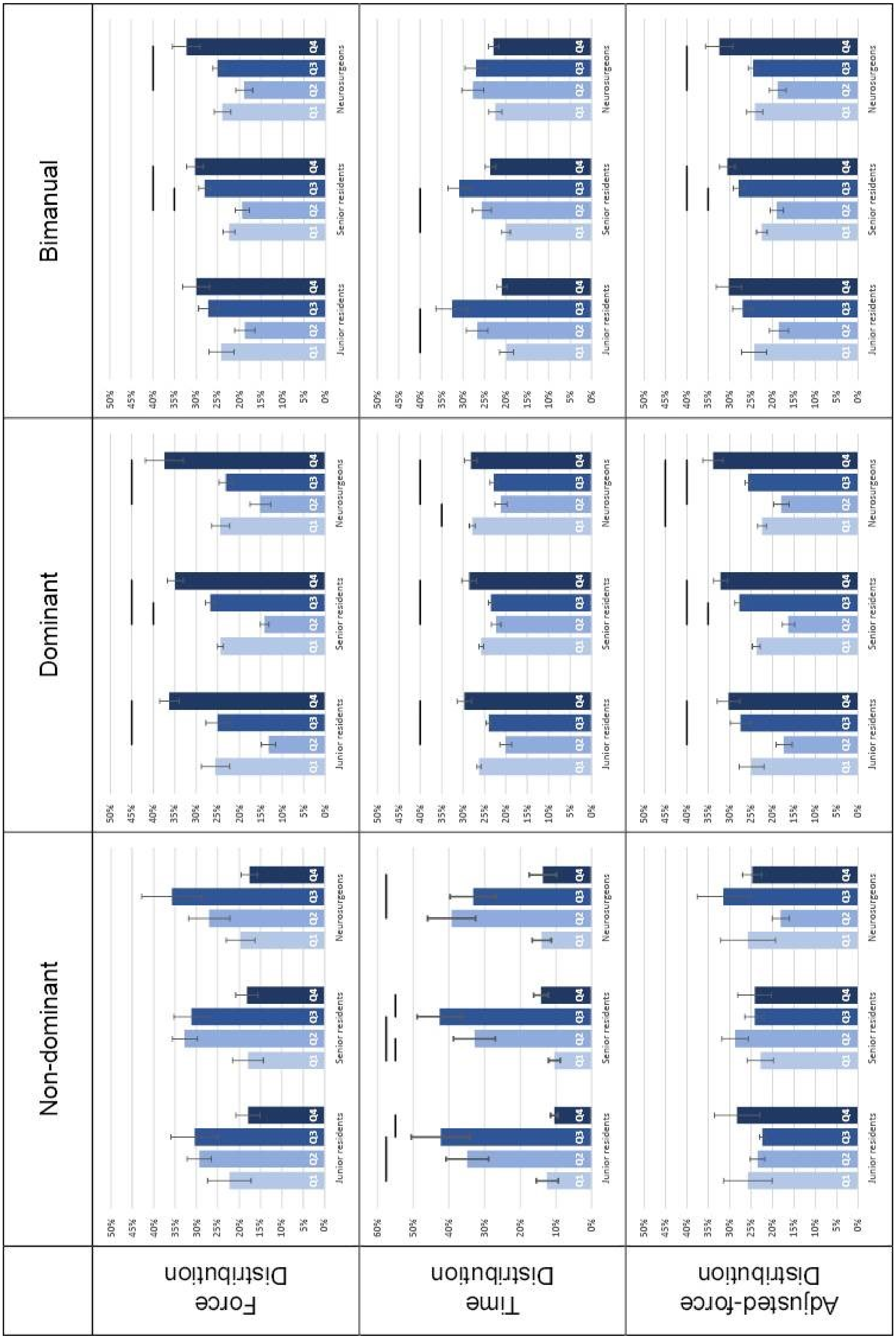
Non-dominant
Dominant
Bimanual
Force Distribution
Time Distribution
Adjusted-force Distribution
Junior residents
Senior residents
Neurosurgeons
Q1
Q2
Q3
Q4

Figure 6. Non-dominant, 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 ($p<0.05$).

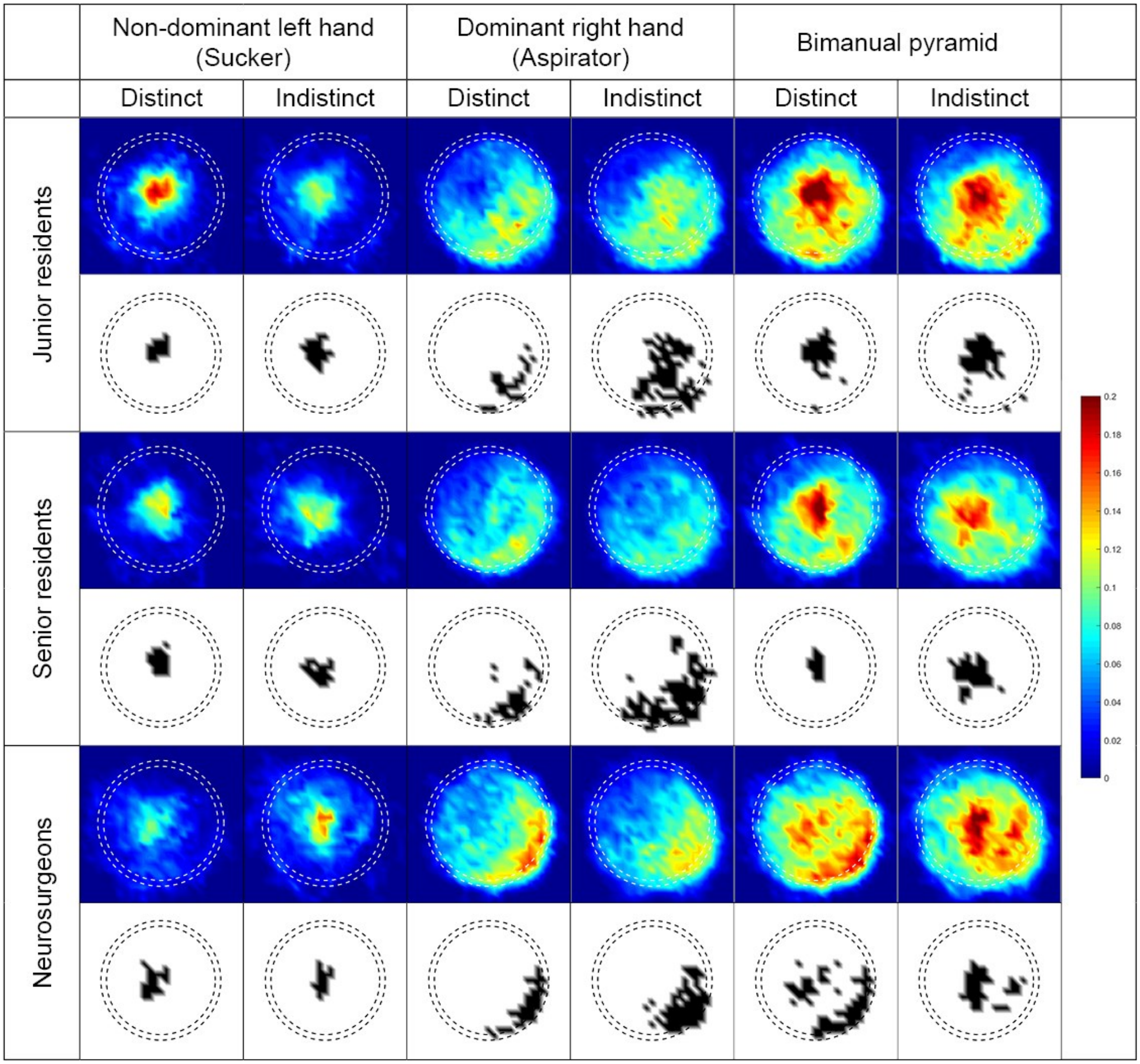

Figure 7. Right-handed non-dominant, dominant and bimanual force pyramids (3D and top views) for junior resident (n=5), senior resident (n=6), and neurosurgeon (n=6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for 4 distinct and 4 indistinct tumors.

The highest forces for non-dominant force pyramids are located at the center for all groups. The dominant forces for tumors with distinct borders are distribute in a crescent going from Q3 to Q4 for residents, but distribute 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 left outlines the colors corresponding to different forces in Newtons.

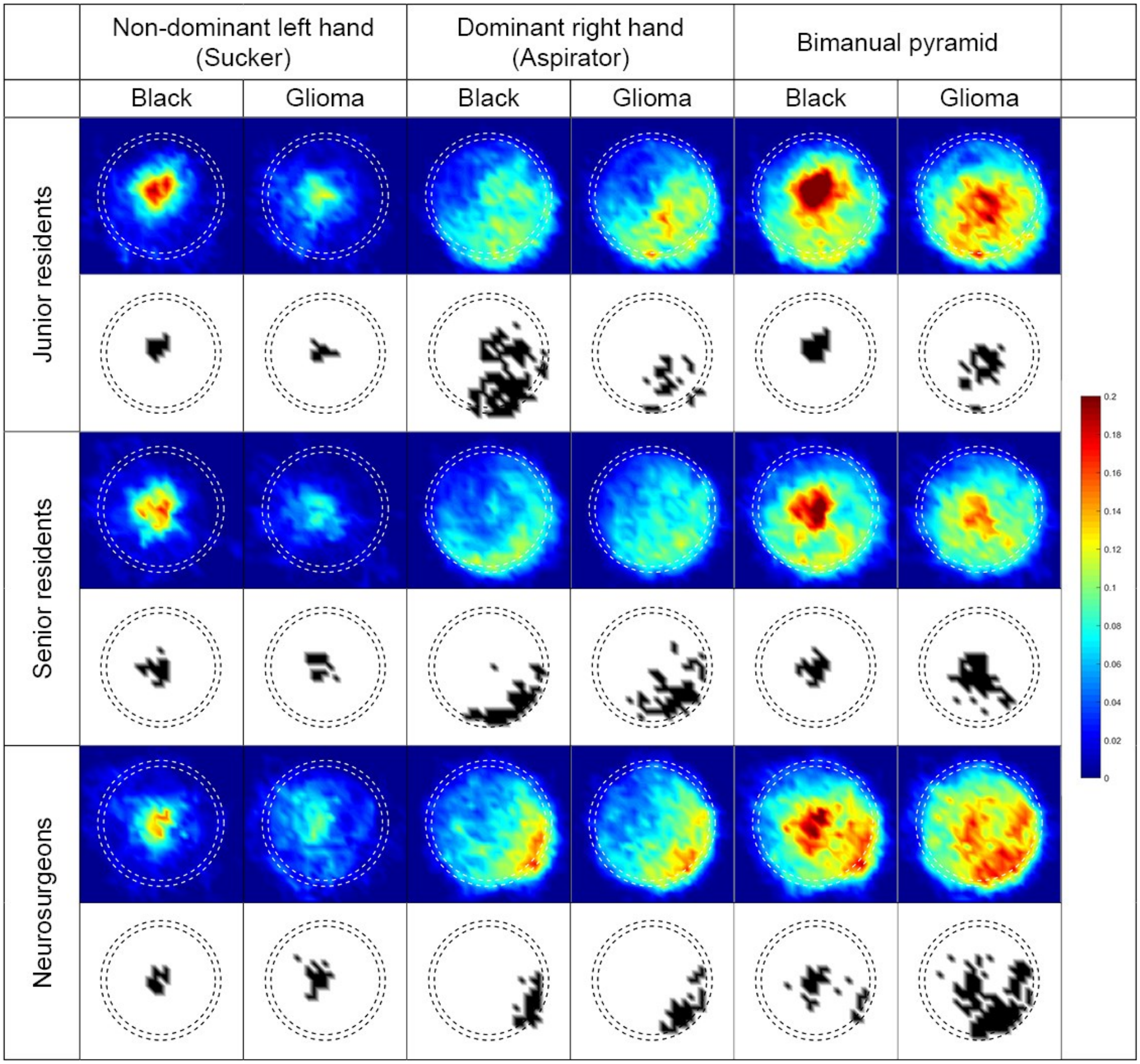

Figure 8. Right-handed non-dominant, dominant and bimanual force pyramids (3D and top views) for junior resident (n=5), senior resident (n=6), and neurosurgeon (n=6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for 4 black and 4 glioma-like tumors.

The highest forces for non-dominant force pyramids are located at the center for both tumor types in all groups. The dominant forces are distributed widely for both tumor types in resident groups, while neurosurgeons confine these forces to a crescent in Q4 for both tumor types. The bimanual force pyramids' highest forces located at the center in all groups, with the exception of a Q4 crescent for the glioma-like tumors in the neurosurgeon group. The color map on the left outlines the colors corresponding to different forces in Newtons.

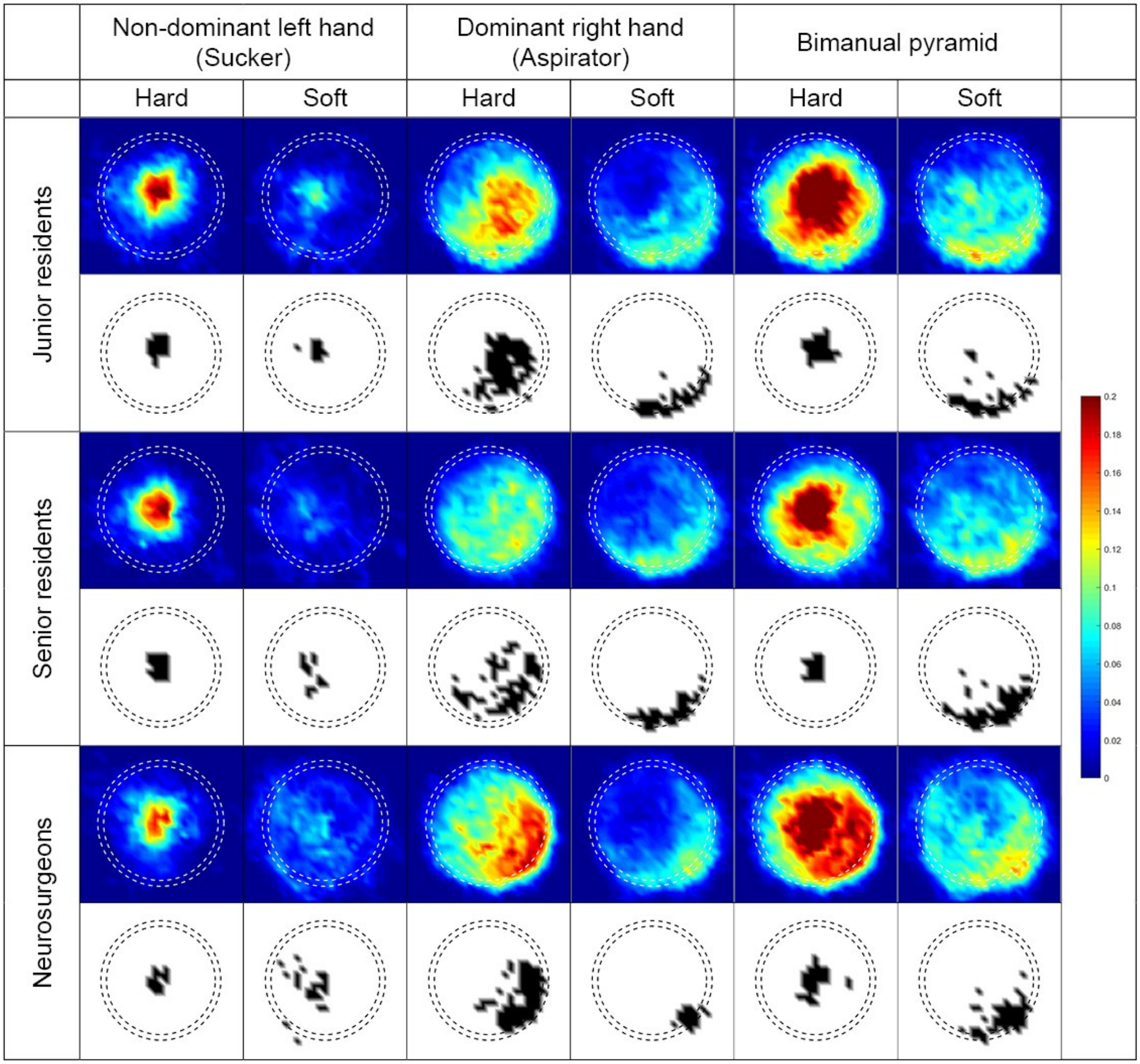

Figure 9. Right-handed non-dominant, dominant and bimanual force pyramids (3D and top views) for junior resident (n=5), senior resident (n=6), and neurosurgeon (n=6) groups. Each participant group's pyramid represents the forces (in Newtons) applied at each xy coordinate for 4 hard (15 kPa) and 4 soft (3kPa) tumors.

The highest forces for non-dominant force pyramids are located at the center for all groups, but are much higher for hard tumors. The dominant forces of hard tumors distribute in multiple quadrants for residents while neurosurgeons confine these forces to a crescent in Q4. For soft tumors, residents confine their highest forces into a crescent extending from Q3 to Q4 while neurosurgeons limit these forces to Q4. The bimanual force pyramids' highest forces are located at the center for hard tumors but more widely distributed for soft tumors. The color map on the left outlines the colors corresponding to different forces in Newtons.

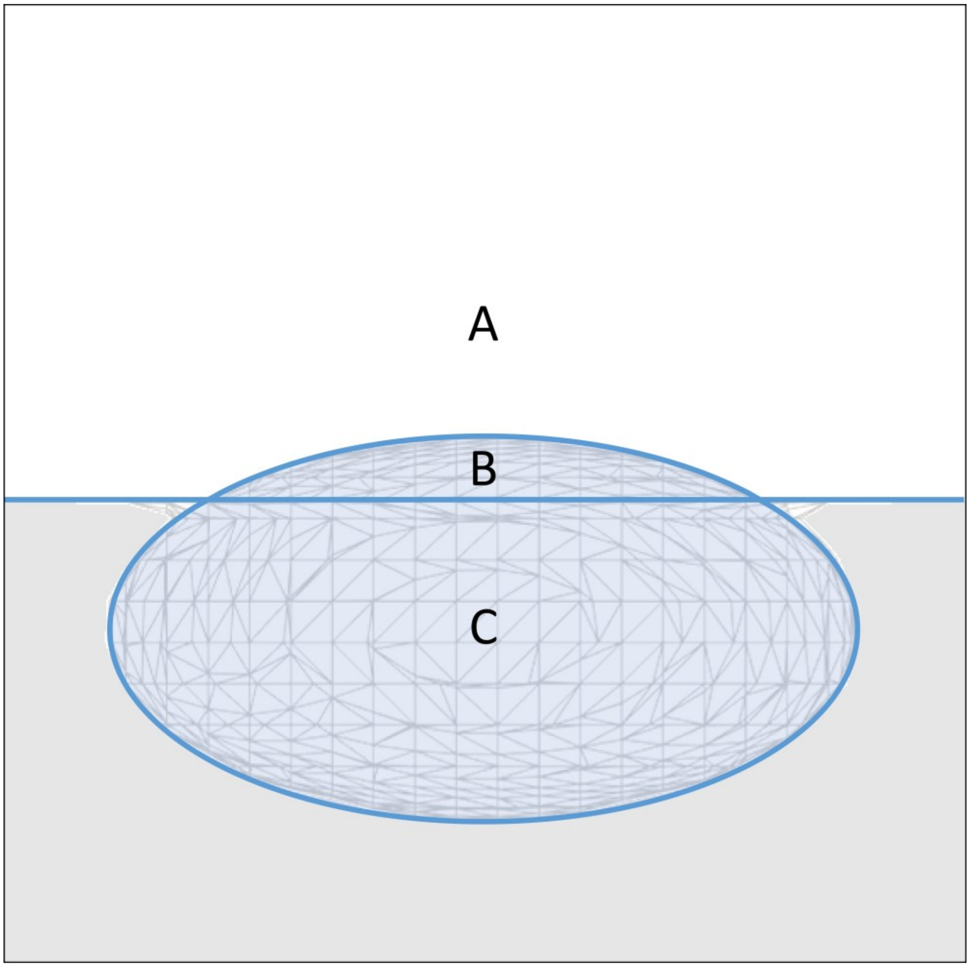

Figure 10. Side view of the tumor embedded in normal tissue (gray). Area A represents all non-tumoral areas. Area B represents the region of the tumor above the surface of the brain. Area C represents the region of the tumor below the surface of the brain.

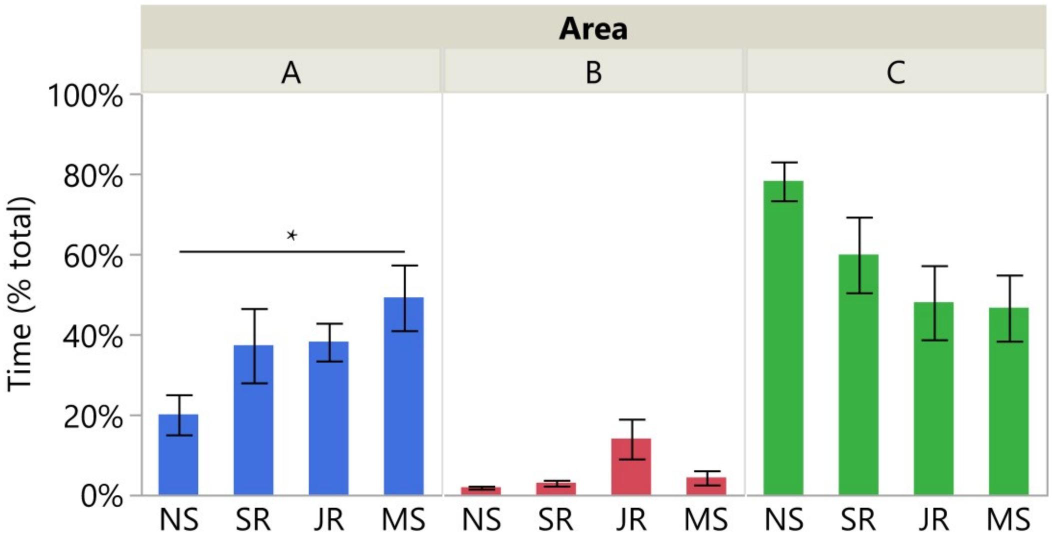

Figure 11. Time expended per area. The percent of the total time spent in each area is shown for all participant groups (neurosurgeons NS, senior residents SR, junior residents JR, medical students MS). Area A corresponds to all components that are not the tumor; area B corresponds the tumor above the surface of the brain; area C corresponds to the tumor below the surface of the brain. P-values are represented as * ($p<.05$) or ** ($p<.01$).

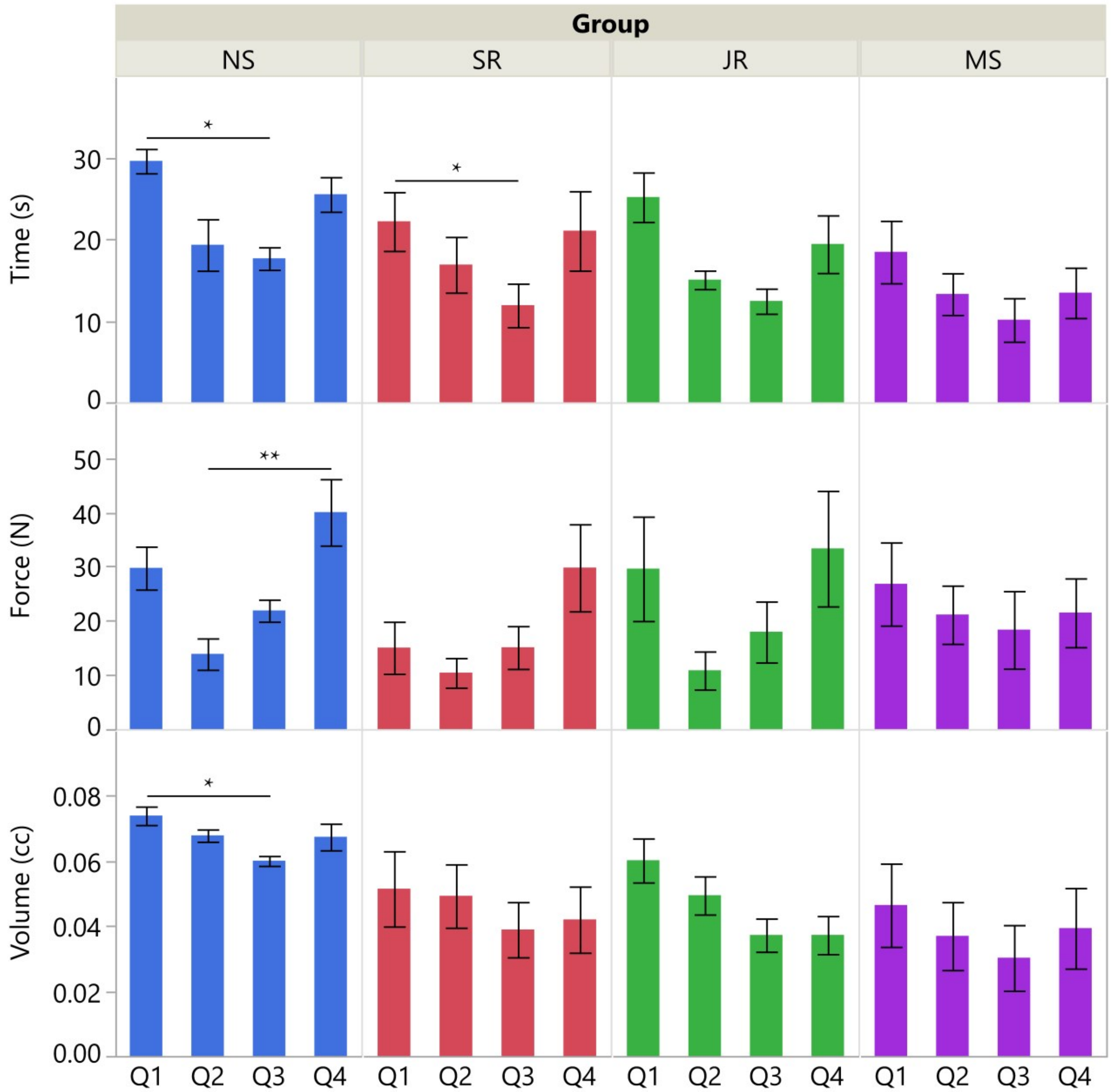

Figure 12. Time expended, force applied, and volume of tissue removed for each quadrant. The time expended (seconds), force applied (Newtons), and volume of tissue removed (cubic centimeter) is calculated per quadrant for each group (neurosurgeons in blue, senior residents in red, junior residents in green, medical students in purple). P-values are represented as * ($p<.05$) or ** ($p<.01$).

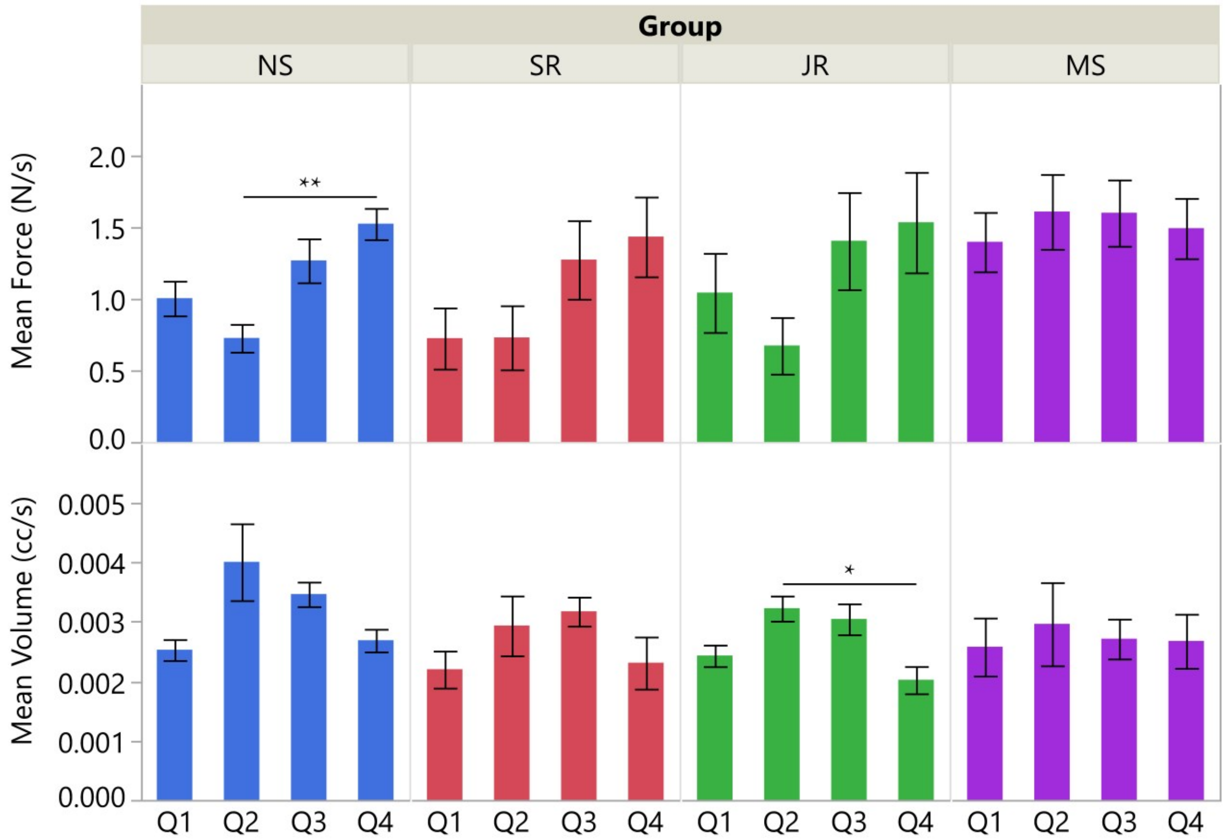

Figure 13. Force applied and tumor volume removed per second for each quadrant. The mean force applied (Newtons per second) and mean tumor volume removed (cubic centimeter per second) are calculated per quadrant for each group (neurosurgeons in blue, senior residents in red, junior residents in green, medical students in purple). P-values are represented as * (p<.05) or ** (p<.01).

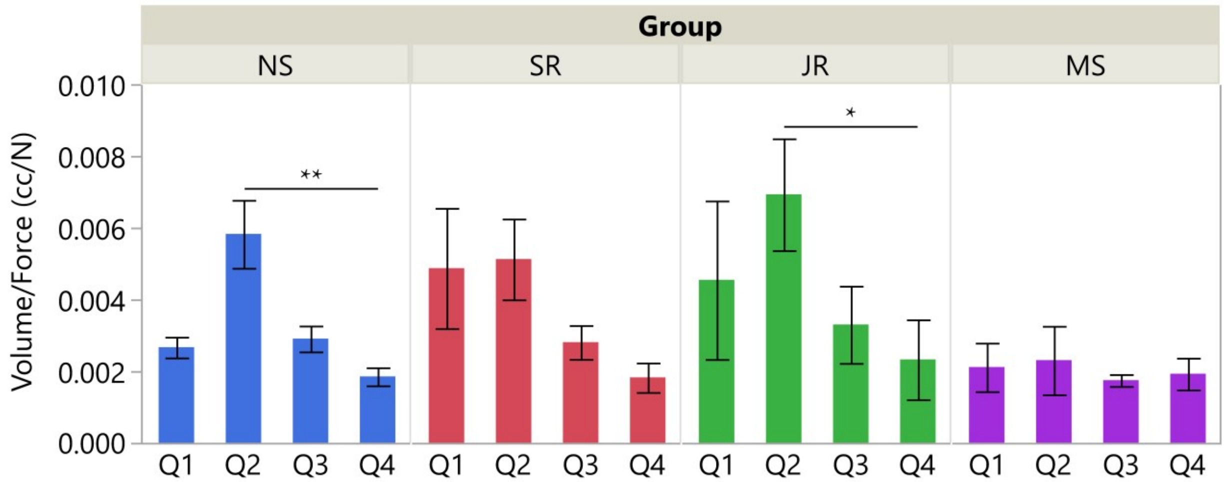

Figure 14. Tumor volume removed per force applied for each quadrant. The tumor volume removed per unit of force applied (cubic centimeter per Newton) is calculated per quadrant for each group (neurosurgeons in blue, senior residents in red, junior residents in green, medical students in purple). P-values are represented as * ($p<.05$) or ** ($p<.01$).

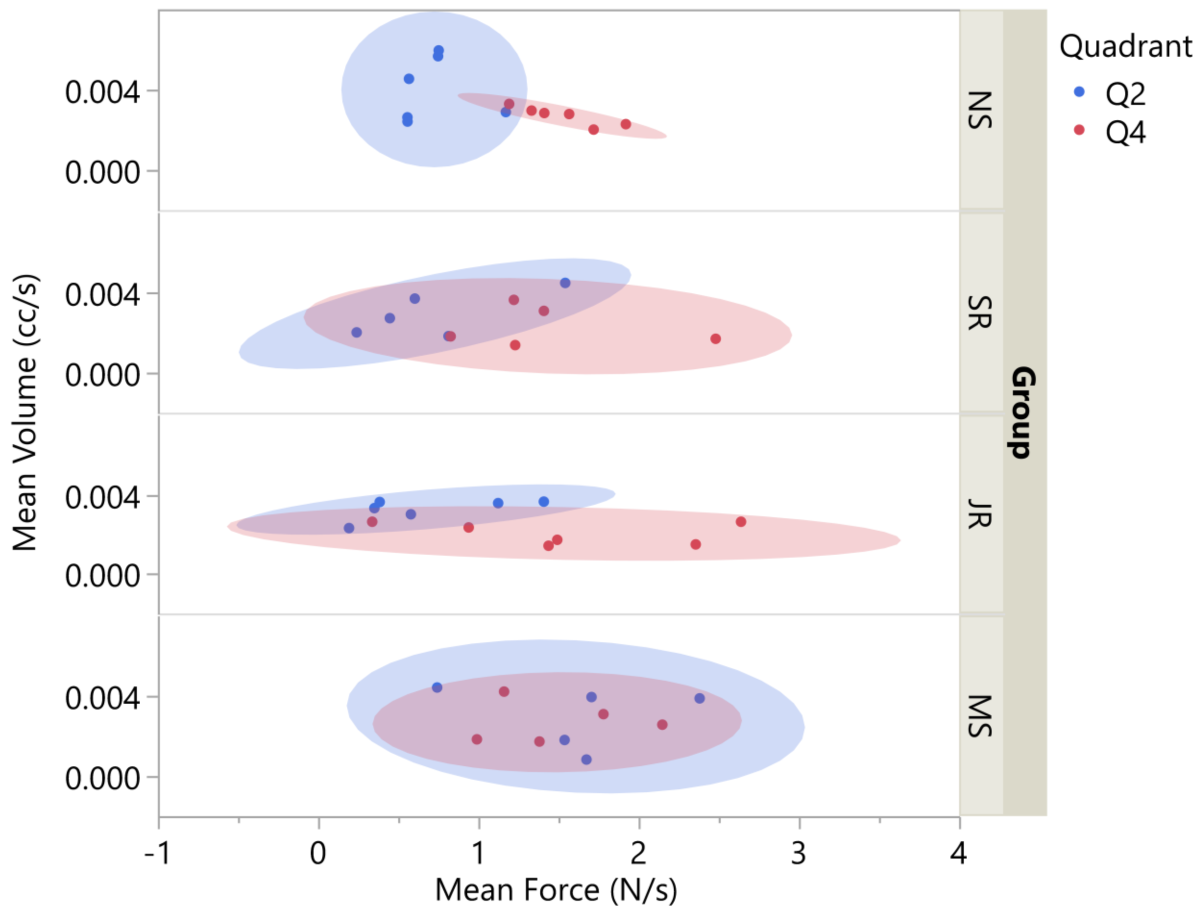

Figure 15. 95% confidence ellipse per group for Q2 and Q4. The 95% confidence ellipse shows the spread and relationship between mean force applied (N/s) and mean tumor volume removed for Q2 (blue) and Q4 (red), the quadrants that are the most significantly different. There is minimal overlap between the two quadrants for neurosurgeons in comparison to other groups.