Examining surgeon's eye-hand coordination during microsurgery

by

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Abstract

Surgical simulation is now an essential component of surgical education and is now accepted as a valid tool for improving the skills of surgeons. Ultimately, this result in better outcome and patient safety. To maximize the benefit of practicing in a surgical simulation environment, objective assessment of surgical skill is essential but remains difficult to achieve. Criteria-based evaluations, where checklists and global rating scales are the two principal examples, are subject to inter-observer variability and subjective bias. Researchers believe that a more objective assessment of surgical skills should include force analysis, kinematic analysis and eye-tracking analysis. While these technologies have been used to a certain extent to describe surgeons' eye-hand coordination in general surgery and laparoscopic surgery, little is known for microsurgery. This knowledge cannot be directly extrapolated to microsurgery as operating under a surgical microscope and looking at a magnified surgical field imply a different depth perception and adjustment of the eye-hand coordination.

Aided by eye-tracking technology and video analysis to characterize surgeon's movements, this thesis explored the acquisition of eye-hand coordination of microsurgeons. Specifically, we use these methods to detect the differences between expert and novice microsurgeons while they were performing three distinct surgical tasks under the microscope. Ultimately, these findings can be used to objectively assess the level of expertise of microsurgeons.

The thesis concludes with a summary of findings and surgical education applications at this point. A brief discussion about future works is also present and these new studies would help to reinforce the importance of characterizing expert surgeons' gaze behavior as it might lead to gaze training and facilitate skills learning.

Preface

This thesis is an original work by Jonathan Chainey. The research project, of which this thesis is a part, received research ethics approval from the University of Alberta Research Ethics Board, Project Name "Examining Surgeon's Eye-Hand Coordination During Microsurgery", Study ID Pro00085187, November 5, 2018.

Some of the research conducted for this thesis forms part of an international research collaboration, led by Professor R. Bednarik at the University of Eastern Finland, with Dr. Zheng being the lead collaborator at the University of Alberta.

A version of Chapter 2 of this thesis has been submitted for publication as J. Chainey, C.J. O'Kelly, M.J. Kim, A-P. Elomaa, R. Bednarik and B. Zheng "Action-Related Fixation in Microsuturing, a New Gaze Behavior Metric to Differentiate the Level of Expertise" in *BMJ Simulation & Technology Enhanced Learning (BMJ STEL)*. I was responsible for the design of the experiment, assembly of the simulation apparatus, literature review, assisted with data collection and analysis, and composition and significant revisions of the manuscript. A-P. Elomaa and R. Bednarik assisted with the design of the experiment, the data collection and contributed to manuscript edits. C.J. O'Kelly, M.J. Kim were supervisory authors who assisted with revision of the manuscript. B. Zheng helped with the design of the experiment, data analysis, revision of the manuscript and was a supervisory author on this project.

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Dedication

Keep your eye at the place aimed at, and your hand will fetch [the target]; think of your hand, and you will likely miss your aim

-William James, 1890(1)

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I would like to thank my family and friends for always being supportive, for encouraging me to pursue my goals even when I had doubts. A special thanks to Pascale who walked with me on this segment of my journey.

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List of Symbols and Abbreviations

AOI	Area of Interest
BORIS	Behavioral Observation Research Interactive Software
CLT	Cognitive Load Theory
CNN	Convolutional Neural Network
EVD	External Ventricular Drain
GRS	Global Rating Scale
ICSAD	Imperial College Surgical Assessment Device
MFD	Mean Fixation Duration
OSCE	Objective Structured Clinical Examination
OSATS	Objective Structured Assessment Skills
PGY	Postgraduate year
PSE3eye	Sony Playstation Eye Camera
RMS	Root Mean Square
RPM	Revolution per Minute
QE	Quiet Eye
UWOMSA	University of Western Ontario Microsurgical Skills Acquisition/Assessment
VOG	Video-Oculography

Glossary of Terms

Expert Microsurgeons: currently practising, board-certified neurosurgeon.

Medical student: a student currently enrolled in medical school.

Novice Microsurgeons: neurosurgery resident currently involved in a training program.

Postgraduate year: number of years of medical training that occur after medical school. For example, PGY1 means 1st year of training after completion of medical school.

Resident: graduate of a medical school pursuing training in a specialized field of medicine.

Chapter 1 - Introduction

Attending surgeons working at a university hospital have a teaching component associated to their clinical duties. They are working constantly with medical students and residents, and these interactions are essential to the learning of trainees. However, a negligible number of surgeons actually receive adequate teaching training. Medical education is a field that has been present for a considerable time and a fair amount of scientific literature is present and constantly evolving. Surgical education is however more recent and not as well integrated to the daily activity of surgical residency training. Current surgical residency curriculum needs to change on multiple aspects: better feedback and teaching in the operating room, improvement of clinical teaching (case rounds, grand rounds, individual teaching), development of mentorship programs and maximizing simulation-based education. The latest is particularly important to surgical trainees as learning manual skills require repetition, involve mistakes and is time consuming. Simulation centers can allow resident to learn at their own pace, practice as often as they need until they achieve mastery of the skill. More importantly, simulation centers are a safe environment to practice because of the absence of repercussion on patients and ultimately result in better patient safety. Are we using surgical simulation the right way? At present, the surgical curriculum uses simulation mainly to familiarize students with instruments and surgical techniques or as an objective assessment of skills performance. What if we could use surgical simulation to personalize the teaching of a surgeon in training? That is where, in my literature review, I came across the interesting and complex field of eye-tracking. Going into this study, I wanted to better understand the skills acquisition in microsurgery and how the eye-hand coordination (reflected in part by the gaze behavior) differs in function of the level of expertise. By characterizing the differences in gaze behavior between experts and novices, we could ultimately personalize the teaching of a surgical residents so they can develop a gaze strategy similar to their staff and improve their surgical technique.

The movement of your eyes can tell us more than you think!

1.1 Microsurgery and Skills Training with Simulation

Surgeon's necessity to excellent illumination, unobstructed vision and access to the small details of the whole operative field led to the development of microsurgery. The definition of microsurgery according to Merriam-Webster dictionary is "minute dissection or manipulation (as by a micromanipulator or laser beam) of living structures (as cells or tissues) for surgical or experimental purposes" (2). However, I find this definition, given by M.G. Yasargil, more appropriate: "surgery performed upon small structures usually with the help of some form of magnification, in particular the dissecting microscope" (3). I think a magnification view of the surgical site, which can be obtained by using loupes or microscope, is a unique and specific characteristic of microsurgery. Nowadays, microsurgery is used in multiple surgical specialties including neurosurgery, plastic surgery, ophthalmology and otolaryngology. However, the essential question still remains, i.e., what are the impacts to a surgeon when his/her vision is magnified? Is a surgeon well-trained in open surgery need to re-learn skills for microsurgery? If yes, how long does it take? These are the questions I am exploring in this study, first from past literature, then by simulation experiments.

Training surgeon to perform under microscope is a challenging task. It takes practice for a surgeon to have the ability to reset his/her eye-hand coordination when the image of surgical site is magnified. To provide opportunities for skill training, simulation is becoming an important part of health care education and is now accepted as a valid tool for improving the skills of surgeons and safety of patients. In 2011, the American Council of Graduate Medical Education (ACGME) implemented residency duty-hour restrictions aiming to improve patient safety and residents' quality of life (4). Since then, the ACGME has encouraged medical institutions to implement alternative methods of residency training. Presently, up to 70 % of medical schools have already incorporated some type of simulation in their curricula (5). Surgical simulation is now an ACGME requirement in the specialities of general surgery (6) and anesthesiology (7). In addition to duty-hour restrictions, other driving forces for the development of surgical simulation are early acquisition of surgical skills before operative practice (8), improvement of quality of care and increased expectations from patients and families (9) all resulting in the principle goal: improving patient safety. The motto "see one, do one, teach one" is not appropriate in this culture where patient safety is at the center of surgical care.

The ideal surgical simulator model would be realistic, objective, valid, generally accepted, widely available, cost-effective and maintainable. The validity of a simulator model is evaluated based on the different types of validity (10).

→ Face validity: tasks performed are similar to those during a real-life surgical procedure

→ Content validity: the test assesses a specific skill

→ Construct validity: discriminate between experts and novices

→ Concurrent validity: test yields same results as the gold standard tool

Predictive validity: predict future performance and is transferable to the operating room in real-life surgery→

In surgical context, the construct validity refers to "an ongoing process, in which the skill measured by the (educational) instrument is linked to some other attribute by a hypothesis or construct. This is usually done by measuring performance in 2 groups who are hypothesized to differ in the skill being measured by the instrument." (11). Construct validity is an important concept for this thesis as it is the main point of analysis for the three experiments that I will be presenting in the following chapters. However, defining surgical expertise is not an easy task because of the multiple facets that it is composed of. For example, expertise is domain and task-specific (12, 13). A neurosurgeon may be an expert at cranial surgery, but a novice at complex spine surgery. Expertise is also characterized by adaptability and the ability to manage unfamiliar situations and uncertainty (13-15). Another element that is associated with expertise is the automatization of action. This specific memory skills allow the expert surgeons to perform the task with minimal attentional effort and also to multitask easily (16). Alderson (17) adapted the Hoffman's model of expertise (18) to the current training stages of becoming surgeon. In this adaptation, the expert is the consultant surgeon and the novice correspond to foundation doctor. Similarly, in the context of this thesis, we used the current Canadian neurosurgery training curriculum to defined expert and novice neurosurgeons. The novice group was composed of neurosurgery resident currently involved in a residency training program. Currently practising and board-certified neurosurgeons were part of the expert group.

Surgical simulator models can be divided in four main categories: physical, virtual, web-based and mixed. For the purpose of this thesis and research area, more information will be provided on physical and virtual models. A physical simulator model has for principal characteristic to allow direct manipulation and contact between the surgical instruments and the surgical site. Traditionally, they represent the primary method of surgical training and education outside the operating room. Within the physical category it can be further divided into 3 types of simulator models based on materials that compose the simulator: animals, non-living biologic tissue and non-living synthetic tissue (Table 1.1).

Living animal models have an excellent face validity as the trainee needs to handle bleeding, the anatomy of the surgical site in the model can be similar to human anatomy and the haptic feedback is realistic. However, they can be expansive, require specialized facility and support (veterinarian or vet technician for anesthesia, housing the animals, and food for feeding them). On top of them, there is an ethical issue of using animal for skill training. For these reasons, the use of non-living biologic tissue models has increased as it overcomes these disadvantages while allowing for a good face validity and realistic haptic feedback. Some examples of non-living biologic tissue models are microvascular anastomosis using human or bovine placentas (19) or the radial artery of a chicken wings (20) and specific to neurosurgery, non-living swine head can be used to practice craniotomy and multiple surgical approaches (21). However, use of non-living biological tissue still requires specific facility and there is a cost associated with disposing those tissues after the training. The last type of physical model is the non-living synthetic tissue model and these models are often adopted at an early stage of training due to their relatively low cost, easy access and reusability. They are generally described as having lower face, content and predictive validity (22). However, with improved technologies and innovation some models have a good face and content validity like this model developed by Stryker in 2010 simulating a presigmoid approach (23). This particular model is an excellent illustration of instant feedback that surgical simulation can provide to trainees while they are performing the task. Effectively, this model equipped with specialized sensors produces a sound each time the drill touches a critical structure (dura, facial nerve and venous sinus) and a voice mentions the name of the injured structure.

While most physical models can only allow for one-time use, virtual simulators are designed for repeatedly use for skill training. Virtual simulators are divided in two different types: augmented reality and virtual reality. In the context of surgical education, augmented reality can be defined as an enhanced version of reality created by displaying digital physical object or text on a screen or inside an eyepiece. In comparison, virtual reality models are computer-generated three-dimensional images with or without tactile feedback. Virtual simulators have multiple advantages, they can create a wide range of surgical procedures with numerous anatomic variances. They are reusable which can explained why their long-term cost can be significantly less although their initial cost is definitely a barrier to their acquisition in a surgical simulation lab (24, 25). Ethical and legal issues related with the use of animal models and the limited access to cadaver models are problems that virtual simulator addresses. Disadvantages of these simulators are the inability to recreate the physical properties of surgical instruments and the realistic tactile feedback of the interaction between the instrument and the tissue (25, 26)

To optimise simulation training outcomes, cognitive load theory (CLT) (27, 28) needs to be taken into consideration. This framework stipulates that human working memory is limited (29) and when the total cognitive load associated with performing a task is greater than the working memory, performance and learning are suboptimal (30). The total cognitive load of a learning task is composed of three sources of cognitive load: intrinsic, extraneous and germane loads (28, 31). The intrinsic load represents the cognitive demands associated with performing a task and is influenced by the leaner's level of expertise specific to the task and the task complexity (28, 30). The amount of information that need to be simultaneously processed in the working memory determined the task complexity. The extraneous load is associated with material and information that need to be processed but that are not directly related to the learning goals. This can be modified by changing the manner the material is being presented to the learner and by improving the instructional design (32). Lastly, the germane load corresponds to the cognitive resources to create automation of schemas that are stored in long-term memory and contributes to optimal learning (30). To facilitate and promote learning in the simulation environment, surgical educators need to reduce the total cognitive load of a task by adjusting extraneous load (selecting cases with appropriate level of complexity and task requirements), optimising germane load (facilitating the creation of frameworks) and reducing intrinsic load (enhancing clinical reasoning of surgeon in dealing with information with efficiency). I believe, such a training process should carry out in the simulation environment with a goal to protect patient safety to a maximum level.

Category	Type	Description	Example	Advantages	Disadvantages
Physical	Animals	Live animals	Pigs, mice	Good to excellent face validity	Costly, not reusable, hygiene/health and safety issues, specialized facilities and support, ethics
	Non-living, biologic tissue	Dead tissue but originate from humans or animals	Chicken wings, pig leg, placenta	Good face validity, low cost	Not reusable, hygiene/health and safety issues, ethics
	Non-living, synthetic tissue	Tissue engineered to replicate biologic tissue	Artificial skull and brain, practice card with latex gloves	Low cost	Poor face, content and predictive validity
Virtual	Augmented reality	enhanced version of reality created by displaying digital physical object	Surgical planning, placement of EVD	Reusable, collect metrics, update models, accurate representation of surgical procedure	Initial cost
	Virtual Reality	Computer-generated 3D images with or without tactile feedback	NeuroTouch	Case library, good face validity, collect metrics, good variability	Initial cost, time-consuming to produce new cases, technical support
Web-based	----	Evaluate knowledge and decision-making	Self-assessment test	Evaluate decision-making and knowledge	No haptic controls or tactile feedback
Mixed	----	Combination of other types			

Table 1.1 Surgical simulation models

1.2 Methods of Assessment

More than a century after the introduction of a new residency training system into North America by Sir William Halsted (33), the Halstedian apprenticeship model is still omnipresent in surgical training programs. This German-style residency training is based on the exposure of the trainee to a diversity of surgical procedures and pathologies, and that the trainee is given gradually more important responsibilities. The surgical trainee is ultimately assessed by his/her mentor and if passes this subjective assessment will be granted the privilege to work independently as a surgeon (34).

Currently, the majority of the evaluation and feedback that a surgical resident receives happens sporadically in the operating room. In 1983, Ende (35) defined feedback as "an informed, non-evaluative, objective appraisal of performance intended to improve clinical skills". The quantity and the quality of feedback depends on multiple factors such as the attendings present in the operating room and the contribution of the resident during the surgical case. Jensen et al. (2012) showed that there is a discrepancy between surgical residents and faculty members in regard to the amount, the quality and the specificity of the feedback following the operating room. In general, residents are less satisfied with the feedback that they received (36).

Intraoperative teaching is a complex science and its efficacy can be limited by few obstacles. For example, a relatively small number of surgeons actually receive formal training in regard to educational theory and know the systematic approach that they should be using to meet trainee educational needs (37, 38). In addition, communicating effectively where the surgical resident should look and place his/her hands can be challenging. This inefficiency ultimately leads to increased operating time and can create unnecessary risks for the patient (39). Surgical simulation can certainly be a solution to this scenario as the surgical skills are performed in a controlled environment and time restriction is not an issue which allows for more teaching and application of objective criteria for evaluation.

To overcome the subjectivity that is often present in the current surgical skills assessment of residents, criteria-based assessments have been developed. The two principal examples are the checklists and the global rating scales (GRS) (40). These evaluation tools have for objective to transform the assessor from an interpreter role to an observer of behaviour ultimately leading to a more objective assessment (41). However, checklist can sometime lack construct validity as it does not assess the quality of the task or the order that it was performed. Martin et al. (1997) confirmed this poor construct validity by asking 20 surgical residents to perform operative skills during simulation and the checklist method was not able to discriminate junior and senior residents (42). The global rating scale is a tool usually developed by a group of senior surgeons where they decide the different dimensions that they consider important when performing a surgical task (40, 41). For example, respect of tissue, instrument handling and knowledge of procedure are dimensions frequently encountered in GRS (41, 43). Each dimension is then graded with a Likert scale and points are anchored by explicit descriptors. This tool is used to evaluate more general skills which make them applicable to a diversity of surgical procedures and eliminate the need to develop an evaluating tool for every task. In addition, GRS have been found to have a higher interstation reliability, increased construct validity and have a better predictive value of the quality of the end product compared to checklist (24). Regehr et al. (1998) concluded in their study comparing the use of checklist against global rating scale in the context of objective structured clinical examination (OSCE) that GRS are superior and there is no value in adding a second evaluating tool like the checklist (41).

Some limitations of criteria-based assessments are the necessity to have the evaluator present during the simulation which is labour-intensive and costly in resources. Part of these disadvantages can be overcome by video recordings of the task and evaluated at a more convenient time (40).

More specifically for this research project two different criteria-based assessments are relevant: the University of Western Ontario Microsurgical Skills Acquisition/Assessment (UWOMSA) and the Objective Structured Assessment of Technical Skills (OSATS).

The UWOMSA tool was developed in 2010 by Temple et al. (2011) from London, Ontario, Canada as a validated and formal method to assess microsurgical skills (44). It was created by literature review and expert panel. It is composed of two modules evaluating two different surgical tasks: knot tying and vascular anastomosis. In this study, they confirmed the validity of their assessment tool by showing a good criterion validity and construct validity. The criterion validity compared the correlation of the tool being studied with an external criterion, which in this case is the Reznick’s global rating scale, an accepted standard for evaluating operative performance. In addition, the inter-rater reliability which can be defined as the agreement between two raters and the intra-rater reliability which is the agreement within a single rater at two different point in time (in that study it was three weeks apart) were both reported as “good”. The inter-rater and intra-rater reliability were 75% and 69% respectively. Some critics say that it is a too simplistic tool and that a three criteria assessment might not be appropriate when the goal is to improve a microsurgical technique and not just to familiarize the resident (34).

The Objective Structured Assessment of Technical Skills (OSATS) was one of the first tools developed to assess objectively surgical skills. It has been the subject of a large amount of research and is often considered the gold-standard of global rating scale to assess surgical skills (41, 45-51). Consequently, it is widely used in the field of surgical education and it has been validated for the assessment in microsurgical training (52, 53). This method was proposed by Reznick et al. (1997) from University of Toronto in 1997 (42, 54). It is designed to assess the technical skills of surgical residents to different situations and is not restricted to a specific task. Seven different domains are assessed while using this evaluation tool: 1) Respect of tissue, 2) Time and motion, 3) Instrument handling, 4) Knowledge of instruments, 5) Flow of operation, 6) Use of assistants and 7) Knowledge of specific procedure. The OSATS tool has been used in a simulation environment with both live animal and bench models with similar results (45). A higher OSATS score is usually associated with a more senior level of expertise thus demonstrating the construct validity of this tool. For example, after assessing surgical residents' technical skills over a period of 3 years, Niitsu et al. (2013) confirmed this positive correlation between OSATS score and level of training (47). However, in this study from the orthopedic field, there was no correlation between the quality of surgical result (reduction of intra-articular fractures and fixation of extra-articular fractures) and the OSATS score (55).

Criteria-based assessment are an improvement toward a more objective evaluation of surgical skills. However, some examiner bias could still be present and is hard to quantify. Consequently, hand motion analysis and instruments tracking technology have been used to eliminate this bias and can provide richer information towards objective assessment on surgical skills.

1.3 Movement Tracking in Surgery

Hand motion analysis and instrument tracking technology have been developed with the objective to quantitatively assess surgical skills and eliminate the potential examiner bias that can occurred with global rating scale assessment and other subjective assessment tools. Other than having quantitative data to compare participants, advantages of movement tracking technology include a good construct validity, the possibility to collect data instantaneously and in a relatively less labour intensive manner because it does not require an evaluator to be present during the surgical task performance (34). However, these technologies required expensive equipment, can be cumbersome for the surgeon as wires, sensors and other devices are sometimes applied to the surgeon's hands and can limit the freedom of movements (34). In addition, depending on the quantity and the size of the technology, the room where the experiment is being conducted can easily become crowded. Also, as with any electronic technology it can be prone to problems and computer science or engineering expertise might be required to fix the problem. Another disadvantage of hand motion analysis and instrument tracking technology is the need for specific and expensive software. The disadvantages mentioned previously are all related to the logistics of applying and implementing these technologies in surgical simulation. On a more fundamental aspect, a criticism of using motion analysis is that it does not assess the quality of the performance and the end product (56). Thus, many studies have suggested to use global rating scales in conjunction to movement tracking for a more objective skills assessment. These studies have also found a good correlation between the global rating scores and the hand motion analysis (53, 57-60).

Hand motion analysis and instrument tracking technology can be achieved using multiple methods and these can be categorized as: video analysis using computer science algorithm, mechanically-based motion detection, electromagnetic-based motion detection and finally optically-based motion detection.

First, interesting studies have emerged from the computer science and engineering literature about using video analysis to provide individualized and objective feedback to surgeons about their surgical technique. Different methods have been used to detect the position of the surgical instrument in a video and to track the movement of this instrument over consecutive frames. Kranzfelder et al. (2013) used radiofrequency identification technology to detect instrument position in minimally invasive surgery (61). Image-based analysis applying segment and contour processing as well as 3D modelling have also been reported (62). Other studies have used deep learning approaches based on convolutional neural networks (63-66). The results using these technologies are promising but are still limited in term of information that can be collected.

Second, multiple companies sale surgical gloves that allow to collect joint position data and hand velocity data (67, 68). Some examples are Immersion's Cyberglove II (Cyber glove Systems, San Jose, California), Measurand's ShapeWrap II (Measured, Fredericton, New Brunswick) and the Fifth Dimension Technologies' 5DT Data Glove (Fifth Dimension Technologies, Irvine, California). These gloves have embedded sensors that when mechanically bend generate the data. The downside of these gloves is their bulkiness and can limit the surgeon's tactile and haptic feedback.

Third, electromagnetic-based motion detection is another technology that could be used to assess hand motion. For instance, the trakSTAR™ (Ascension Technology Corp, Shelburne, VT) is an electromagnetic tracking system that can track up to sixteen sensors of different sizes at once. Each sensor is tracked in six degrees of freedom (6DOF) and can measure between 0.56 mm and 2 mm of outer diameter. The accuracy of the trakSTAR™ is estimated by the manufacturer at 1.4 mm root mean square (RMS) and 0.5 degrees RMS (69). Considering the small size of these sensors, this tracking system could be used by inserting and gluing the sensors between two surgical gloves without affecting the surgeon's dexterity. However, disposing the gloves after surgery or the simulation task also mean disposing the sensors, resulting in significant cost (68). Another disadvantage of these sensors is the fact that they are connected to a unit desktop by wires limiting freedom of movements.

The Imperial College Surgical Assessment Device (ICSAD) is an electromagnetic tracking system widely used to collect motion data in surgical simulation (56, 70-73). The isotrak II system (Polhemus Inc, Colchester, VT), which is an electromagnetic sensor measuring 10 mm, is placed on the dorsal side of each hand and surgical gloves are then put on to stabilize and secure the position of the sensor. ICSAD records the x,y,z Cartesian coordinate information of each tracker with an accuracy of 1 mm and a frequency of 20Hz (56). The data collected allow to measure the number of hand movements, the hand-travel distance, the direction and acceleration of the hand movements and finally the total task time (56, 74, 75). Grober et al. (2003) evaluated the construct and concurrent validity of the ICSAD as a hand-motion analysis system for microsurgery task (57). Fifty junior surgery residents (postgraduate years 1-3) from different specialities performed a suturing task under the surgical microscope at baseline and after a one-day microsurgical training. The surgical performance was assessed using global rating scales by blinded, expert microsurgeons. In this study, they found a correlation statistically significant between the number of hand movements as well as the hand-travel distance and the participant's global rating score. Authors also reported an improvement of hand-motion after the microsurgical training. One limitation of this study, as raised by Harada et al. (2015), is that this tracking system is not adequate to assess most of the microsurgical procedures as surgeons move the fingers rather than the entire hand (76).

Finally, optical-based motion detection is a technology that uses a camera or an array of cameras to locate the position of an object or a hand. In general, these tracking devices are not cumbersome and do not impact the movements of the surgeon during the surgical procedure. However, the main issue that can arise from this technology is when the trajectories between the cameras and the optical markers are obstructed. This result in the inability of the software to record the position of the object of interest and lead to omitted data. This limitation can be overcome by a good positioning of the cameras, increasing the number of cameras used in the simulation setting and adjusting the position and the number of optical markers for each object that are tracked. Modifying the optical markers configuration can improve the quality of the tracking system as a minimum of 3 optical markers need to be seen at all time by the array of cameras to allow for object detection.

Harada et al. (2015), used an optically-based motion detection technology to assess the surgical skills of 23 neurosurgeons performing end-to-end anastomosis of a 0.7 mm artificial blood vessels (76). This group developed their own tracking instruments: each pair of tweezers were mounted by an inertial measurement unit with Bluetooth data transmission capability and 3 optical markers. In addition, each tweezer had strain gauges attached to it allowing to measure the needle-gripping force. The authors evaluated the RMS error to be 0.3 mm with a sampling frequency of 60 Hz. This is significantly better than the 1.4 mm RMS error of the electromagnetic-based motion detection trakSTAR™. 3 blinded expert surgeons compared the stitches of the participants using a global rating scale developed by the authors (77) and named it visual assessment score. They had 19 neurosurgeons categorized as skilled and 23 in the unskilled surgeon category. They found that skilled surgeons performed a stitch significantly faster than unskilled surgeons. In addition, tool path for both hands were significantly shorter in the skilled surgeon group.

Depending on the technology used for hand motion analysis and instruments tracking, different data can be collected. Common metrics *include path following* and *length* (56, 68, 76, 78-80), *number of movements* (56, 57, 74, 75), *task completion time* (68, 76) and *velocity* (81-83). In general, the path length which correspond to the distance traveled by an instrument or the surgeon's hand decreases with surgical experience. This is also the case for the number of movements performed during a surgical task. These measures demonstrate that the economy of movements result in a more efficient manipulation and is acquired with experience. Additionally, a difference exists between expert surgeons and novice surgeons in term of time to complete a surgical task. Effectively, expert surgeons usually perform the task faster without affecting the quality of the end product. Peak velocity and mean velocity are other measures that can be obtained from motion analysis. Dosis et al. (2004) found that a sudden and wide movement of the instrument correlate with a velocity peak (84). This velocity peak could help identify potential inaccurate and dangerous movements. Motion smoothness can be obtained by measuring the rate of change in acceleration or counting the number of sudden accelerations and decelerations (81). It is now accepted that motion smoothness is associated with the level of expertise, dexterity and hand coordination.

Rosen et al. (2002) analyzed 30 surgeons at different levels of their residency training while they were performing seven minimally invasive surgery tasks on a pig model using the BlueDRAGON system (85). This system acquires kinematic and dynamic information of two endoscopic tools equipped with position sensors, three-axis force/torque sensors and contact sensors. Markov models were used to analyze and predict the skill level of the surgeon. The authors found differences between resident levels in term of the tool/tissue interactions, tool/tissue interactions applied by each hand, the amount of time the tool is being used during the task, the overall completion time and the variation of force/torque applied on the surgical instruments.

The NeuroTouch, a virtual reality simulation system with haptic feedback, was developed by the National Research Council (Canada) and a consortium of university centres across Canada and an important collaboration of the Neurosurgical Simulation Research Centre at Montreal Neurological Institute and Hospital (78). This simulation model is specially oriented toward neurosurgery and it is possible to practice multiple neurosurgical procedures varying from brain tumor resection to endoscopic approach. This virtual reality model is worth mentioning because it gives the participant immediate and cumulative metrics to track their performance. The researchers developed unique measures to evaluate motor and cognitive bimanual skills interaction. For example, the efficiency index assesses the cognitive-motor skills interaction, the coordination index evaluates 2-hand interaction ability and the bimanual forces ration measures the quality of the 2-hand interaction (78). This virtual reality simulation model is expansive and not easily accessible.

In conclusion, movement tracking in surgical simulation is a tool to objectively assess the surgeons' surgical techniques and is better combined with global rating scales to assess the quality of the final product. Multiple technologies can be used for hand motion analysis and instrument tracking, but optical-based motion detection has shown promising results and good accuracy for microsurgery procedures. Thus far, basic measures such as instrument's path length, number of movements and velocity have been reported with optical marker technology but advance measures evaluating 2-hand coordination, like those reported by the NeuroTouch, are still lacking from the surgical simulation literature.

In addition, purely assessing hand and instrument movements is not sufficient to evaluate the complexity of surgeon's eye-hand coordination. We review technology behind tracking surgeon eye motion with the hope to provide a comprehensive description of surgical skills acquisition using psychomotor evidence.

1.4 Eye Tracking in Surgery

1.4.1 Eye Tracking Technology

Eye tracking refers to the process of measuring where a person is looking. This technology is used in a variety of domains, from psychological research looking at patients suffering from depression (86), to neuromarketing and advertisements (87) to healthcare research. Two components are essential to eye tracking technology: a light source and a camera. An infrared light source is directed towards the center of the eye and hit the pupil causing a reflection in the cornea which is called the corneal reflection. This reflection is then captured by the infrared camera. The position of the pupil center and of the corneal reflection allows to extrapolate the rotation of the eye and the direction of the gaze (88).

Eye tracking technology can be divided in two types: screen-based (Figure 1.4.1.1) or head mounted-based (Figure 1.4.1.2). Screen-based is also called remote eye tracker requires the participant to sit in front of a screen while the eye tracker is usually located below or close to the screen to capture the eye movement. This allows the participant to be wireless but limit the freedom movement of the head. Effectively, if the participant's head rotates and stop looking at the monitor, eye-tracking data can be missing. This downside can be overcome by using head mounted eye tracker. In that situation, the participant usually wears an eyeglass frame on which the eye tracker has been mounted on. This provides the participant a liberty of movement; however, if the glasses shift during the experiment the eye calibration could be modified and measurements become inaccurate (88).

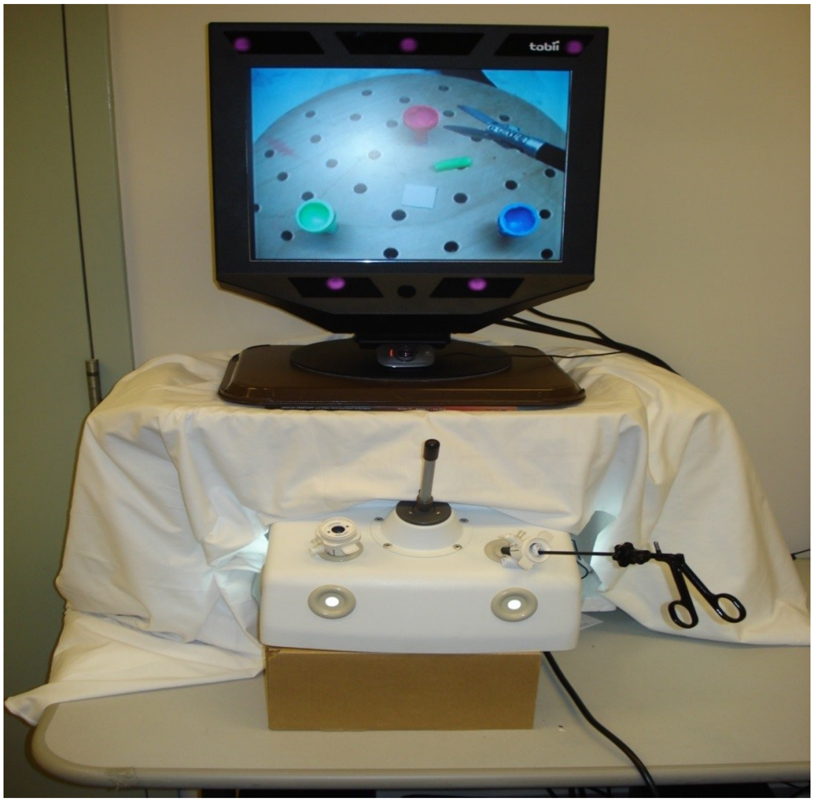


Figure 1.4.1.1 Screen-based eye tracker

Figure 1.4.1.2 Head mounted-based eye tracker

Different measurements can be obtained from an eye tracker and they include position and duration of *fixation* (pauses greater than 200 msec over informative region of interest) (89), *saccade* (rapid movements between fixations) (89), saccade amplitudes and velocities, *quiet eye* (final fixation prior to a critical movement involved in a skill) (90), *gaze overlap* (distance of less than 120 pixels between two gaze points) (91), *pupil diameter* (92) and the *coordinates* of estimated eye gaze.

1.4.2 Eye Tracking in Medical and Surgical Research

Eye tracking in medicine was first used in radiology in the early 1960 to teach resident the scanning pattern of radiologist reading chest X-ray (93) and has continued to be an important research area in radiology (94, 95). This technology has now gained importance in surgery and surgical education. In their literature review of eye movements in surgery, Hermens et al. (2013) clustered researches of eye tracking in surgery in four different categories (96). The first category studies the difference in eye patterns between expert and novice surgeons. The second category look at the link between these differences and the skill of the surgeon. The third investigates if the eye pattern is influenced by the task the surgeon is performing. The last category examines how eye tracking technology can be used as an educational tool.

Multiple studies, mainly from general surgery field, have found a difference in eye movement patterns between expert and novice surgeons. For example, Law et al. (2004) found three dominant gaze patterns in their study where they compared the eye movements of 5 experts and 5 novices performing a task on a computer-based laparoscopic surgery simulator (97). The authors described a target gaze behavior which happens when the participant looks directly at the target, a switching behavior defined as an alternating gaze between the target and the instrument, and finally a tool following behavior when the eye gaze follows the instrument on its way to the target. They found that experts have a more efficient gaze pattern with more target gaze behavior while moving the surgical instrument, whereas novices exhibited more switching and tool following behavior. The same conclusion was obtained in two different studies done by Wilson et al. (2010 and 2011) in the context of virtual laparoscopic surgery during surgical simulation (98, 99). Other metrics have been used to differentiate experts and novices using eye tracking technology. For instance, expert surgeons fixate for a longer period of time the vitals monitor during a simulated operation (100), and they have a lower saccadic rates and higher peak velocity while performing a surgical task (101). An important concept introduced in 1996 by Vickers is the quiet eye which is defined as the final fixation prior to a critical movement (102, 103). This measurement has been reported to be longer in duration for expert surgeons and has been used to assess objectively surgeon's visuomotor skill (99). This behavior could also be trained by video modeling and verbal feedback in order to improve novices' surgical performance. New literature continues to demonstrate the difference in gaze patterns between expert and novice surgeons, however little is known regarding the intermediate level of expertise. Kocak et al. (2005) separated the participants in three levels of experience: novice, intermediate and expert, and asked them to perform three different laparoscopic tasks. The authors reported a difference between novices and experts, with gaze pattern of intermediate level for the surgeon of intermediate skill, however no statistical difference was found between the intermediate level of expertise and the two other groups. This study suggested that gaze pattern changes in a gradual fashion (101). More research is needed comparing gaze pattern for the three level of expertise before coming to a conclusion.

Another interesting area of research that is related to eye tracking in surgery looks at how gaze training can improve novice surgeons performing a surgical task. For instance, Wilson et al. (2011) evaluated thirty medical students without any previous experience of laparoscopic surgery while they performed a task in a laparoscopic surgical simulator (104). The authors separated the students equally into three groups: gaze-training, movement training and standard feedback. Gaze-training was achieved by showing to the students a video of the gaze of an expert surgeon performing the same task. Explanations were given to this group about the gaze pattern of the expert and the concept of target-focused gaze strategy. They were then asked to perform the task while mimicking the gaze strategy of the expert and to analyze the differences between their gaze pattern and the expert's gaze pattern. They had the chance to perform the surgical task seven more times and to receive after each trial verbal feedback of their gaze behavior from the experimenter. A similar training was given to the movement training group where instead of watching the video of a surgeon's gaze, they watched the video of the surgeon's performing the task and analyzed the movement of the surgical instruments. The last group only received verbal feedback after each attempt. The researchers found that the gaze-training group learned more quickly, as measured by a faster completion times, and the difference was more pronounced when multitasking, thus concluding that gaze-training also help to reduce cognitive load during the surgical task. Similarly, Vine et al. (2012, 2013) also found that gaze-trained participants had a decreased completion time, an improved accuracy with less mistakes made during the surgical task. The gaze training group also had a gaze pattern similar to expert with increased target-locking strategy. Finally, they reported that the gaze-trained participants still performed better than traditional teaching after 1-month retention interval (105, 106). Another advantage of gaze training is that participants maintained their accuracy and still perform better than control group when the task is performed under pressure (106, 107). Different methods can be used to gaze-trained a participant: 1) expert surgeon's eye gaze pattern can be recorded during the task and superimposed on the recorded surgical video allowing novices to know where to focus their attention on the surgical field (91), 2) gaze training can be combined with verbal feedback (104, 108) 3) using a surgery training template which is a video software that captures the field of view and his controlled by the experimenter. The experimenter can force the participant to adopt a target-locking strategy of the expert by unmasking the region of interest for each step of the procedure (106).

1.4.3 Eye Tracking in Microsurgery

Most of the research exploring the implementation of eye tracking technology in surgery took place in the speciality of general surgery and most commonly with laparoscopic surgery. Research combining eye tracking and microsurgery is a new phenomenon and started in 2012 (109). The findings known by the scientific community about gaze pattern of novice and expert surgeons while performing a laparoscopic surgical task cannot be extrapolated to microsurgery. Effectively, operating under a surgical microscope implies a different depth perception and an adjustment of the eye-hand coordination. Surgical microscopes increase the magnification between 2 and 20 times the magnification of the human eye.

The first study exploring the gaze behavior of microsurgeons was done displaying still images of a micro-neurosurgical procedure (109). The authors selected four images from a surgical resection of a malignant brain tumor performed under a microscope. These images represented four distinct segments of the procedure such as resection of the tumor, presence of bleeding and fluorescent tumor tissue after injection of 5-ALA prodrug. Each image was annotated by two experienced neurosurgeons and they identified four common areas of interest (AOI): 1) tip of instrument, 2) bleeding areas, 3) tumor resection cavity and 4) exterior of tumor resection. In total, eight neurosurgeons participated in the study and they were divided based on their experience level resulting in four experienced surgeons and four novices. Each image was displayed on a screen for ten seconds and a screen-based eye tracker (Tobii T120) was used to record the participant's eye movements. The authors found that expert neurosurgeons have a time to first fixation shorter than novices for areas that require extra-attention such as oozing bleeding and areas of residual tumor revealed by the 5-ALA prodrug. The mean fixation duration (MFD), which is thought to correlate with the depth of the required processing, was longer for experts than for novices for areas of interest: tumor resection cavity and tip of the instrument. From that study, a defining characteristic of expert microsurgeons is their ability to have a gaze behavior that is more compact and locally defined as shown by small saccadic amplitudes. In addition, once the expert microsurgeons focus on a specific area of interest, they tend to have a longer fixation time.

After comparing gaze behavior of microsurgeons on still images, Eivazi et al. (2016) developed an eye tracker that could be embedded into the eye pieces of a surgical microscope using the video-oculography (VOG) principle (110). This concept required to project a light in direction of the eye and record the reflection of the light on the eye using a video camera. Other characteristics of the eye, such as pupil, iris and sclera, are used to measure the eye movements. During the conception of the eye tracker, the authors established six requirements in order to create a device that is safe to use and easily use in a sterile operating room. These principles are as followed:

1) The eye tracker installation should not require any modification to the surgical microscope.
2) The installation of the device on the microscope should be short
3) The system should not be intrusive and should not interfere with the flow of the surgery
4) Sterility should be conserved after the installation of the eye tracker
5) The surgeon's face and eyes should not be harm while using the device
6) It should be safe for the eye to use the eye tracker considering the long exposure time to infrared light.

After multiple prototypes, the researchers were able to design an eye tracker that could be attached to a surgical microscope and that is respecting their six requirements (Figure 1.4.3.1). They used a combination of low power density infrared LED light, mirror and a Sony PlayStation Eye Camera (PSE3eye) to create the eye tracker. The authors also tested the accuracy of the eye tracker by asking five participants to pass a 9-point eye tracking calibration test before performing the accuracy test. The accuracy test consisted of a repetition of the 9-point calibration test and thus, they were able to compare the difference between the predicted gaze points measured by the eye tracker and the real gaze value for each of the 9 points. They found on average a 1.1 degree of accuracy and 0.55 RMS which are values similar to other custom-made eye tracker (111, 112).

Figure 1.4.3.1 Eye tracker embedded on a surgical microscope

After designing the eye tracker, Eivazi et al. (2017) analysed the eye movements of nine neurosurgeons (six novices and three experts) while performing a cutting and suturing task under a surgical microscope (113). The participants were asked to cut along the line drawn on a surgical glove and forming a quarter circle with a radius of 4mm. They were then asked to suture the cut back together using a 7-0 suturing material and microinstruments. The authors found a difference in gaze patterns between novice and expert neurosurgeons. For the cutting task, experts had fewer fixations but longer fixation times on the operating field, more specifically the area where the tip of the scissors meets the cutting-angle gap. The average fixation duration for novices was 402 msec in comparison to 848 msec for experts. The authors explained this difference with the information-reduction hypothesis. This hypothesis stipulates that with practice, experts learn to differentiate between task-relevant and redundant information (114, 115). This illustrates why experts have longer fixation time because they concentrate their attention to the tips of the microscissor in contrast to novices that move their eyes from relevant areas to redundant areas, thus decreasing the length of fixation. For the suturing task, microsurgeons have to change their gaze pattern to adapt to a task that requires to collect more information with their eyes and is less static. This result in shorter fixation duration and modification of the saccade pattern which is analog to their visual search strategy. Expert neurosurgeons had increased saccade rate, but shorter saccade duration compare to novice neurosurgeons.

This is the only study in the scientific literature looking at gaze pattern during microsurgical task and using a surgical microscope. Their data samples are small with only nine participants and limited to one center. In addition, the authors evaluated a suturing and cutting task which does not represent the breadth of microsurgical techniques that a neurosurgeon needs to master. Further studies need to be done analysing gaze pattern during various microsurgical procedures.

Having reviewed the past literatures, we understand motion and eye-tracking can provide valuable data for describing surgical expertise. Scientists started to use the eye-tracking data into microsurgery, however, empirical evidence to describe eye-hand coordination pattern of neurosurgeons operating under surgical microscope remains rudimentary. Starting in Chapter 2 and the following chapters, I am going to present three controlled laboratory studies to further explore the eye-hand coordination evidence from neurosurgeons. These three studies use typical tasks extracted from neurosurgical procedures such as suturing, grasping and suctioning, and drilling. We will present details for each study followed by a general discussion. The final goal is to present our reader an integrated picture of surgical expertise using eye-hand coordination evidences.

Chapter 2 – Suturing under Microscope: Action-Related Fixation Helps to Differentiate the Level of Expertise

This chapter describes a complete study focused on comparing gaze behavior of experts and novices during a microsuturing task using a new eye-tracking measurement.

Introduction

In this chapter, we examine the eye-hand coordination of microsurgeons using a suturing task, one of the most common and essential task in microsurgery. Important eye-tracking literature can be found in Chapter 1 of this thesis. More specifically relevant to this chapter is the concept introduced in 1996 by Vickers (1996): The Quiet Eye. It is defined as the duration of the final fixation on the target before a critical movement (i.e. basketball free throw) (102, 103). This measurement was used by Wilson et al. (2011) to assess objectively surgeon's visuomotor skill during laparoscopic task (99). This behavior could also be trained by video modeling and verbal feedback in order to improve novices' surgical performance (99).

These findings from general surgery and laparoscopic surgery cannot be directly extrapolated to microsurgery as operating under a surgical microscope implies a different depth perception and an adjustment of the eye-hand coordination. Surgical microscopes increase the magnification between 2 and 20 times the magnification of the human eye. After designing an eye tracker that can be embedded into a surgical microscope (110), Eivazi et al. (2017) analyzed the eye movements of nine neurosurgeons (six novices and three experts) while performing a cutting and suturing task under a surgical microscope (113). The authors found a difference in gaze patterns between novice and expert neurosurgeons. For the cutting task, experts had fewer fixations but longer fixation times on the operating field, more specifically the area where the tip of the scissors meets the cutting-angle gap (113). In another study, the group also found that pupils size varies in function of the suture segments and the level of expertise of the participant

(116). However, their studies only report average fixation numbers and durations. It is difficulty to connect Eivazi's gaze report to Quiet Eye (QE) analysis as suggested by Vickers and Wilson.

In this paper, we are proposing a new eye-tracking metric, inspired by the QE concept, connecting gaze behaviors of microsurgeons to their on-going surgical movements, that we named "action-related fixation". We hypothesise that this level of analysis will allow to differentiate surgeon's level of expertise during microsurgery.

Material and Methods

This project was designed by surgeons at the Division of Neurosurgery of University of Alberta. Methods used in the study was reviewed and approved by the Heath Research Ethics Board of the University of Alberta (Pro00085187). Through the international collaboration, our data collection was conducted in the Eastern Finland Microsurgery Centre at Kuopio University Hospital.

Participants

In total, seven neurosurgeons (2 females and 5 males, mean age = 38) participated in the study. Participants had normal or corrected-to-normal vision. In the context of this study, we defined an expert as a currently practising, board-certified neurosurgeon. A novice is a neurosurgery resident currently involved in a training program. All participants were right-handed. Signed consent and demographic information were obtained for each participant before entering the study. Table 2.1 shows a summary of participants' characteristics.

	Expert (n = 4)	**Novice (n = 3)**
Age	42	33
Gender		
Female	0	2
Male	4	1
Hand-Dominance		
Right	4	3
Left	0	0
Years of experience	13	3

Table 2.1 Participants' characteristics

Task

A training board for microsurgical suturing that has been previously described in the literature (116) was used for this study. The suture training board contains one row with three suturing sites. Each suturing site was lined with a latex material and a pre-cut incision of 5 mm using a scalpel blade No.11. Participants were asked to execute two independent sutures for each incision, each suture was composed of one surgeon's knot and four single knots. A total of six sutures were required by each participant.

A box of 15cm height and having a craniotomy hole measuring 7 cm by 5 cm covered the suturing board to recreate a surgical environment with a deep surgical field (Figure 2.1). Participants used a polypropylene-polyethylene monofilament, non-absorbable suture with a needle length of 8mm and a curvature fraction of 3/8 of circle (6-0 Optilene blue 2xDR8 Double Armed). The thread was cut at 10 cm from the base of the needle. Participants had accessed to microforceps, a needle driver and microscissors during the suturing task.

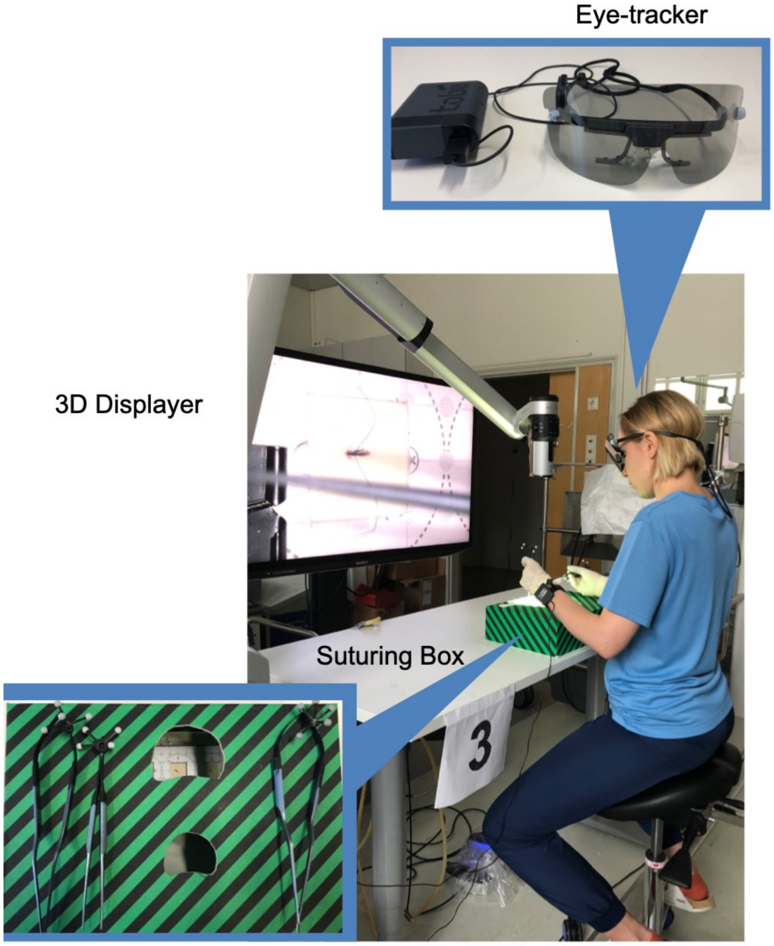


Figure 2.1 Display of the surgical task with a box covering the suturing board, the Olympus ORBEYE – 4K 3D surgical microscope and the Tobii Pro 2 Glasses wearable eye tracker with the CFV-E30D 3D EYE Shield.

Apparatus: Display and Eye-tracking

The Olympus ORBEYE – 4K 3D surgical microscope (ORBEYE model OME-V200) in 3D mode was used in combination with the LMD-X550ST LCD monitor. The monitor had a picture size (diagonal) of 1387.8 mm (54 3/4 inches) and was placed at a distance of 2 m from the participant as recommended by the manufacturer.

Prior to the experiment, the Tobii Pro 2 Glasses wearable eye tracker was calibrated by asking the participant to hold gaze at a single point located at arm length as per manufacturer's instructions. After the calibration was deemed successful as per the manufacturer's software, the validation process was performed by asking the participant to look at a target. The CFV-E30D 3D EYE Shield provided by the microscope company was then installed on the Tobii Pro 2 glasses to allow the participant to see the procedure in three dimensions (Figure 2.1). The gaze sampling frequency of the eye-tracking and the scene camera were 50Hz.

While performing the surgical task, the participants were in a sitting position and were allowed to rest their hand on the surface of the box to improve stability. Figure 2.1 depicts the setup of the experiment.

Data analysis

Both the video of the full-HD scene camera from the Tobii Pro 2 Glasses and the video integrating the eye movement and the scene camera (automated gaze-mapping technology and synchronization) were exported from iMotions 8.0 software. Parameters from Tobii I-VT (Fixation) filter was used for fixation identification. Thus, the velocity-threshold was set at 30 degrees/second, the minimum fixation duration at 30 msec and the maximum angle between fixation at 0.5 degrees (117).

The videos were then segmented as previously described in the literature (116) using the free and open-source event logging software Behavioral Observation Research Interactive Software (BORIS) (118). Every suture trial was divided into four subtasks, the needle handling, the needle penetration, the knot tying, and cutting. Total task time and the time spending on each of subtask were recorded.

Total time was defined from the moment the needle was seen entering the frame of the video to when the last thread of the suture was cut. The handling time corresponds to the period where the needle was seen in the video frame to the moment where the needle was stabilized on the needle driver and the forceps hold the edge of the incision. The penetration time correlates with the needle piercing the latex glove on the first side of the incision and the base of the needle exiting the latex on the opposite side of the incision. The cutting time was defined from the moment the 5th knot was secured and completely tight to the time where the last thread of the suture was cut.

Action-related fixation were computed on these three distinct actions: the needle piercing, the needle existing, and thread cutting. The piercing corresponded to the action of the needle piercing into the first wall of the incision. The exiting action occurred when the tip of the needle exited the second wall of the incision, and cutting action was the moment when the last suturing thread was cut.

Figure 2.2 illustrates the concept of action-related fixation. On each of these distinct actions, participant's eye would move to and fixate the surgical site and might stay on the same site a few milliseconds after the action. Therefore, we were able to compute pre-action fixation, post-action fixation, and total fixation duration related to that action. The pre-action fixation duration is the length of time from the beginning of the fixation to when the action occurs, and the post-action fixation duration corresponds to the period from the action until the end of the fixation. The total fixation is the sum of pre and post-action fixation.

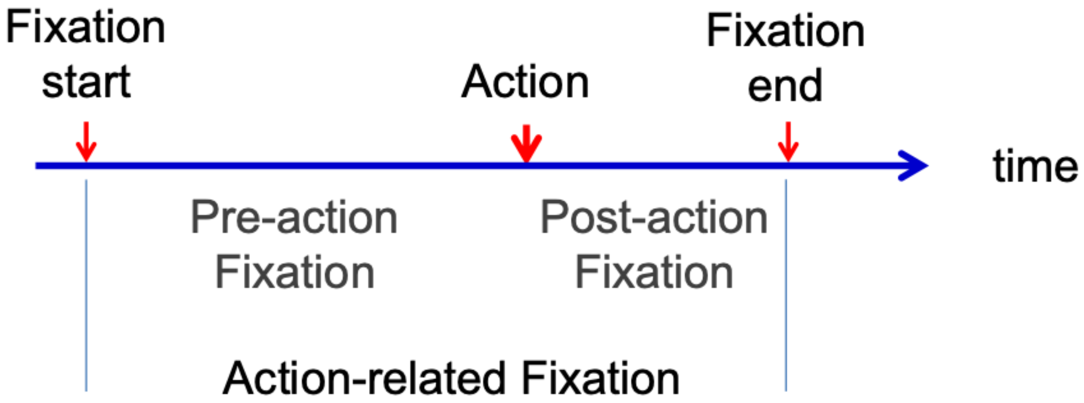


Figure 2.2 Concept of Action-Related Fixation

Statistics

We performed a One-way ANOVA on complete duration of total suturing time and subtask times over novice and expert surgeons. The Shapiro-wilk's test ($p > 0.05$) and a visual inspection of histograms and normal Q-Q plots showed that fixation data were approximately normally distributed for both experts and novices.

For the action-related fixation analysis, a 2 x 3 x 2 mixed ANOVA analysis with repeated measures on the last 2 factors was used. In our experiment, the first factor corresponds to the level of expertise (expert vs novice), the second factor was the 3 subtasks (piercing, exiting and cutting) and the third factor was the time of fixation related to the action. Each individual fixation was the unit of analysis.

All statistical analyses were done using IBM SPSS Statistics version 21. Results were reported as mean ± standard deviation. $P < .05$ was considered significant difference.

Results

In this study each participant performed 6 suturing trials. However, one expert abandoned the experiment after completing the first suture, resulting into 19 trials in the expert group instead of 24 trials.

One-way ANOVA revealed significant difference between expert and novice on the measure of total task time ($p = .038$) as well as for the penetration time ($p = .043$) and knot tying time ($p = .025$, Table 2.2). There was no difference found in the needle handling time. Specifically, expert surgeons completed the suture with shorter total time (258.52 ± 102.14 s) than novice surgeons (330.02 ± 96.52 s). Novices seemed not prolong their time in needle handling, but often time their needles were not grasped in the ideal position. This might contribute to the longer penetration and knot tying time than the experts (Table 2.2).

	Total (s)	**Needle handling (s)**	**Penetration (s)**	**Knot tying (s)**
Expert trials (n = 19)	258.52 ± 102.14	31.44 ± 16.67	17.15 ± 3.50	194.63 ± 94.55
Novice trials (n = 18)	330.02 ± 96.52	39.15 ± 21.56	26.26 ± 18.58	262.52 ± 79.05
P-value	0.038	0.230	0.043	0.025

Table 2.2 Suturing task – Time analysis

The mixed ANOVA (Table 2.3) on fixation measures showed significant differences on the main effect of expertise, ($F_{(1,1)} = 3.169$, $p = .044$, $\eta^2 = 0.083$), subtask ($F_{(2,1.6)} = 6.049$, $p = .008$, $\eta^2 = 0.147$), and the fixation pre- and post-action ($F_{(1,1)} = 52.166$, $p = .000$, $\eta^2 = 0.598$). On average, experts displayed longer fixation time (833 msec) than novices (619 msec). When performing task with higher level of precision, participants displayed longer fixation time (piercing: 1063 msec) than those less-demanding tasks (exiting 550 msec, cutting: 573 msec). Before action, participants fixated their eyes on the target significantly longer (1141 msec) than after action performed (317 msec).

There was a significant interaction (p = .008) between the subtask being performed and the level of expertise (Figure 2.3). Specifically, the experts maintained their visual engagement constantly over the 3 level of subtask (piercing = 849 ± 212 msec, exiting = 755 ± 136 msec, cutting = 912 ± 112 msec) in comparison to the novices who required a much longer fixation time for the challenging subtask (piercing) than in the intermediate and easy level of difficulty tasks (piercing = 1276 ± 218 msec, exiting = 346 ± 140 msec, cutting = 234 ± 115 msec). This suggests that novices did not develop stable visual searching strategy on the target like experts.

We found a significant interaction between the level of expertise and the duration of the fixation pre-action and post-action (p = .019). As displayed in Figure 2.4, experts used significantly longer pre-action (1391 ± 162 msec) than post-action fixation (287 ± 35 msec), In contrast, novices employed equivalent fixation time before and after action (891 ± 167 msec vs. 891 ± 36 msec). These findings suggested that experts focused on current surgical task much earlier and once the action was completed, they were faster to bring their attention to the next action.

There is a significant three-way interaction among expert, subtask and pre- and post-action fixation (p = .022, Figure 2.5). Specifically, expert use longer pre-action fixation than post-action fixation, and this pattern is distributed over all three subtasks (Figure 2.5 A). However, such a gaze engagement strategy was not shown in novice (Figure 2.5 B). In this expertise group, long pre-action fixation was seen in piercing, but not as drastically in the other two subtasks.

Source	df	F	P-value	Partial Eta Squared
Between-Subjects (expertise)	1	3.169	0.044	0.083
Subtask	1.561	6.049	0.008	0.147
Prepost	1	52.166	0.000	0.598
Expertise * subtask	1.561	5.997	0.008	0.146
Expertise * prepost	1	6.034	0.019	0.147
Subtask * prepost	1.678	2.387	0.109	0.064
Subtask * prepost * expertise	1.678	4.369	0.022	0.111

Table 2.3 Action-related fixation analysis - 2x3x2 mixed ANOVA analysis.

Where expertise (expert, novice), subtask (piercing, exiting, cutting) and prepost (pre-action fixation, post-action fixation)

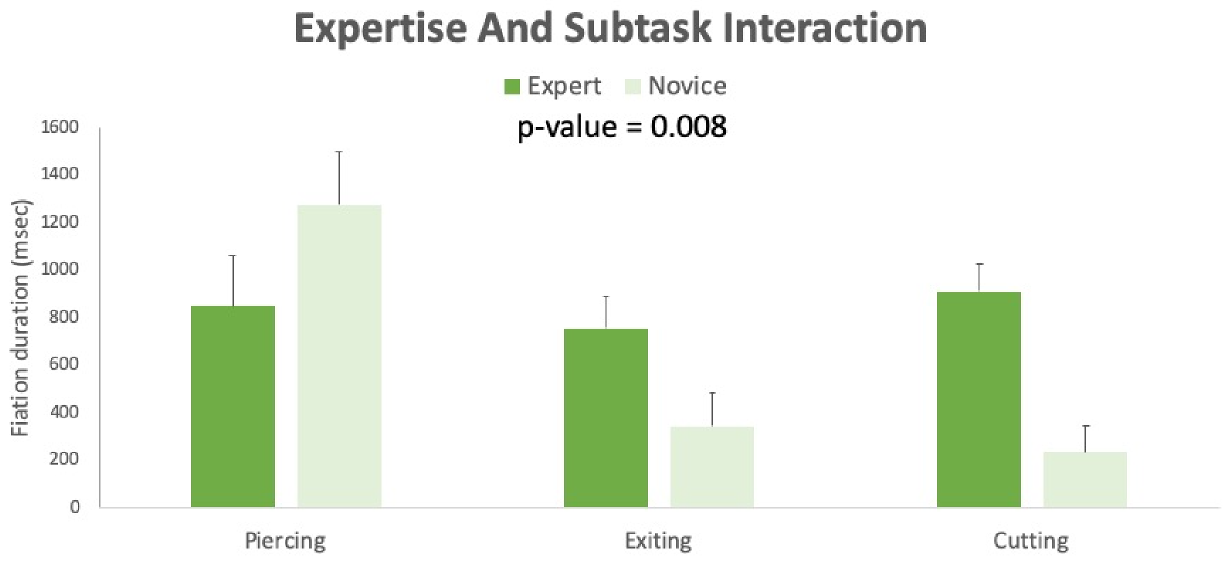


Figure 2.3 Expertise and subtask interaction

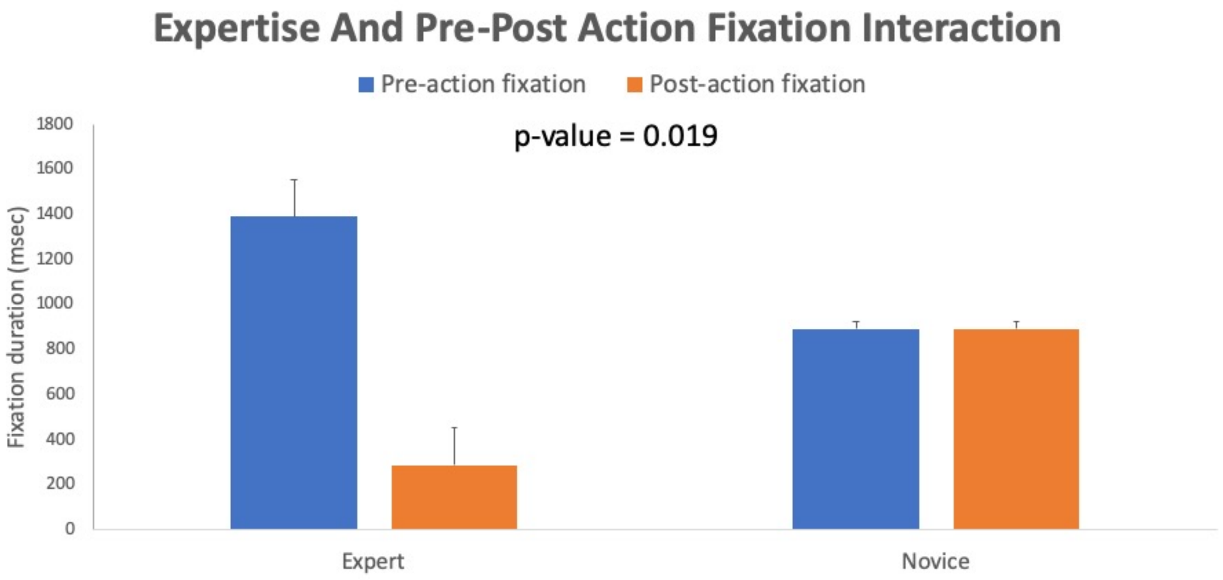


Figure 2.4 Expertise and pre- and post-action fixation interaction

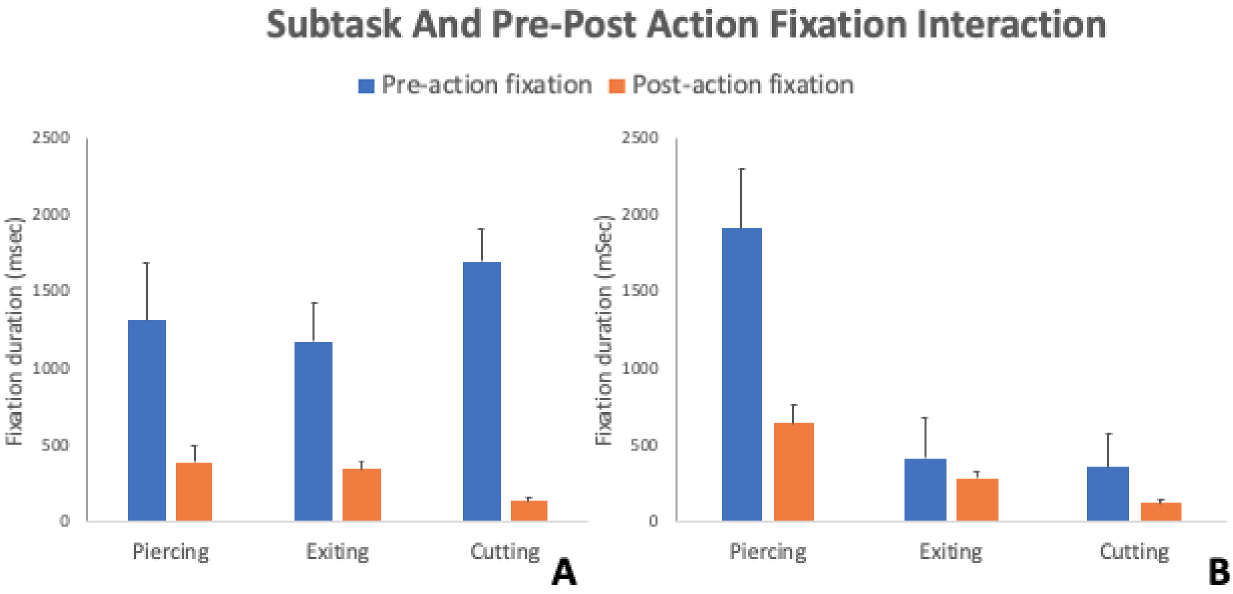


Figure 2.5A (expert) and 4.5 B (novice). Three-way interaction among expert, subtask and pre and post-action fixation

Discussion

Gaze behavior has been described in the surgical literature as a validated method to differentiate the level of expertise of surgeons (91, 98-100) as well as a teaching tool to facilitate skills acquisition for surgical trainees (104-106). Previous studies related to gaze behavior in microsurgery have used an embeddable eye-tracker mounted on the oculars of regular surgical microscope (110). This apparatus is not commercially available at the moment. In this study, we employed an alternative method for collecting surgeon's eye movement during microsurgery procedures with a combination of an exoscope and a wearable eye-tracker. Video telescopic intraoperative microscopes or exoscopes have gained popularity in neurosurgery in recent years and are seen as an evolution of the operative microscopes (119). As a result, we feel that gaze behavior research using this specific microscope is becoming more relevant. In addition, the Tobii Pro 2 Glasses wearable eye tracker is also an eye-tracking device easily available to researchers.

Our experiment found that experts were faster to complete a suturing task as well as for subsegment of the task such as penetration time and knot tying time. These findings are similar to what have been reported in the literature (56, 76, 116). We were surprised to see that the needle handling time was not different among experts and novices, however it can be explained by the tendency of trainees to pierce the tissue with the needle even when the needle was not in an optimal position on the needle driver. This behavior had for consequences to significantly increase the penetration time as novice surgeons had to re-grasp the needle during the insertion.

In this study, we proposed a new eye-tracking metric - the action-related fixation and hypothesized that it would be able to differentiate the gaze behaviors of experts and novices. Our hypothesis was supported by the results. When performing a specific surgical action, the surgeon did gaze on target with a single fixation. This fixation is critical for assessing target properties for guiding action of hands. The action fixation can further be divided into pre-action fixation and post-action fixation. Our experiment found that expert's gaze behavior was characterized by a pre-action fixation duration that was statistically longer than the post-action fixation duration and this pattern was constant over the three level of subtask (piercing, exiting and cutting).

We suggest that experts bring their attention to the region of interest for longer period of time before executing the action, which is consistent with the longer quiet eye phases of expert basket player found in Vickers's study (102). The new contribution of this study is that we found that experts were also quicker to move their attention to the next region of interest once the action was completed. This illustrates that experienced surgeons have an optimal strategy to relocate their visual attention to the upcoming subtask.

In addition, experts had a fixation duration constant in all three subtasks in contrast to the novices who had a longer fixation duration in the piercing subtask. This reflects that novices' visual behaviors were more affected by the level of task requirement; when they perform the subtask with higher level of difficulty as piercing the needle in the tissue it requires more focus and attention than exiting the needle on the other side of the incision or cutting a thread.

Applying our findings to surgical education, it will be interesting to see how gaze training can improve novices' performance of a surgical task. In other words, whether showing expert's gaze behaviors to novices could help the novices learn faster. Furthermore, it will become important to monitor whether such gaze patterns relate to actual individual performance in addition to the experience. Wilson et al. (2011) evaluated thirty medical students without any previous experience of laparoscopic surgery while they performed a task in a laparoscopic surgical simulator (104). They found that the gaze-training group learned more quickly, as measured by a faster completion times, and the difference was more pronounced when multitasking, thus concluding that gaze-training also help to reduce cognitive load during the surgical task. Similarly, Vine et al. (2012, 2013) also found that gaze-trained participants had a decreased completion time, an improved accuracy with less mistakes made during the surgical task. The gaze training group also had a gaze pattern similar to expert with increased target-locking strategy. Finally, they reported that the gaze-trained participants still performed better than traditional teaching after 1-month retention interval (105, 106). Verbal instructions can also be used to help novices to adopt gaze behaviors similar to experts' and ultimately improved their performances(120). These findings reinforce the importance of characterizing the gaze behavior of expert surgeons as it can be concretely used for teaching purposes.

A limitation of the current study is the smaller sample size of 4 experts and 3 novices resulting in 19 and 18 trials respectively; we invite others to replicate our work. In addition, this research is limited to a neurosurgery division from one single institution. Caution will be needed when applying our finding to other surgical expertise. On a technical note, we noticed that some eye-tracking data were not collected by the wearable eye tracker when the participants looked down directly at the surgical field instead of looking in front of them where the LCD monitor was located. This can be remediated by adding a small piece of cardboard underneath the google, filling the gap between the google frame and the participant's cheek. Another potential limitation is related with the simulation setting that this study took place. The presence of a wearable eye-tracker, 3D exoscope and the type of instruments used could have affected the participants' performance.

Conclusion

We are proposing a new eye-tracking metric, the action-related fixation, that can be used to differentiate gaze behavior between expert and novice microsurgeons in the context of microsuturing using a 3D exoscope and a wearable eye-tracker. We believe that this new eye-tracking metric can be added to the current measurements used in gaze behavior research such as number or duration of fixations, saccades and quiet eye. This research is another step towards better understanding surgeon's eye-hand coordination and the visuo-motor skills acquisition of microsurgery. It would be interesting in future research to apply the action-related fixation principle to surgical trainees' education and see if teaching this gaze behavior improve surgical performance compare to control group.

Chapter 3 – Bipolar Grasping and Suctioning Task: How Vision is Guiding our Action

Introduction

When surgeons practice their surgical skills, their performance can be assessed using various methods. Paper-based assessment form such as checklists and global rating scales are common tools employed in surgical education (41, 44, 54). Other frequent criteria are temporal measures such as task completion time or time used for different task segments (113, 121, 122). Temporal analysis is more objective as it limits the subjective component of human evaluation. However, it is still a basic level analysis of a surgical performance. It lacks power to describe the surgeon’s performance features or to the cognitive activities during the surgical task. To enhance our understanding of surgical performance and the power for describing surgical expertise, we started to use eye tracking technology in the surgical setting (123).

Eye tracking is a technology measuring the gaze location of a human operator using a special device called eye-tracker. This field of research has gained importance in surgery and in surgical education. Signals from eye tracking has been shown to accurately evaluate the surgeon’s level of expertise (97-99) as well as proved to be a valuable tool to improve the performance of trainees (104, 105). More recently, this technology was used to assess the surgical skills of microsurgeons while performing a suturing task under the surgical microscope (113, 116). A suturing task is often the principal training exercise that researchers employed in their studies (53, 56, 124). While a suturing task is a benchmark to access skills under microscope in a surgical simulation environment, we believe that analyzing other type of microsurgical tasks that use different surgical instruments can bring additional information for us to better describe the skills of microsurgery as a whole.

Bipolar forceps and suction are common instruments used during neurosurgical procedures. The bipolar forceps can coagulate various structures and tissues such as vessels, dura, pia-arachnoid and tumor (81). The two instruments can also be used for dissecting tissues and to manipulate objects (picking up and placing cotton patties (81, 125), gripping and manipulate the tumor tissue (81)). In this project, we asked neurosurgeons to perform a surgical task using bipolar forceps and the suction in a simulated training environment. We are reporting the gaze behaviors of expert and novice neurosurgeons beyond temporal measures with a goal to describe their dexterity and cognitive skills. We hypothesize that expert and novice surgeons will display different performance measured by hand and eye variables.

Methods

This project was designed by neurosurgeons at the University of Alberta and ethical approval was received from the Health Research Ethics Board of the University of Alberta (Pro00085187). As a joint research between two institutes in Canada and Finland, the data collection was done in the Eastern Finland Microsurgery Centre at Kuopio University Hospital of Finland.

Participants

Four expert and three novice neurosurgeons participated in this experiment. Board-certified neurosurgeons practicing independently were categorized as expert (4 males, mean age = 42 years, 4 right hand-dominance, mean years of training = 13 years) whereas neurosurgery residents (2 females, 1 males, mean age = 33 years, 3 right hand-dominance, mean years of training = 3 years) were in the novice group. Informed consent and demographic information were collected from all individual participants included in the study.

Task

A wooden board with 30 holes (radius of 5 mm and a depth of 5mm) organized in a grid fashion with 10 of these holes randomly numerated was used for this study (Figure 3.1). A plastic cup containing 10 small cotton balls was located next to the board. Participants were asked to pick up a cotton ball with the suction first then to release the ball in the hole numerated #1 then proceed with the same task with the bipolar for the hole #2. This was done in a chronologic order while alternating between suction and bipolar until the 10 cotton balls were placed in their appropriate location. The surgeon needed to constantly scan targets on the board and manipulated instruments in both hands to achieve a satisfactory task performance. A trial was counted after moving one cotton ball, thus each participant completed 10 trials in total.

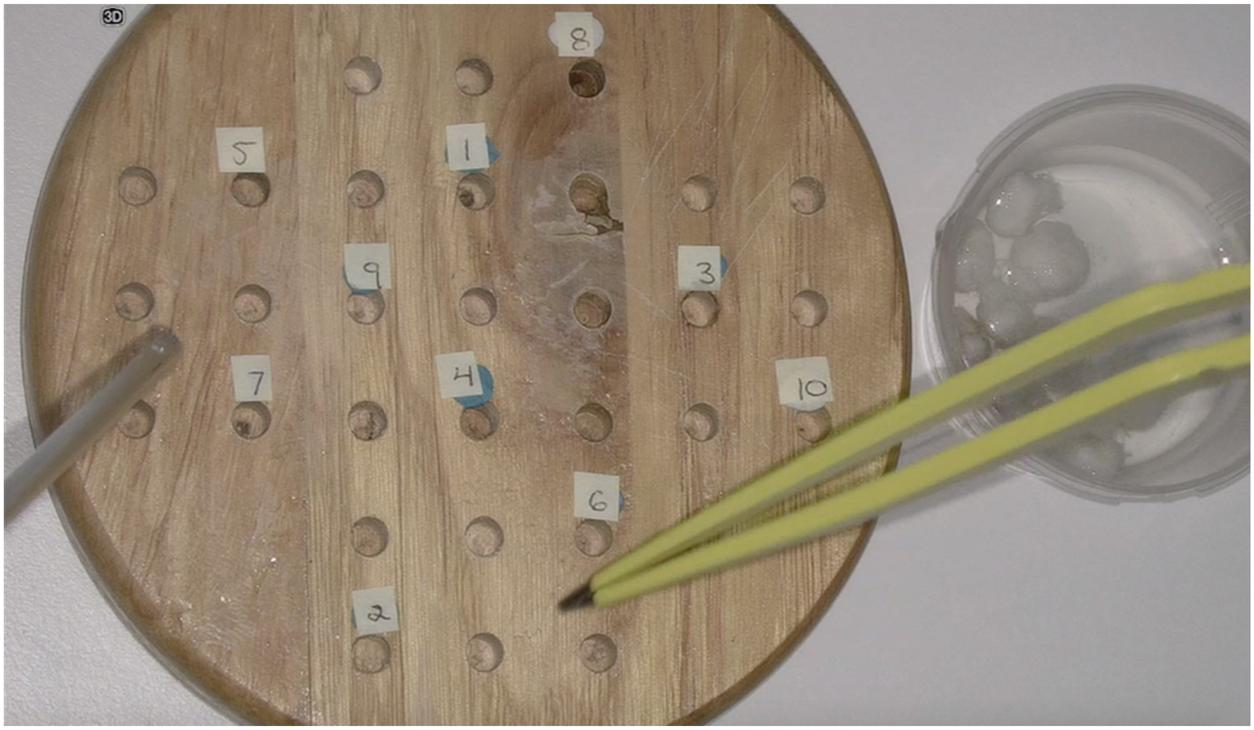


Figure 3.1 Wooden board used for the dexterity task

Apparatus: Display and Eye-tracking

The Olympus ORBEYE – 4K 3D surgical microscope (ORBEYE model OME-V200) in 3D mode was used in combination with the LMD-X550ST LCD monitor. The monitor had a picture size (diagonal) of 1387.8 mm (54 3/4 inches) and was placed at a distance of 2 m from the participant as recommended by the manufacturer.

Prior to the experiment, the Tobii Pro 2 Glasses wearable eye tracker was calibrated by asking the participant to hold gaze at a single point located at arm length as per manufacturer's instructions. After the calibration was deemed successful as per the manufacturer's software, the validation process was performed by asking the participant to look at a target. The CFV-E30D 3D EYE Shield provided by the microscope company was then installed on the Tobii Pro 2 glasses to allow the participant to see the procedure in three dimensions (Figure 3.2). The gaze sampling frequency of the eye-tracking and the scene camera were 50Hz.

While performing the surgical task, the participants were in a sitting position and were allowed to rest their hand on the table to improve stability if necessary. Figure 3.2 depicts the setup of the experiment.

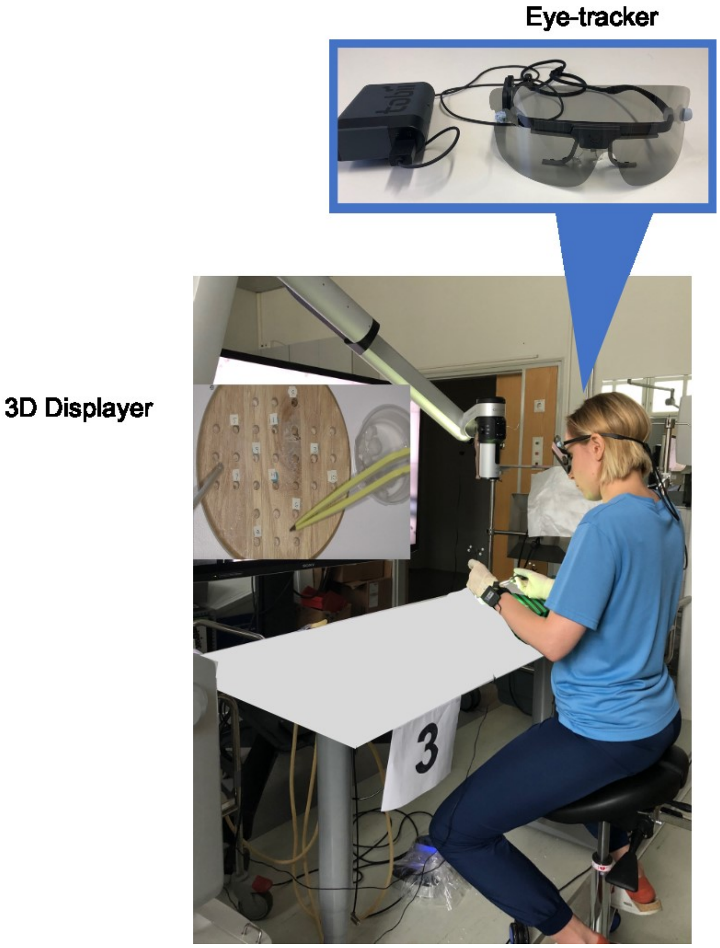


Figure 3.2 Display of the surgical task, the Olympus ORBEYE – 4K 3d surgical microscope and the Tobii Pro 2 Glasses wearable eye tracker with the CFV-E30D 3D EYE Shield

Data extraction

Videos from both hand motion (captured by the full-HD surgical scene camera of the eye tracker) and eye motion (Tobii Pro 2 Glasses) were synchronized in time and exported from iMotions 8.0 software. We applied Tobii I-VT (Fixation) filter for computing eye fixation. Specifically, the minimum fixation threshold was set at 30 msec and the maximum angle range of a fixation was set at 0.5 degrees (117).

Using the open-source event logging software Behavioral Observation Research Interactive Software (BORIS) (118), the videos were segmented, and for every trial, 6 different events were annotated. More precisely, 3 events were related to the movement of the surgical instruments (Instrument events) and 3 events were related with the surgeon's gaze behavior (Eye events) (Table 3.1)

Total task time, boarding time, gaze-tool time gap, number of fixations during the screening process and target-locked fixation duration for each trial were recorded. *Total task time* was defined from the moment the instrument picked up the cotton ball from the plastic cup to when the instrument released the ball in the appropriate hole. The *boarding time* was the period of time the instrument spent over the wooden board after picking up the cotton ball. The *gaze-tool time gap* corresponds to the length of time between the first gaze on the wooden board and the moment where the instrument is first on top of the board. This measurement reflects the length of time between the moment the participant starts to screen the board for the correct number and the moment he makes the decision to move the instrument out of the safe position. The *number of fixations* during the screening process for the correct number on the board indicates to a certain level how much the participant remembers the location of each number based on previous screening. Finally, the *target-locked fixation duration* is the time that the surgeon's gaze stays on the correct number for that specific trial. Table 3.1 summarizes these measurements.

Events and event definitions	
Instrument (suction and bipolar) events	Eye events
1. Instruments picks up the cotton ball	1. First fixation on the wooden board while the instrument is located over the plastic cup
2. Instruments is over the wooden board	2. Beginning of the fixation when participant first localizes the appropriate hole
3. Instruments releases the ball in the appropriate hole	3. End of the fixation when participant first localizes the appropriate hole
Dependent measures	
1. *Total task time (Instrument event 3 - Instrument event 1)*: from the moment the instrument picked up the cotton ball from the plastic cup to when the instrument released the ball in the appropriate hole	
2. *Boarding time (Instrument event 3- Instrument event 2)*: from the moment the instrument was over the wooden board to the moment the instrument released the ball in the appropriate hole	
3. *Gaze-tool time gap (Instrument event 2 - Eye event 1)*: from the first gaze on the wooden board to the moment where the instrument was over the board	
4. *Number of fixation during the screening process*	
5. *Target-locked fixation duration*: duration of the fixation associated with localizing the correct number for that specific trial	

Table 3.1 Events and dependent measures

Statistics

We performed a one-way multivariate analysis of variance (one-way MANOVA) on total task time, boarding time, gaze-tool time gap, number of fixations during the screening process and target-locked fixation duration between novice and expert surgeons.

All statistical analyses were done using IBM SPSS Statistics version 21. Results were reported as mean ± standard deviation. P < .05 was considered significant difference.

Results

In this study, each participant performed 10 trials (5 trials with the suction and 5 trials with the bipolar forceps) resulting in 40 trials in the expert group and 30 trials in the novice group.

There is not significant difference between experts and novices in term of total task time, boarding time and the number of fixations during the screening process. However, the level of expertise had a statistically significant effect on both gaze-tool gap ($F_{(1,68)} = 63.48$; $p < .001$, partial $\eta^2 = 0.54$) and the target-locked fixation ($F_{(1,68)} = 17.60$; $p < .001$, partial $\eta^2 = 0.24$). Specifically, expert microsurgeons had a longer gaze-tool time gap compared to novice microsurgeons (1.01 ± 0.30 s vs 0.44 ± 0.17 s) respectively. The target-locked fixation duration was also longer in experts compared to novices (experts: 1161 ± 819 msec, novices: 398 ± 290 msec). (Table 3.2 and Figure 3.3).

	Total Time (sec)	Boarding Time (sec)	Gaze-Tool Time Gap (sec)	Number of Fixation During Screening Process	Target-Locked Fixation Duration (msec)
Expert (N = 40)	5.02 ± 3.42	4.05 ± 3.35	1.01 ± 0.30	1.89 ± 1.62	1161 ± 819
Novice (N = 30)	4.94 ± 3.02	3.70 ± 2.65	0.44 ± 0.17	2.09 ± 1.34	398 ± 290
P-value	0.928	0.682	< 0.001	0.622	< 0.001

Table 3.2 One-way multivariate analysis of variance (one-way MANOVA) on total task time, boarding time, gaze-tool time gap, number of fixations during the screening process and locked-target fixation duration over novice and expert surgeons.

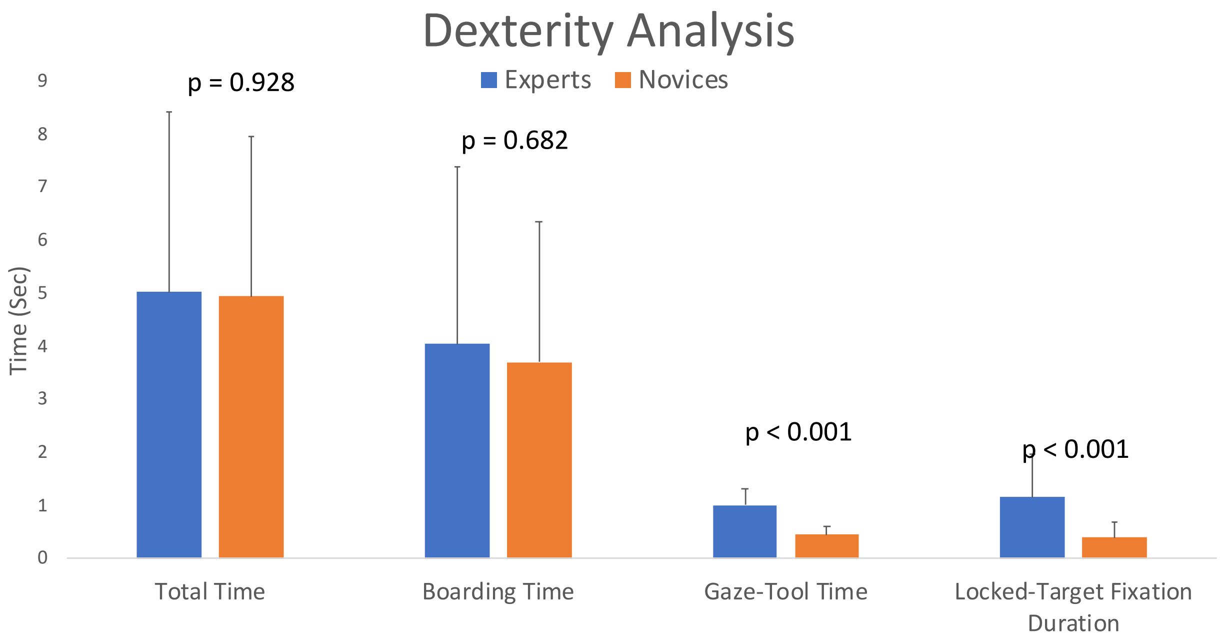


Figure 3.3 One-way multivariate analysis of variance (one-way MANOVA) on total task time, boarding time, gaze-tool time gap, number of fixations during the screening process and locked-target fixation duration over novice and expert surgeons.

Discussion

We hypothesized that expert and novice surgeons will display different performance measured by hand and eye variables. However temporal measures failed to distinguish surgical expertise the eye gaze measures did. Specifically, both gaze-tool gap and target-locked fixation were both longer in experts compared to novices.

The utilization of surgical microscope is omnipresent in neurosurgery and a constant effort is made to understand microsurgical skills acquisition. Describing the gaze behavior of microsurgeons using eye-tracking technology is relevant as it has shown to accurately discriminate the level of expertise (113, 116).

The task used in the experiment was different from most other microsuturing task such as suturing where surgeon's gaze is fixed in a relatively narrow surgical field. Surgeons' behaviors during suture task have been described before in the literature (113, 116). In contrast, surgical field in our current setting was larger and surgeon's gaze needs to scan a broader area before fixating a target. Unlike suturing task where hand movements and surgeon's gaze are mainly concentrating on the incision and the close surrounding area, our current setting require more active visual scanning on a wider surgical field. We intended to study the microsurgeon's scanning behavior in a task requiring a different gaze strategy than in suturing. The ball transporting task designed in this simulation setting is still relevant to the surgery and has similar movements executed by neurosurgeons under the surgical microscope while operating on a patient.

Our results indicate that gaze behavior information is more sensitive to discriminate the level of expertise than what the human eye can judge. In our experiment, there was no difference found between experts and novices in term of temporal measure, including total task time and boarding time. However, differences were found related to their fixation associated with the task. The absence of differences in time measurement might be related to the relative simplicity of the task. Thus, even the novice surgeons perform the task in a timely manner compared to the experts.

In this study, we show that experts had a longer gaze-tool time gap than novices. In other words, while searching for the appropriate hole to deposit the cotton ball in, experts kept their instrument over the plastic cup in a safe area. This can translate to the moment in the operating room where the surgeon would analyze the surgical field for the next step of the procedure while not moving the instrument. This helps to reduce the number of movements thus increasing efficiency. More importantly, keeping an instrument away from the surgical field would reduce the risk to injure critical anatomic structures. This finding is similar to what Law et al. (2004) described as the target gaze behavior predominantly exhibited by expert surgeons compared to novices (97). On the other hand, novice microsurgeons tended to keep the instrument on the board (surgical site) while scanning the wooden board in search for the appropriate number for placing the ball.

In addition, the target-locked fixation duration was significantly longer in experts than novices. When the correct number was identified, expert microsurgeons had a longer fixation associated with that specific action.

The findings from this project reinforce the importance of characterizing the gaze behavior of microsurgeons as it can differentiate the level of expertise. This knowledge can latterly be used in surgical education for teaching purposes. Some scientists have proved that gaze training (showing expert's gaze behaviors to novices at the critical step) can improve surgical performance, measured by completion time, movement accuracy and retention rate of trainees in laparoscopic simulation task (104-106).

A limitation of the current study is the small sample size of 4 experts and 3 novices resulting in 40 and 30 trials respectively. This study is also limited to a single institution. Caution will be needed when applying our finding to other surgical expertise.

Conclusion

Using a 3D exoscope and a wearable eye-tracker, we found differences in gaze behavior of expert and novice microsurgeon in a bimanual task where regular time analysis was not able to discriminate the participant's level of expertise. This research yields another evidence to support the use of gaze behavior for describe surgical expertise during microsurgery.

Chapter 4 – Drilling Task: Visual and Haptic Control

Introduction

Decompressive lumbar laminectomy is one of the most common orthopedic and neurosurgical procedures perform on the spine. It is used to treat spinal stenosis, herniated discs and tumors (126). In this procedure, the surgeon needs to drill the lamina of the vertebrae using a power tool to gain access to the spinal canal and reduce the pressure on the thecal sac and nerve roots. The power drill often generates significant amount of mechanical vibrations. Vibrations can be challenging for the surgeon who needs precise and controlled movements to avoid damage to nearby neurological structures. Another factor that can affect the surgeon's movement accuracy is the interaction between the drill bit and the bone. This interaction is influenced by multiple elements such as the angle of contact between the bur and the bone, the speed of the drill and the bone density. Expert surgeons, through experience, have integrated these factors to avoid involuntary movements of the drill.

Studies in human movement control have revealed that human fine movements are controlled primarily through visual and haptic pathways. Before our hand gets in contact with an object, our visual system collects information about the target, including distance, shape, weight, texture, etc. Once our hand makes contact with the object, mechanoreceptors beneath our skin gather information specific to that object whereas the sensors inside our joints and muscles collect information in order to adjust the position our hand and the force needed to manipulate the target. Sensory and kinematic pathways are delicate and fragile. Damage to these mechanoreceptors, like in the context of constant and repetitive vibration, can ultimately impair the accuracy of fine movements of the human operators by impeding the perception of the object's surface and the grip of the object (127).

In the surgical environment, this procedure is often performed under the surgical microscope which adds another level of difficulty to achieve precise movements. The image amplification caused by the microscope influence the surgeon's eye-hand coordination compare to direct-vision environment, as demonstrated by our previous study entitled "Action-Related

Fixation in Microsuturing, a New Gaze Behavior Metric to Differentiate the Level of Expertise" (not yet published).

To our knowledge, there is a lack of scientific literature regarding surgeon's movement accuracy for the drilling task. It requires special skills to master this task because of the magnified image, the constant vibration of the drill and the fact of working against resistance while drilling bone can cause involuntary and imprecise movements.

In this paper, we are analyzing gaze behaviors of expert and novice neurosurgeons while performing a lumbar laminectomy on 3D printed lumbar spine model. The procedure is done using a surgical microscope, electric drill and a suction instrument. We hypothesize that expert and novice surgeons will display different performance measured by hand and eye variables. More precisely, that experts will have less events with loss of control of the surgical drill, and eye fixation characteristics that would allow them to adjust more rapidly to these events.

Methods

This project was designed by neurosurgeons at the University of Alberta and ethical approval was received from the Health Research Ethics Board of the University of Alberta (Pro00085187). The data collection was done in the Eastern Finland Microsurgery Centre at Kuopio University Hospital.

Participants

Four expert and three novice neurosurgeons participated in this experiment. Board-certified neurosurgeons practicing independently were categorized as expert (4 males, mean age = 42 years, 4 right hand-dominance, mean years of training = 13 years) whereas neurosurgery residents (2 females, 1 males, mean age = 33 years, 3 right hand-dominance, mean years of training = 3 years) were in the novice group. Informed consent and demographic information were collected from all individual participants included in the study.

Task

A lumbar spine model composed of 3 vertebrae was fixed to the table using 2 bar clamps (Figure 4.1). A box of 20 cm height and having a hole measuring 4 by 3 cm covered the lumbar spine model to recreate a surgical environment with a deep surgical field (Figure 4.1). Participants had accessed to a drill and suction instrument during the lumbar laminectomy task.

Participants were asked to perform a one level laminectomy and were not limited to a specific technique.

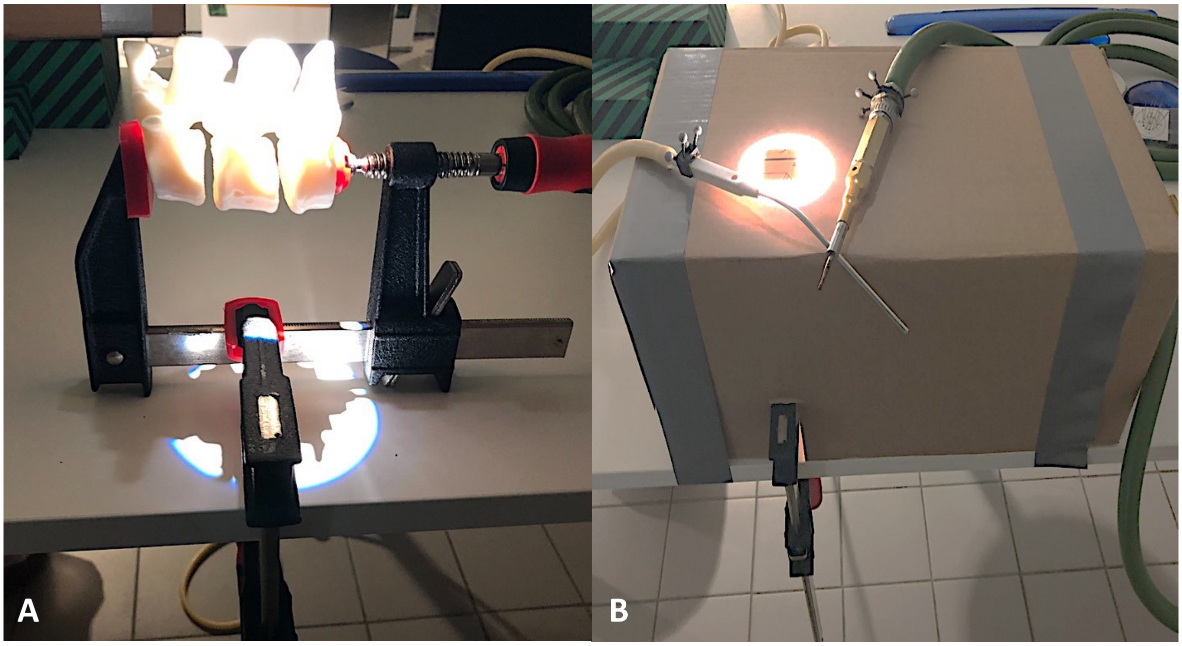


Figure 4.1 A) 2 bar clamps stabilizing the lumbar spine model to the table. B) Box covering the lumbar spine model with a hole creating a surgical environment with a deep surgical field.

Apparatus: Display and Eye-tracking

The Olympus ORBEYE – 4K 3D surgical microscope (ORBEYE model OME-V200) in 3D mode was used in combination with the LMD-X550ST LCD monitor. The monitor had a picture size (diagonal) of 1387.8 mm (54 3/4 inches) and was placed at a distance of 2 m from the participant as recommended by the manufacturer.

Prior to the experiment, the Tobii Pro 2 Glasses wearable eye tracker was calibrated by asking the participant to hold gaze at a single point located at arm length as per manufacturer's instructions. After the calibration was deemed successful as per the manufacturer's software, the validation process was performed by asking the participant to look at a target. The CFV-E30D 3D EYE Shield provided by the microscope company was then installed on the Tobii Pro 2 glasses to allow the participant to see the procedure in three dimensions (Figure 4.2). The gaze sampling frequency of the eye-tracking and the scene camera were 50Hz.

The Stryker Core Saber Drill with a 3.5mm round fluted bur medium was set to 50000 revolution per minute (RPM).

While performing the surgical task, the participants were in a standing position. They were allowed to rest their hand on the box to improve stability and move the surgical microscope if necessary. Figure 4.2 depicts the setup of the experiment.

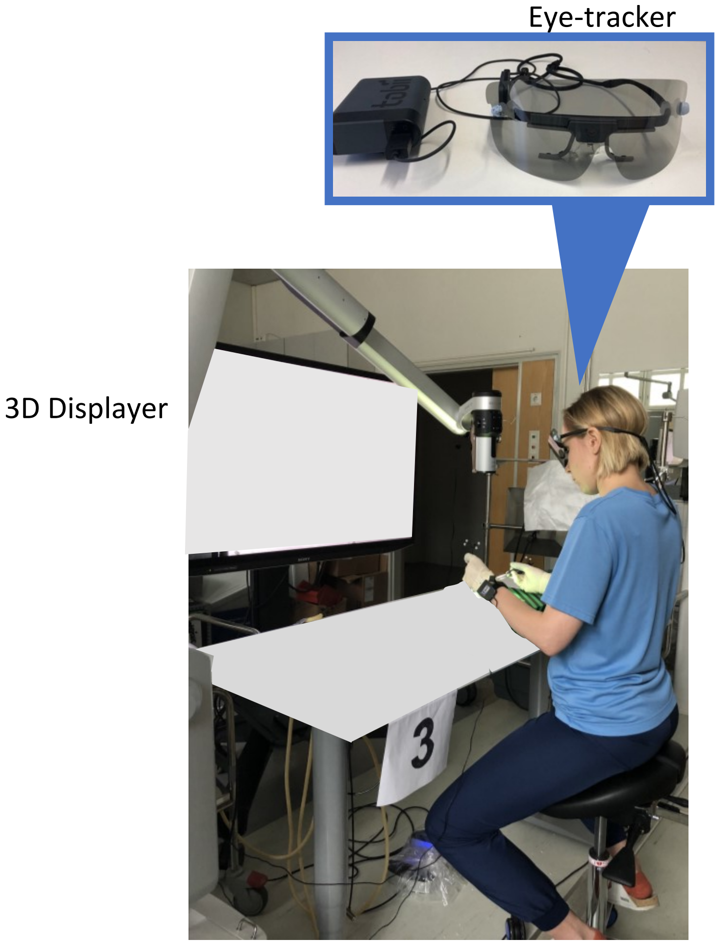


Figure 4.2 Display of the surgical task, the Olympus ORBEYE – 4K 3d surgical microscope and the Tobii Pro 2 Glasses wearable eye tracker with the CFV-E30D 3D EYE Shield.

Data extraction

Both the video of the full-HD scene camera from the Tobii Pro 2 Glasses and the video integrating the eye movement and the scene camera (automated gaze-mapping technology and synchronization) were synchronized in time and exported from iMotions 8.0 software. Parameters from Tobii I-VT (Fixation) filter was used for computing the eye fixation (gaze on a particular target area for a period of time). Thus, the velocity-threshold was set at 30 degrees/second, the minimum fixation duration at 30 msec and the maximum angle between fixation at 0.5 degrees (117).

Using the open-source event logging software Behavioral Observation Research Interactive Software (BORIS) (118), the video of each participant were analyzed. *Jumping event*, defined as moment where the drill bit moves unexpectedly and evident loss of control of the instrument is shown, was recorded. For the majority of these events an eye fixation would be associated with it. Therefore, we were able to compute *pre-jump fixation duration*, *post-jump fixation duration* and *total fixation duration* related to each of these jumping events. The pre-jump fixation duration is the length of time from the beginning of the fixation to when the jumping event occurs, and the post-jump fixation duration corresponds to the period from the jumping event until the end of the fixation. The total fixation is the sum of the pre and post-jump fixation. In addition, using BORIS' geometric measurement tool, the *jump distance* which can be defined as the distance in millimetres from the drill bit location before the jumping event to the furthest location of the drill bit during the jumping event was measured for each of these events. The presence of a marker measuring 6mm on the surgical instrument allowed the conversion of pixels into millimeters by the software.

Statistics

We performed an independent sample T-Test on number of jumping events, total fixation duration, pre-jump fixation duration, post-jump fixation duration and jump distance over novice and expert surgeons.

All statistical analyses were done using IBM SPSS Statistics version 21. Results were reported as mean ± standard deviation. $P < .05$ was considered significant difference.

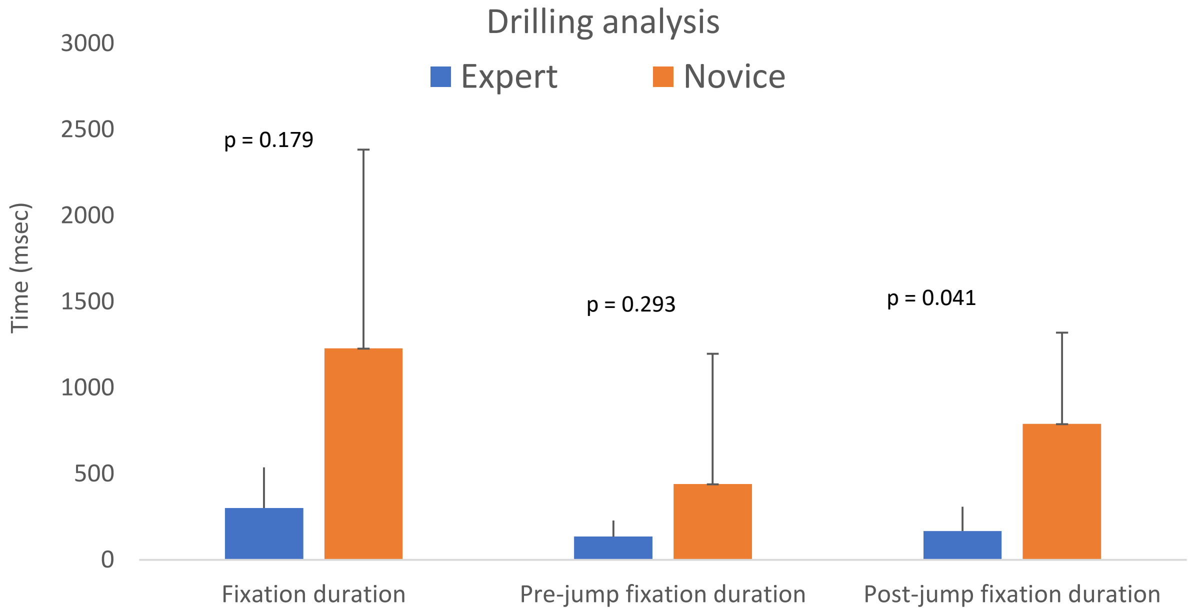
Results

The statistical analysis revealed significant difference between the expert and the novice surgeons in measures of drill jumping events, jumping distance and post-jump fixation duration; however, total fixation duration and pre-jump fixation duration were not showing significant difference.

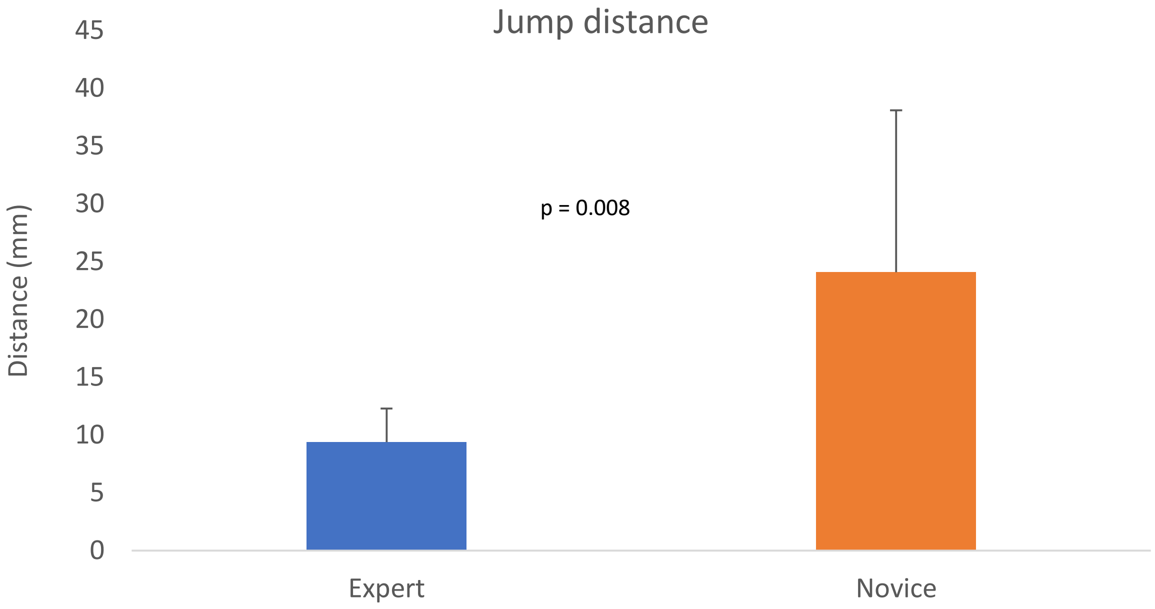
More precisely, novice neurosurgeons had significantly more jumping events than experts (10.33 ± 16.2 events vs 1.25 ± 1.5 events; $p = .008$). The post-jump fixation duration was also longer in novices compared to experts (novice: 789 ± 531 msec vs expert: 167 ± 141 msec; p = .041) (Table 4.1 and Figure 4.3 A). The jump distance was greater for novice (24.1 ± 14.0 mm) in comparison to expert (9.4 ± 2.9 mm) with a p-value of .008. (Table 4.1 and Figure 4.3 B).

	Drill jumping Event	Fixation duration (msec)	Pre-jump fixation duration (msec)	Post-jump fixation duration (msec)	Jump distance (mm)
Expert (N = 4)	1.25 ± 1.5	301 ± 235	134 ± 94	167 ± 141	9.4 ± 2.9
Novice (N = 3)	10.33 ± 16.2	1228 ± 1155	439 ± 758	789 ± 531	24.1 ± 14.0
P-value	0.008	0.179	0.293	0.041	0.008

Table 4.1 Independent sample T-Test on number of jumping events, total fixation duration, pre-jump fixation duration, post-jump fixation duration and jump distance over novice and expert surgeons.



A



B

Figure 4.3 A) Independent sample T-Test on total fixation duration, pre-jump fixation duration, post-jump fixation duration over novice and expert surgeons. B) Independent sample T-Test on jump distance over novice and expert surgeons.

Discussion

Our hypothesis was mainly supported by the results which showed important differences between experts and novices in term of gaze analysis and movement analysis.

In this study, novice neurosurgeons were recorded with an increasing number of drill jumping event and longer drill jumping distance during a lumbar laminectomy task which indicated a lower degree of control of the drill. We believe that these results can be explained in part by the detrimental effect of vibration caused by the power drill. Expert surgeons, with their numerous hours of drill manipulation, might have developed a strategy of upgrading their threshold to their sensory pathways comparted to novices and developed ergonomic techniques that directly improve their surgical performance during a drilling task. Studies in industries outside healthcare found that human operators can adopt into this situation by increasing the threshold of information in the haptic pathway, meaning that they can filter out noise after a long practice. For example, a study done by Brammer et al. (2007), found that forest workers, whom operate vibrating power tools such as chain saws and brush cutters regularly, have a change in mechanoreceptor-specific vibrotactile threshold at their fingertips over a period of months to years (127). In other words, after repetitive exposure to vibration, workers' mechanoreceptors underneath their skin change overtime and require a larger stimulus to perceive the vibration. This phenomenon defined as vibrotactile adaptation has also been studied by neurophysiologists. This adaptation is characterized by a reduction of vibrotactile sensibility such as hypoesthesia or by an increase in vibration detection threshold (128-130). It can be observed at different vibration frequency and exposure duration to vibration (131-133).

A study looking at work environment and hand-held tool vibration exposures showed that there is a temporary threshold shifts of fingertip vibrotactile perception depending on the tool position in the working surface (134). Researchers found that the effect of vibration could be reduced when the tool was held to the front of operator's body and ideally within 45° angle (right and left) from arms to the body. Applying this knowledge to surgical training, our finding suggests we need to give our trainees a longer period of practice with power drill before they can potentially develop adaptation strategy to the vibration and have precise movements during the surgical performance. Such training, we believe, should be performed on a simulation model to ensure patient safety. It would be interesting to repeat the experiment with a longer drilling task (multilevel laminotomies) and notice if there is a decrease number of drill jumping event and drill jumping distance because of vibrotactile adaptation in the novice group.

Analysing eye movements of surgeons using eye-tracker device can improve our understanding of surgical performance. Eye tracking technology has demonstrated it value in discriminating the level of expertise (expert vs novice) of participants performing a surgical task (97-99). Studies looking at surgeon's gaze behavior are principally limited to the general surgery and laparoscopic surgery and these findings cannot be directly extrapolated to microsurgery because operating under a surgical microscope implies a different depth perception and an adjustment of the eye-hand coordination. After developing an eye-tracker that can be embedded into a surgical microscope (110), researchers have characterized the surgical skills and found gaze behavior differences between expert and novice microsurgeons while performing a microsuturing task (113, 116). In our experiment, the gaze analysis revealed that novices tend to have a longer post-jump fixation duration than experts. In other words, when an unpredicted event happened, such as the loss of control of the drill, the novice took longer to adjust his gaze and analysed the situation to further adjust his movement. The motion analysis showed that on average the novice will move the tip of the drill 1.5 cm further from where he was working just before the jumping event compared to the expert. Jump distance seems to be a reliable marker for describing the expertise in drilling task.

Characterizing the gaze behavior of experts during a surgical task is important as it can be used in surgical education for teaching purposes. Gaze training in a laparoscopic simulation task has been shown to improve surgical performances of trainees on multiple aspects (104-106). Microsurgery is unique because of the use of a surgical microscope which change the depth perception and eye-hand coordination of the surgeon. Better understanding of microsurgical skills acquisition is important. Eye-tracking technology can help to achieve that goal.

3-Dimensional (3D) printing in medicine has evolved rapidly in recent years and has multiple purposes: surgical templates and diagnostic tools, organ printing and disease modeling to name a few applications (135). This technology is becoming more accessible on university campuses, hospitals and in the community. In our experiment, we downloaded from internet a 3D lumbar spine model in a StereoLitography (STL) file format. Having access to The Institute for Reconstructive Sciences Medicine (iRSM) which is affiliated with the University of Alberta, we printed the model with Acrylonitrile butadiene styrene (ABS) material and the cost was CAD$ 43 per model. This material has the advantage of being firmer than the foam cortical shell model (Sawbones) that is more frequently used in surgical simulation lab. Our participants expressed an appreciation of the realism of our model. Scientists are in constant search to find the perfect combination of materials to create a 3D printed spine model that would have the same tactile feeling and mechanical characteristics than human spine (136). At the moment, these realistic models are not easily available. Some limitations are present in our experiment. First of all, the small sample size of 4 experts and 3 novices is limited to a neurosurgery division from one single institution. We invite others to replicate our work. Secondly, we have noticed that some participants performing on the simulation model were not as careful compared to their performance on a patient. The lack of thecal sac in the simulation model allowed surgeons to drill the lamina faster and deeper. A way to palliate to this would be to insert a condom filled with water in the spinal canal, this would force the participant to be careful during the drilling task in order to avoid a tear in the latex material. This modification can simulate the cerebrospinal fluid leak related to a dural tear. On a technical note, the type of bur is also important to take into consideration. A shallow cutting-edge bur like the one we used, creates a lot of friction with the ABS material which then has the tendency to melt. However, if a 3.0 mm fluted match head bur is used, the ABS material is removed in a small pieces fashion because the depth of the angle bur is more important. This will increase the fidelity for simulating the interaction of the bone with a drill bit.

Conclusion

Differences in gaze behavior were found between expert and novice neurosurgeons during a simulated microscopic lumbar laminectomy using a power drill and surgical microscope. We found that novice neurosurgeons have increased jumping event and jump distance and they have a longer post-jump fixation duration than experts. The difficulty in controlling the instrument movements was mainly caused by the vibration induced by the power drill. This could translate to unsafe surgical performance and can impaired patient safety. We argue that providing our trainees with longer training time on a power drill simulator would allow them to develop a coping strategy before performing on patient. This study is another step towards understanding surgeon's eye-hand coordination in microsurgery and is promising for surgical education.

Chapter 5 – Discussion

Nowadays, surgical microscope has become an essential tool for multiple surgical specialities. From personal experience during my neurosurgery residency training, I have noticed that not using the microscope for a surgical case is the exception. Effectively, the microscope is being used in most of our cases: from lumbar microsdiscectomy to craniotomy for tumor removal to craniotomy for cerebral aneurysm clipping. This implies that trainees need to learn how to perform a variety of task and manipulate diverse surgical instruments when the image of the surgical site is magnified. Considering the importance and the omnipresence of the microscope in neurosurgery, it is essential to better understand the skill acquisition and the development of the eye-hand coordination of surgeons under the surgical microscope. We wanted to achieve this goal by using eye-tracking technology, which refers to the process of measuring the gaze location of an operator using an eye-tracker. Characterizing the gaze behavior of a surgeon is an essential component of its eye-hand coordination skill.

Eye-tracking literature in surgery is limited to open surgery and laparoscopic surgery. There is a definite lack of information in that regard for microsurgery. One of the main reasons is the complexity of acquiring the gaze location of a subject while he/she is looking directly into the oculars of the microscope. A group of researchers from the University of Eastern Finland accomplished this by designing an eye-tracker that can directly be embedded into the microscope (110). They were able to compare the gaze behavior (113) and pupillary size (116) of experts and novice neurosurgeons in a microsuturing task. This specific eye-tracker is not commercialized at the moment and is only available at this institution. This limit the ability to expend the eye-tracking literature in microsurgery. Our research proposes an alternative method for collecting surgeon's gaze location employing materials that are more easily available: wearable eye-tracker and exoscope. First, multiple wearable eye-trackers are present on the market and although they can be expensive, they are definitely a valuable acquisition to any research laboratories specializing in eye-tracking technology. For our experiment, we used the Tobii Pro 2 Glasses wearable eye tracker which is easy to operate, calibrate, do not compromise the surgeon's visual field, is not cumbersome during the surgical task and has a software exporting and interpreting the data that is user-friendly. Second, the video telescopic intraoperative microscopes or exoscopes have gained popularity in neurosurgery in recent years and are seen as an evolution of the operative microscopes (119). As a result, we feel that gaze behavior research using this specific microscope is becoming more relevant and reflect the rapidly evolving and changing reality of surgeons that need to master the surgeries that they know using more refined and improved instruments. Although proposing a new method to collect the gaze location of subjects while they perform a surgical task under the microscope is a contribution to eye-tracking literature, it is unclear at this point if one approach is more accurate than the other. It would be interesting to design a study in which surgeons would be performing the same microsurgical task using both methods (arrangement #1: eye-tracker that can be embedded into the surgical microscope and arrangement #2: combination of wearable eye-tracker and exoscope).

In Chapter 2, we analyzed the gaze behavior of microsurgeons with different level of expertise (expert vs novice) while they performed a microsuturing task. We defined an expert as a currently practicing, board-certified neurosurgeon. A novice is a neurosurgery resident currently involved in a training program. Previous studies describing gaze behavior in microsurgery reported information regarding the fixations (number, duration, time to first fixation, fixation rate) and saccades (number, duration, rate and amplitude) for a specific region of interest on the surgical field or for a segment of the task (109, 113). While these measurements provide valuable knowledge and characterize accurately the differences in gaze behavior between experts and novices, our research group thought that providing gaze location directly related to a critical moment or specific hand movement, similar to the concept of quiet-eye movement (137), would better reflect the eye-hand coordination of the participant. Better understanding the gaze behavior at a critical moment of a task could possibly facilitate the gaze training and provide focus feedback to the trainee. In comparison to provide feedback to an entire segment of the task.

In this chapter, we are contributing to the scientific literature by proposing a new eye-tracking metric - the action-related fixation that can differentiate the level of expertise of microsurgeon in a microsuturing task. It can thus be used for evaluation purposes and confirming when a trainee has achieved the level of an expert microsurgeon for this specific surgical task. The action-related fixation is a metric that can be applied to a surgical action that is associated with a single fixation. This fixation is critical for assessing target properties for guiding action of hands. The total fixation duration can further be divided into pre-action fixation duration and post-action fixation duration. The important finding of this paper is that expert's gaze behavior is characterized by a pre-action fixation duration that was statistically longer than the post-action fixation duration and this pattern was constant over the three level of subtask (piercing, exiting and cutting). Experts bring their attention to the region of interest for longer period of time before executing the action and are quicker to move their attention to the next region of interest once the action was completed. This illustrates that experienced surgeons have an optimal strategy to relocate their visual attention to the upcoming subtask.

The other finding is that the difficulty level of a subtask influences the gaze behavior of a novice as measured by the action-related fixation metric. For the piercing subtask which requires increased focus compared to the other subtasks (exiting and cutting), novices have a longer pre-action fixation duration. Their eyes need to fixate the region of interest for a longer period of time before the action takes place. This prolong time probably allows this group to collect information that would influence the end result of the subtask (ideal point of entry on the skin, position of the needle tip, interaction between the needle and the tissue etc.).

Surgical education implications:

As the different difficulty level of each subtask is inherent to the microsuturing task, I suspect that trainees would be able to adopt a similar gaze behavior than experts (consistent ratio pre- and post-action fixation duration over the 3 subtasks) only with time and practice, until they feel comfortable performing the piercing subtask. However, I am hopeful that by knowing that they should reduce their gaze on the region of interest before piercing the needle in the tissue, trainees would be able to reduce their pre-action fixation duration to some extent. Surgical trainees should also know that in order to improve their gaze behavior efficiency, once the action is completed, they should immediately focus their gaze to the next region of interest that is related to the next step of the procedure. That implies that the trainee, while performing the task, needs to think about the next step and where to look after. Also, to reduce the post-action fixation duration, the trainee needs to shorten the time spent at analysing the end result of the subtask.

While microvascular anastomosis is an important benchmark exercise in surgical simulation and has the advantage to practice participant's dexterity and precision to a high level, I don't think it truly represents the surgical skills required to practice general neurosurgery.

Mastering the skill of microvascular anastomosis is limited to a subset of neurosurgeons (vascular neurosurgeons) and in clinical practice, this procedure is performed in the operating room very rarely. This was my rational to design an experiment where suturing skill was still evaluated but would be more translatable to general neurosurgery practice. Suturing under the surgical microscope is a task perform regularly. For example, it is done when you need to repair a dural tear during spinal surgery or closing the dura after removal of an intra-dural spinal tumor. These examples do not need the high magnification power, or the same needle size employed during a microvascular anastomosis.

In order to be as relevant and translatable to clinical reality, I think it was important to characterize the gaze behavior of surgeon in different contexts where surgical microscope is being used. Situations where various surgical instruments are employed, and the magnification power of the surgical field is not as critical. This led to designing an experiment of ball transporting task using a bipolar forceps and suction as instruments and another experiment of looking at surgeons performing a lumbar laminectomy with a power drill.

In Chapter 3, we examined microsurgeon’s (expert and novice) scanning behavior in a task requiring them to pick up a cotton ball with a bipolar forceps or suction, transport it and release the cotton ball on a wooden board with randomly numerated holes. This was done in a chronologic order while alternating between suction and bipolar until the 10 cotton balls were placed in their appropriate location. This study found that temporal measures (total task time and boarding time) were not sensitive enough to detect a difference between experts and novices. We observed that for a simple task, such as the one described in this experiment, even a participant with a lower level of expertise is able to complete the task in a timely manner because they have acquired and mastered the basic skills for this particular task. In the scientific literature, temporal measures have often been reliable to discriminate the level of expertise (56, 76, 116), however we encourage other researchers to be cautious about these metric as they can be influenced by the level of difficulty, the duration of the task and they do not assess the quality of the task. We suggest that temporal measures should be one of various metrics when designing an experiment.

In this study, we show that experts had a longer gaze-tool time gap than novices. In other words, while searching for the appropriate hole to deposit the cotton ball in, experts kept their instrument over the plastic cup in a safe area. This can translate to the moment in the operating room where the surgeon would analyze the surgical field for the next step of the procedure while not moving the instrument. This helps to reduce the number of movements thus increasing efficiency. More importantly, keeping an instrument away from the surgical field would reduce the risk to injure critical anatomic structures. Another finding is that target-locked fixation duration was significantly longer in experts than novices. When the correct number was identified, expert microsurgeons had a longer fixation associated with that specific action.

Surgical education implications:

Even if the concept of minimizing unnecessary movements is common knowledge in surgery, this article reinforce to surgical trainees that while analysing and scanning the surgical field for information and thinking about the next movement they will need to do, it is important for them to keep their surgical instruments in a safe zone. This is a technique that expert surgeons have developed in order to reduce the risk of complications and injuries to anatomic structures.

In Chapter 4, we aimed to understand the task performance during a decompressive lumbar laminectomy. This procedure is one of the most common orthopedic and neurosurgical surgery perform on the spine. It consists in using a power drill to remove the lamina of the vertebrae to gain access to the spinal canal and reduce the pressure on the thecal sac and nerve roots. The first contribution of this article is the objective results from a gaze and movement analysis of a task that uses a power drill under the surgical microscope. This level of eye-hand coordination analysis has not been done in a task using that type of surgical instruments. The motion analysis found that novice microsurgeons have more jumping events than experts and the jump distance is also greater in the trainee group. Jumping event was characterized as moment where the drill bit moves unexpectedly and evident loss of control of the instrument is shown. The jump distance was defined as the distance in millimetres from where the drill bit was before the jumping event to the furthest location of the drill bit during the jumping event. These two findings are not surprising and confirm the clinical impression of attending surgeons when watching trainees perform this procedure in the operating room. We believe that these differences between the 2 groups can be explained in part by the vibrotactile adaptation phenomenon. Expert microsurgeons, with their numerous hours of drill manipulation, have mechanoreceptors in their hands with higher vibration detection threshold which improve the movement precision when manipulating the power drill.

Using the concept of action-related fixation described in chapter 2, eye-tracking analysis showed that post-jump fixation duration was longer in novices compared to experts. In other words, when an unpredicted event happened, such as the loss of control of the drill, the trainee took longer to adjust his gaze and analysed the situation to further adjust his movement. This finding is similar to what was observed in the microsuturing task in our article "Action-Related Fixation in Microsuturing, a New Gaze Behavior Metric to Differentiate the Level of Expertise".

The second contribution of this paper is to bring awareness that 3D printed model can be a cheap and easily available alternative to more commercial surgical simulation models. In the context of lumbar laminectomy, animal bones offer a realistic haptic feedback than when the surgery is performed in the operating room on a human patient, however it does not have exactly the same anatomy and dimension. In addition, the access to this model is not always easy and there can be hygiene, health and safety issues associated with animal models. Sawbone vertebral models are often used in simulation center and they do offer realistic anatomy. One disadvantage of this model is the porous quality of the material which makes the bone easy to drill and the operator does not encounter the same tactile resistance than human bone. Using the sawbone vertebral model cannot teach trainees how to react to unpredictable movements of the drill that is quite common with human bone. With the important technological advancements in 3D printing such as the possibility of combining different materials of various consistencies during the printing process and the fact that 3D printing is becoming more available in academic institutions, we think that 3D surgical simulation models are the future. They provide great face validity with patient specific anatomy and good haptic feedback, they can be cheap and rapidly available.

Surgical education implications:

Our findings could be used as an assessment tool to evaluate the level of expertise and the skill progression of trainees in a lumbar laminectomy task. However, it is unclear, at this point, how our gaze analysis findings can be used for gaze training purposes. In order to reduce the post-jump fixation duration, trainees should have a quicker response in analysing the surgical field after the jump event. Practicing a drilling task in a safe environment such as a simulation center, would allow the novice to familiarize himself with his reaction after the unexpected event and improve his time response. In addition, more training time on a power drill simulator before performing the task on a patient would help trainees to have a better vibrotactile adaptation.

Our findings can also facilitate future researches in the field of automatic assessment on surgical performance using artificial intelligence. Recent years have been marked by a growing collaboration between computer science and healthcare, surgical education is no exception. Artificial intelligence and deep learning algorithm have been used to objectively assess the surgical performance of surgeons in various settings (138, 139). For example, Fawaz et al. (2019) designed a convolutional neural network (CNN) that is able to predict the OSATS score of a participant when analysing the kinematic data from the recorded video of the participant performing a suturing task (140). Other researchers collected kinematic and force data during a virtual reality spinal task and manipulated the data to create twelve metrics that relate to safety of the procedure, efficiency, motion of the tools and coordination. These metrics were then used to train five different machine learning algorithms and researchers found that support vector machine achieves a 96.7% accuracy in predicting whether the task was performed by a senior or junior participant (141). These studies illustrate how artificial intelligence and machine learning can improve the efficiency of analysing video of surgical performance compared to manual annotation. Computer science technology is time efficient, required less human labor, and the results are accurate and reliable.

In this thesis, I have identified a number of key behaviors markers presenting in surgeons' eye and hand movements during three different microsurgical tasks that distinguished the level of expertise. Manual annotation on these behavioral markers is labor intensive but manageable when done on a small number of participants. The findings of my research could be used to guide designing deep learning algorithms that could differentiate the level of expertise with a large quantity of data. For example, artificial intelligence could identify in a surgical video each action that is associated with a single fixation and analyze the action-related fixation. This would provide a shortcut for the computer algorithm focusing on special moments, instead of analysing the entirety of the surgical video.

Limitations

The main limitation of this work is the small sample size of 4 experts and 3 novices. The recruitment of participants is an obstacle often encountered by researchers. Factors that influenced the enrollment in this project was the limited time that I had access to the Olympus ORBEYE – 4K 3d surgical microscope and the limited number of microsurgeons available at the institution where the experiment was conducted. During my stay at the University of Eastern Finland, the surgical exoscope was present for a demonstration period of 10 days. During this time, priority was given to the operating room to allow attending surgeons to familiarize themselves with the microscope during surgical cases. Consequently, I had access to the microscope when not needed in the operating room during the day and in the evening. In order to palliate to the small simple size, the design of the experiment was modified when possible. For example, in the microsuturing task, participants were asked to perform 6 independent sutures which increased the number of trials in each group.

In addition, this research is limited to a neurosurgery division from one single institution (University of Eastern Finland). It would be important to replicate this study at other institutions to reduce the bias that a training program can have on the results. Simultaneously, it would increase the number of participants in the study.

Increasing the sample size of my experiment would not only have improved the statistical power of this research but also would have allowed to create three groups of different level of expertise (novice, intermediate and expert). This would have been relevant to postgraduate residency program directors and surgical educators because neurosurgery residency program in Canada are often divided into junior residents (PGY1, PGY2 and PGY3) and senior residents (PGY4, PGY5 and PGY6). In this context, the novice group would have been composed of junior residents, intermediate group of senior residents and expert group from board-certified surgeons. In the eye-tracking literature, only one study examined three levels of experience (101). The researchers detected differences in gaze behavior between experts and novices but were unable to find differences between these two groups and the intermediate level. The existence of specific gaze behavior characteristics for each level would be relevant as you could objectively document the progression of the junior residents to an intermediate level of expertise and then to an expert level.

Some limitations are related to performing in a simulation environment and on surgical simulation models. For example, our participants had a wearable eye-tracker device on their head while doing the surgical task. It is possible that the device changed the performance of the surgeons by causing visual obstruction or simply by distracting them. In addition, practicing in a simulation environment doesn't involved the same risks and complications as in the operating room while doing surgery on a patient. Some participants can unconsciously perform the task more rapidly and less precisely on the simulation models. The predictive validity of the different tasks in our experiment is also uncertain. It is unclear at this moment that performing well on those three tasks means that participants will also do well if done in a real-life setting in the operating room. When it comes to surgical simulation models, they have inherent limitations and face validity is an important one. Even with models becoming more realistic on different levels (visual, tactile etc.) there will always be some components that make them different than performing on human tissue.

On a technical note, we noticed that some eye-tracking data were not collected by the wearable eye tracker when the participants looked down directly at the surgical field instead of looking in front of them where the LCD monitor was located. When looking down, the eyelid would cover the participant's pupils which would make impossible to extrapolate the gaze location. This can be remediated by adding a small piece of cardboard or Styrofoam underneath the google, filling the gap between the google frame and the participant's cheek. I would also recommend researchers using the same set up (combination of wearable eye-tracker and exoscope) to constantly remind participants to look straight in front of them at the LCD monitor. This would help to reduce the amount of eye-tracking data that was not collected.

Chapter 6 – Conclusion and Future Research Directions

Since residency duty-hour restrictions has been implemented in 2011, medical institutions found alternative methods to supplement residency training and surgical simulation has increased in popularity. It has become an important part of education and is now accepted as a valid tool for improving the skills of surgeons and consequently, the safety of patients. It is critical to use these centers at their full potential and maximize two of their main functions: increase the learning experience of surgical residents and assess the skills acquisition and level of expertise of trainees.

In this work, we compared the gaze behavior and kinematic of expert and novice microsurgeons while performing three different tasks under the surgical microscope. We were able to demonstrate various metrics that distinguish the level of expertise of the performer. We provided a detailed eye-tracking analysis that directly correlate surgeon's eye movements and their surgical movements to better understand microsurgeon's eye-hand coordination which is fundamental to surgical skills. This research reinforces the adoption of eye-tracking technology in surgical simulation environment to objectively assess the surgeon's surgical skills. Practical implication of these findings could be used by postgraduate residency program directors. Effectively, eye-tracking technology could be a component of the surgical residency curriculum and help document the progression of the trainees and verify that they have achieved the surgical skills required for their level of training.

Future Research Directions

Other than an assessment tool, eye-tracking technology can also be used to enhance and facilitate the learning of surgical skills. Gaze training is definitely where eye-tracking has the biggest potential and could have a significant impact in surgical education. Gaze behavior analysis in microsurgery is still in its infancy and the first step was to demonstrate that expert microsurgeons have gaze strategies that are different than novice microsurgeons. This is what we accomplished in this project. The next step is to demonstrate that gaze training can also be applied to microsurgery. Similarly, to the study done by Wilson et al. (2011), we could have 30 participants separated equally into three groups: gaze-training, movement training and standard feedback. The surgical exercise would be the microsuturing task with the same methodology described in chapter 2. Gaze-training would be achieved by showing the students a video of the gaze of an expert surgeon performing the same task. Explanations about the differences in gaze strategies between expert and novice microsurgeons, as reported in chapter 2, would be given to the participants of the group. They would then complete the task five times and receive verbal feedback of their gaze behavior after each trial. For the second group, movement training, participant would be shown the video of an expert microsurgeon performing the task and they would have the chance to analyze the movement of the surgical instruments and have verbal feedback after each trial. The last group would only receive verbal feedback from the experimenter after each attempt for a total of five attempts. The primary outcome would be the mean percentage reduction in completion time between the first and last trial for each group. We hypothesize that trainees in the gaze training group would have higher percentage reduction in completion time than other groups. Another outcome that could be measured is the pupillary size difference between the first and last trial for each participant. Knowing from the literature that an increase pupillary size is associated with a more important cognitive load, we hypothesize that gaze-training participant would have more significant reduction in pupillary size compared to the other two groups.

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