Functional Magnetic Resonance Imaging of Laparoscopic Surgery Training Tasks

by

Parisa Bahrami

A thesis submitted in conformity with the requirements for the degree of Master of Health Sciences
The Institute of Biomaterials and Biomedical Engineering
University of Toronto

© Copyright by Parisa Bahrami 2010
Functional Magnetic Resonance Imaging of Laparoscopic Surgery Training Tasks

Parisa Bahrami

Degree of Master of Health Sciences

The Institute of Biomaterials and Biomedical Engineering
University of Toronto

2010

Abstract

Previous studies have shown that not all surgical residents can acquire the required skills for performing laparoscopic surgery. Therefore, the training methods can be improved to accommodate trainees with different psychomotor abilities. The first step towards improving training methods is understanding the brain function in performing the laparoscopic surgery training tasks, which can be facilitated by neuroimaging methods such as functional magnetic resonance imaging (fMRI). In this study, a laparoscopic surgery training box for use in fMRI was developed. Experiments confirmed the fMRI-compatibility of the device. Nine right-handed subjects underwent fMRI while performing the surgical training tasks after ten practice sessions in a simulated fMRI environment. Behavioural and fMRI results confirmed the feasibility of using this simulator and revealed the neuroanatomical correlates associated with performing the training tasks. Accordingly, this study may facilitate the evidence-based development of strategies to improve the quality of laparoscopy training and assessment strategies.
Acknowledgments

It is a pleasure to thank those who made this thesis possible, Fred Tam and Michael Pozzobon, for their technical support, Tara Dawson for her administrative help, and Annette Weekes-Holder for performing the fMRI of volunteers. I also wish to express my gratitude to my supervisor Tom Schweizer, and committee members Simon Graham, Michael Cusimano, and Teodor Grantcharov. Thank you to Oscar Henao, Jemey Joy, Lauren Forrest, Katie Churchill, Timour Al-Khindi, and Zeyu Li for their help and support. I also wish to thank Karen Kan for her creative inspiration. Finally, I want to send many thanks and love to my dearest family and friends Parsa, Parvane and Houshang for their patience, support, and encouragement.
Table of Contents

Abstract ........................................................................................................................................... ii
Acknowledgments.......................................................................................................................... iii
List of Tables ................................................................................................................................ vii
List of Figures .............................................................................................................................. viii
List of Appendices .......................................................................................................................... x

1. Introduction ............................................................................................................................. 1
   1.1. Summary ...................................................................................................................... 1
   1.2. Introduction to Laparoscopic Surgery .......................................................................... 2
   1.3. Fundamental of Laparoscopy Surgery (FLS) Training Box ........................................ 3
   1.4. Neurophysiological Basis of Laparoscopic Surgery Training Task Performance ...... 7
   1.5. Functional Magnetic Resonance Imaging (fMRI) and fMRI Studies on Laparoscopic
       Surgery Training ........................................................................................................ 11
       1.5.1. Review of MRI Signal Generation ................................................................ 11
       1.5.2. Basis of fMRI Signal Generation .................................................................. 16
       1.5.4. fMRI Studies on Laparoscopic Surgery Training ......................................... 18
   1.6. Current Research Challenges and General Project Criteria ....................................... 18
   1.7. Thesis Direction and Hypotheses ............................................................................... 19

2. An fMRI-compatible Laparoscopic Surgery Training Simulator ........................................... 21
   2.1. Introduction ................................................................................................................ 21
   2.2. Materials and Methods ............................................................................................... 21
       2.2.1. Experimental Tools ....................................................................................... 22
       2.2.2. fMRI-compatibility ....................................................................................... 23
Appendix B. Shop drawings of the parts of the surgical tool (ENDOdissect™ 5 mm) that have been modified or redesigned for use in fMRI.
List of Tables

Table 1. Percentage of laparoscopic surgeries performed from 1997 to 2006, and 2007 [6]........ 2
Table 2. Description of tasks and the scoring system used with the FLS training box [15], [16]. 6
Table 3. Measured SNR and SFNR values showing fMRI-compatibility of the device .......... 29
Table 4- p value associated with the t-tests performed between the scores of each pair of tasks 30
Table 5. Brain regions identified for the contrast task 1 vs. baseline in Talairach coordinate space
for all participants (N = 9) ........................................................................................................ 48
Table 6. Brain regions identified for the contrast task 2 vs. baseline in Talairach coordinate space
for all participants (N = 9) ........................................................................................................ 48
Table 7. Brain regions identified for the contrast task 3 vs. baseline in Talairach coordinate space
for all participants (N = 9) ........................................................................................................ 49
Table 8. Brain regions identified for the contrast task 4 vs. baseline in Talairach coordinate space
for all participants (N = 9) ........................................................................................................ 49
Table 9. Brain regions identified for the contrast task 5 vs. baseline in Talairach coordinate space
for all participants (N = 9) ........................................................................................................ 50
List of Figures

Fig. 1. a) Fundamental of Laparoscopic Surgery (FLS) portable simulator and its key components. In this figure, the back of the box has been removed to display the details of the simulator [14]. ................................................................. 4

Fig. 2. Representative images illustrating the five tasks used with the training box: a) peg transfer, b) pattern cutting, c) ligating loop, d) suturing with extracorporeal knot-tying, and e) suturing with intracorporeal knot-tying [13]. ......................................................... 4

Fig. 3. Some major brain areas involved in performing a motor task. ........................................ 8

Fig. 4. a) Precession of a hydrogen nucleus around the external magnetic field at the Larmor frequency; b) the net magnetization due to the summation of magnetic moments. ...... 12

Fig. 5. a) Spiralling precession of net magnetization due to application of an RF pulse; and b) generation of emf in the coil due to the decaying transverse net magnetization. ......... 13

Fig. 6. Echo-planar imaging a) pulse sequence and b) k-space trajectory............................... 16

Fig. 7. a) Circuit diagram and b) photograph of the infrared (IR) illuminator. The IR intensity of the diodes is controlled by c) an intensity controller whose circuit diagram is shown in d). The IR illuminator is used as a light source for e) the MRI-compatible infrared CCD camera.............................................................. 22

Fig. 8. ENDOdissect™ surgical tool and the fMRI-compatible tool modified in the laboratory. 23

Fig. 9. Subject undergoing pre-scan training of laparoscopy tasks using the MRI simulator and fMRI-compatible training box. The subject is not shown within the simulator bore for display purposes................................................................. 27

Fig. 10. Mean, standard deviation, maximum, and minimum task performance scores for tasks 1-5. ......................................................................................................................... 30
Fig. 11. fMRI results of the 2nd scan, showing dominant areas of activation vs. Baseline in: a) Pointing task, b) uni-manual pegboard transfers using the right hand (RH), c) uni-manual pegboard transfers using the left hand (LH), d) bi-manual pegboard transfers using the both hands (BH), and e) Knot tying task........................................................ 32

Fig. 12. fMRI results of the 1st scan, showing dominant areas of activation vs. Baseline in: a) uni-manual pegboard transfers using the right hand (RH), b) uni-manual pegboard transfers using the left hand (LH), c) bi-manual pegboard transfers using the both hands (BH), and d) Knot tying task (No activation was observed in the pointing task)...................... 41
List of Appendices

Appendix A. Brain regions identified for tasks 1-5 vs. baseline in Talairach coordinates........... 48
Appendix B. Shop drawings of the parts of the surgical tool (ENDOdissect™ 5 mm) that have been modified or redesigned for use in fMRI................................................................. 51
1. Introduction

1.1. Summary

Laparoscopic surgery is a minimally invasive surgical procedure that is associated with shorter hospital stay and smaller incision scars [1], [2]. However, learning laparoscopic surgery requires special training as it entails two dimensional (2D) visualization of the three dimensional (3D) surgical field, reduction in depth and tactile perception, and high bimanual hand-eye coordination [3], [4]. Despite the special training provided for teaching this procedure, there is significant variability between the individual trainees in acquiring complex motor skills and not all surgical residents can reach an acceptable level of proficiency with the current training curriculum [5].

The current laparoscopic training tasks as well as simulators can be refined to provide a more comprehensive training that accommodates trainees with different psychomotor abilities. Improving the current training and assessment methods can help to improve the quality and efficiency of training, the efficient use of resources, and ultimately to improve clinical outcome. To achieve this goal, however, additional information beyond a behavioural analysis is necessary. A better understanding of the brain regions involved in this procedure would be a significant step towards improving laparoscopic training and assessment. Functional magnetic resonance imaging (fMRI) can assist in understanding the behaviour and brain function relationships associated with performing laparoscopic surgery tasks. As there is currently no means to investigate this relationship, the first goal of my thesis was to develop a modified laparoscopic surgery training simulator that was compatible in a magnetic resonance imaging environment. The second goal of my research was to identify the neuroanatomical correlates associated with performing laparoscopic surgery training tasks. In the future, this work has the potential to provide a framework for improving our understanding of the dynamic changes that occur in cortical networks as a consequence of training, and intensive practice in laparoscopic procedures. This study can be an important stepping stone for the design of future, comprehensive educational curricula for surgical residency programs and performance standards in minimally invasive surgery.

Chapter 1 reviews the background material for this work and provides an outline of the thesis objectives. Chapter 2 explains the experimental materials and methods, results, and a
discussion of the results. The last chapter summarizes the conclusions that can be drawn from the project and outlines future research directions.

1.2. Introduction to Laparoscopic Surgery

Laparoscopic surgery, a form of minimally invasive surgery, is a surgical procedure mainly performed in the abdominal and pelvic cavity during which the surgeon makes a small skin incision. Through this small cut, carbon dioxide is introduced to inflate the abdominal cavity and increase the working space. Through additional incisions, the surgeon inserts an endoscopic camera and a set of long and narrow surgical tools to perform the surgical procedure. Under high magnification, the surgeon can remotely view the surgical field in a video display and operate with minimal trauma to the patient.

In the past decade, the number of laparoscopic surgeries replacing open abdominal and pelvic surgeries has increased dramatically. For example, Table 1 summarizes one report [6] from the urology department of Fundacio Puigvert Hospital showing that the number of laparoscopic surgeries performed in 2007 more than doubled compared to the laparoscopic surgeries performed from 1997 to 2006.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Laparoscopic surgery (%) 1997-2006</th>
<th>Laparoscopic surgery (%) 2007</th>
<th>Average hospitalization period (days) 1997-2006</th>
<th>Average hospitalization period (days) 2007</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nephrectomy*</td>
<td>31.8%</td>
<td>72%</td>
<td>5.73 (2-25)</td>
<td>5.42 (3-12)</td>
</tr>
<tr>
<td>Partial Nephrectomy</td>
<td>31.3%</td>
<td>88%</td>
<td>6.20 (2-16)</td>
<td>6.29 (3-16)</td>
</tr>
<tr>
<td>Nephroureterectomy**</td>
<td>28.1%</td>
<td>92.9%</td>
<td>8.24 (2-48)</td>
<td>6.54 (3-21)</td>
</tr>
</tbody>
</table>

There are several reasons behind this rapid growth. In laparoscopic surgery, all the major maneuvers previously done in conventional surgery by making large cuts to the skin and its underlying muscles are performed through small incisions. In this manner, laparoscopic surgery reduces pain and trauma [7], blood loss and need for blood transfusion [8]. It minimizes the

* Nephrectomy is removal of kidney.
** Nephroureterectomy is removal of kidney and all or part of the ureter.
exposure of internal organs to possible external contaminations leading to lower risk of infection [9]. This kind of surgery is also associated with faster discharge and return to everyday living [8].

To provide the benefits of laparoscopic surgery to patients, it is crucial that surgeons acquire the complex skills specific to this technique. In open surgery, surgeons rely heavily on tactile feedback, depth perception and hand-eye coordination in a three dimensional (3D) field of view. Laparoscopic surgery, however, involves reduced depth and tactile perception, two dimensional (2D) visualization of the 3D surgical field, and requires high bimanual hand-eye coordination while performing procedures remotely at the end of ergonomically altered instruments [3], [4]. Consequently, special training is required to learn laparoscopy that is commonly provided to surgical residents through either traditional methods such as on-the-job training and practice on animal models or more modern methods such as simulated sessions in surgical skills labs [10]. Surgical simulation is the primary means of early practice and is essential for gaining hands-on experience on laparoscopic surgery techniques without attempting the procedure on an animal model or a patient.

1.3. Fundamental of Laparoscopy Surgery (FLS) Training Box

Laparoscopic surgery simulators can be divided into two main categories: sophisticated simulators that use virtual reality (VR) technology [10] and simple, yet widely used simulators called training boxes. Both categories are equally important and used in training of the psychomotor skills required for laparoscopic surgery. Studies on training surgical residents with VR simulators and training boxes have shown no significant advantage of using one system over the other [3], [11].

The present work focuses on the training box that was developed as a training and assessment tool and is a part of the “Fundamentals of Laparoscopic Surgery” (FLS) program [12]. This training box is widely used in residency programs because it is low cost, and approved and available through the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES), and the American College of Surgeons (ACS) [13]. The FLS simulator kit (Fig. 1) consists of: a white non-reflective plastic box; a video camera; an interior stage simulating the surgical field where specific training tasks are undertaken; surgical tools; insertion points on the box surface; a video cable; and a video display [14]. The video camera is mounted inside the box
at a fixed position and angle to record the simulated surgical field and provide surgeons with visual feedback during training tasks. The trainees cannot view their task performance directly; however, they can insert two surgical tools into the box and practice by operating on a desired task while looking at the video display [15].

Fig. 1. a) Fundamental of Laparoscopic Surgery (FLS) portable simulator and its key components. In this figure, the back of the box has been removed to display the details of the simulator [14].

There are five tasks performed with the FLS training box (Fig. 2). The tasks are: a) pegboard transfers, b) pattern cutting, c) placement of ligating loop, d) suturing with extracorporeal knot tying, whereby the knot is tied outside of the box and is pushed into the box using a knot pusher, and e) suturing with intracorporeal knot tying, whereby the knot is tied entirely inside the box [13], [15].

Fig. 2. Representative images illustrating the five tasks used with the training box: a) peg transfer, b) pattern cutting, c) ligating loop, d) suturing with extracorporeal knot-tying, and e) suturing with intracorporeal knot-tying [13].
Trainees need to practice these tasks at least 10 to 12 times over several weeks towards achieving an acceptable level of proficiency. Task performance is graded based on speed and accuracy. The score for an individual task is calculated by subtracting the task performance time from a preset upper time limit. A penalty score is then deducted from the time score to account for errors or inaccuracy. Consequently, higher scores indicate better performance [15]. Description of each task, the scoring criteria, and score calculation are shown in Table 2.

These tasks and training procedures are intended to improve the psychomotor skills, necessary to perform laparoscopic procedures such as depth perception, visual-spatial perception, coordination, dexterity, instrument navigation and coordinated use of both the dominant and non-dominant hand [16]. Despite the special training provided for teaching laparoscopic surgery techniques, there is significant variability between the individual trainees in acquiring complex motor skills and not all surgical residents can reach an acceptable level of proficiency with the current training curriculum [5]. This suggests that: 1) some trainees may not be able to acquire the skills for laparoscopic surgery; and 2) surgical simulators can be refined to improve the quality and efficiency of training, providing a more comprehensive training that accommodates trainees with different psychomotor abilities.

These issues can be approached from a neuroscience perspective. For the training box tasks, the relative importance of the various sensorimotor and cognitive components that are required to perform each task successfully is not clear. For example, hand-eye coordination and depth perception are required for both peg transfer and knot tying tasks, but the relative importance of each component for performing each task and how these components change as performance improves, deteriorates, or becomes more automatic is not known. Understanding these issues, coupled with the recognition that there is considerable variation in the ability to perform or acquire complex motor skills within the healthy adult population, can potentially assist in refining the current training methods for laparoscopic surgery (i.e. tasks as well as simulators) to improve the quality and efficiency of training, the efficient use of resources, and ultimately to improve the utility of laparoscopic procedures.

The first step toward exploring these issues is to understand how the brain functions when different laparoscopic surgery tasks are performed. Understanding the sensorimotor and cognitive components associated with performing current laparoscopic surgery training tasks can
Table 2. Description of tasks and the scoring system used with the FLS training box [15], [16].

<table>
<thead>
<tr>
<th>Task / Level of complexity</th>
<th>Task description</th>
<th>A=Upper time limit (s)</th>
<th>B=Penalty score</th>
<th>Score calculation</th>
</tr>
</thead>
</table>
| Pegboard transfer /1       | The trainee is required to:  
- lift in turn each of six rings from a peg on the right side of the board using a grasper forceps which is controlled by the right hand  
- transfer the ring in space to a grasper in the left hand  
- then, place the ring around the peg on the left side of the pegboard  
- after transferring all the rings from right to left, do the reverse procedure (transferring the rings from left to right) | 300 | The percentage of rings not transferred either due to slow performance or dropping pegs outside the field of view | A-B-(task performance time) |
| Pattern cutting /2         | The trainee is required to:  
- precisely cut a circular pre-drawn pattern 5 cm in diameter from a 10 x 10 cm² piece of suspended gauze using a scissor in the dominant hand while controlling the gauze using a forceps in the non-dominant hand | 300 | The percentage of the area of deviation from a perfect circle | A-B-(task performance time) |
| Ligating loop /3           | The trainee is required to:  
- place a pre-tied slipknot (USSC Surgitie, United States Surgical Corporation) with a tool in the dominant hand at a specific mark on a foam tubular appendage, while holding the appendage using a forceps in the non-dominant hand | 180 | (50 points for insecure/failed knots) + (the distance in mm that the secured knot deviates from the mark) | A-B-(task performance time) |
| Suturing with extracorporeal knot-tying /4 | The trainee is required to:  
- place a simple suture, 12 cm in length, through two pre-marked points in a longitudinally slit Penrose drain (a 2 cm soft rubber tube)  
- then, tie the suture using an intracorporeal knot-tying technique where the knot is tied outside of the box and is pushed into the box using a knot pusher | 600 | (The distance in mm that the suture placement missed the pre-marked points) + (the gap in mm if the suture failed to approximate the edges of the slit) - an additional penalty if the knot is loose or insecure. | A-B-(task performance time) |
| Suturing with intracorporeal knot-tying /5 | Identical to task #4, except that a longer suture is used and the knot is tied using an intracorporeal technique whereby the knot is tied entirely inside the box | 420 | Same as task 4 | A-B-(task performance time) |
provide some insight into how the brain functions while these tasks are executed. The following section describes the basic neurophysiology of motor task performance and some studies on tasks that can be considered components of performing laparoscopic surgery.

1.4. Neurophysiological Basis of Laparoscopic Surgery Training Task Performance

Multiple brain regions must communicate to perform a motor task. Here, this process is explained with three main neurophysiological systems involved in performing a motor task: somatosensory, motor, and cognitive. Initial input to cognitive processes is provided by the sensory system and motor system manifests behaviours that express cognitive goals [17]. The somatosensory system processes the information received from cutaneous receptors in the body. When stimulated, the mechanoreceptors send electrical signals to the spinal cord, and up to the brain. The brain is activated ipsilaterally (same side) or contralaterally (opposite side) to the side of sensory stimulation depending on which pathway in the spinal cord is used to send the signals to the brain. There are three main areas of the brain that are responsible for processing somatosensory information: primary somatosensory cortex (S1), secondary somatosensory cortex (S2), and somatosensory association cortex. The S1 area, which is located in the postcentral gyrus and consists of Brodmann’s areas* (BAs) 1, 2 and 3, is somatotopically organized, with the somatosensory information coming from each area of the body being mapped and processed in a specific contralateral section of S1. The middle of the strip of S1 is associated with processing somatosensory information coming from the hands and fingers.

The S2 area is the portion of the parietal lobe that forms the posterior ceiling of the lateral sulcus (Fig. 3). This area is not organized somatotopically and it is activated bilaterally in response to somatosensory stimuli. It is responsible for integrating somatosensory stimuli over time linking somato-sensation and motor control.

Somatosensory association cortex includes BAs 5 and 7 and is located posterior to S1 in the superior and posterior parietal lobes. BA 5 is responsible for analyzing the spatial relationship between different body parts and surrounding physical objects. BA 7 plays a role in visual-motor coordination. In this region the somatosensory information coming from S1 is integrated with the visual information coming from visual cortex (occipital lobe).

* Brodmann areas are divisions of the brain based on cell structure.
Fig. 3. Some major brain areas involved in performing a motor task.

The occipital lobe is the center for visual processing and it includes BA 17, 18, and 19. BA 17 is the primary visual cortex and together with BA 18 is responsible for processing and synthesis of visual information. BA 19 is responsible for integrating visual information with information from other senses. However, higher level integration of visual information with the somatosensory information coming from S1 happens in BA 7, as mentioned earlier.

Once the somatosensory processing is finished, the information is sent to motor cortex to plan and execute an appropriate movement. Usually the processed somatosensory information is distributed to premotor cortex (PM) and supplementary motor area (SMA) where motor movements are organized and planned. PM and SMA are both located in the frontal lobes, with PM occupying the lateral part of BA 6 and SMA in the medial portion of BA 6. SMA plays a role in planning voluntary movements that are internally generated in the absence of explicit sensory cues, acting on input received regarding motivation or intention [18]. In contrast, PM plays a role in voluntary movements guided by stimuli, especially vision. One of the major inputs to PM is from the cerebellum, which makes important contributions to planning, executive function [19], visuo-temporal attention [20], and to coordinating visually guided movements. The cerebellum compares intention to move with actual movements that took place. When there is a difference between intention and action, the cerebellum generates an error-correcting signal which is sent to premotor and primary motor cortex [21]. Part of the cerebellum that is
responsible for control of posture and movements of the limbs receive most of its input from the spinal cord whereas the section that participates in the planning of movement receives its input from the motor, sensory, and association areas.

PM and SMA also receive information from the limbic association area, which includes BA 24 (also called cingulate gyrus) and is essential for learning, memory, and emotions. Another input to this area is from the prefrontal association area which is involved in forming motivation and cognition. A portion of the prefrontal association area, called the “executive center” of the brain, consists of BA 9, BA 10, BA 45, and BA 46. This executive center can initiate action independent of external stimuli and allows planning of a movement and error correction in response to feedback. BA 46 provides the ability to hold and control active information, known as working memory, and sustain attention when a complex task is performed.

PM and SMA also receive the integrated somatosensory input from the posterior parietal cortex. By receiving these inputs, PM and SMA translate thoughts and sensations into a plan of action and determine which muscles to contract, and when.

The next step is translating the motor plan into action. Thus, information from premotor cortex is passed to primary motor cortex (M1) for motor execution. Primary motor cortex is located in the precentral gyrus, in BA 4, with large projections to the spinal cord and from there to motor-neurons that innervate the corresponding muscles.

Although the neurophysiological systems that are generally involved in performing motor tasks are known, the brain networks associated with a complicated task like laparoscopic surgery training has not been explored in detail. There have been numerous indirect studies of key components of laparoscopic surgical skills such as depth perception, planning and coordinating hand movements, and tool manipulation. This work is briefly reviewed below.

One of the essential components of performing laparoscopic surgery is realizing depth by viewing a 2D video of the field of operation. Studies show that binocular disparity and texture gradients are major cues in depth perception. Caudal parietal regions respond to depth perception that is due to binocular disparity [22] or surface orientation [23] and temporal cortex near the occipito-temporal junction is activated due to depth perception that happens in response to spatial features or shading [24]. Planning and coordinating hand movements and tool manipulation are other major components of performing surgical tasks. Research has shown that as the spatiotemporal complexity of limb movement increases, activation in the SMA and
superior parietal cortex amplifies, whereas the primary motor cortex and cingulate motor cortex show more activation in movement execution [25]. Research has shown that SMA shows significantly more activation for bimanual than uni-manual tasks [26]. Interestingly, in one study involving right-handed subjects, left SMA showed greater activation in a bimanual task performed at a faster rate with the right hand compared to the left hand, whereas higher activation was not observed in right SMA for an identical task performed at a faster rate with the left hand in comparison to the right hand [26]. This may suggest a relationship between handedness and activation of SMA in performing a bimanual task. Research on manipulation of prehensile tools showed activation in the dorsal and ventral portions of the premotor area (PM), superior parietal and posterior intraparietal area, middle temporal gyrus, primary somatosensory cortex (S1), occipital cortices, and the cerebellum [27], which shows the interplay between different brain regions in performing a complex motor task.

The above studies have been made possible by the advent of functional neuroimaging technologies that enabled non-invasive study of brain activity in humans. Recently, a few studies have investigated laparoscopic surgery training tools using advanced neuroimaging techniques. Ohuchida et al. used functional near infrared spectroscopy* (fNIRS) to study the prefrontal cortex activation while performing a laparoscopic task in a training box, and to highlight activation differences based on years of surgical experience [28]. Leff et al. used the same neuroimaging technique to explore the inter-subject variability in novices learning minimally invasive surgery skills [29]. However, fNIRS has low spatial resolution and has difficulty detecting deep regions of the brain [30] in comparison to methods such as functional magnetic

* Functional near infrared spectroscopy (fNIRS) is a non-invasive functional imaging modality. It is based on the measurement of the NIR light absorption as the concentration of oxygenated and deoxygenated hemoglobin changes in response to neural activity in a cortical region of the brain. The light emitting diodes and detecting sensors provide limited penetration depth [49] as shown in figure below.
resonance imaging (fMRI). As a result, activation of important deep brain structures that may be involved in performing complex motor skills (e.g. the cerebellum) was not observed. At present, assessment of regional activity throughout the brain is better conducted by other methods such as fMRI. Functional MRI is a powerful means to probe the neural activity associated with localized changes in blood oxygenation, volume and flow in the vicinity of neurons engaged in task-related mental processing [31].

The next section provides a brief description of the origin of fMRI signal and its current state of research related to laparoscopic surgery task performance.

1.5. Functional Magnetic Resonance Imaging (fMRI) and fMRI Studies on Laparoscopic Surgery Training

Functional MRI is typically used to reveal the short-term hemodynamic changes associated with neural activity in the brain. When someone engages in any kind of mental activity, the blood supply of the brain is dynamically regulated to give active neural regions more oxygen and glucose than inactive neurons. The localized changes in blood oxygenation, flow and volume associated with these active neurons can be visualized by fMRI with approximately millimetre spatial resolution throughout the brain [32]. To better explain these points, a brief description of the MR image formation and the effect of blood hemoglobin and oxyhemoglobin on the detected signal follow.

1.5.1. Review of MRI Signal Generation

One of the main components of a biological tissue is water which consists of hydrogen atoms. The hydrogen nucleus has a single proton that spins around itself and creates an angular moment, $\mathbf{j}$. Since a proton is a charged particle, its spin also creates a magnetic moment, $\mu$. These two properties are related to each other as shown in equation (1), where $\gamma$ is the gyromagnetic ratio which is dependent on the properties of hydrogen.

$$\mu = \gamma \mathbf{j} \quad (1)$$

In the absence of a strong external magnetic field, the hydrogen nuclei (also referred to as spins) spin in random directions. Thus, the summation of their magnetic moments, which is
called net magnetization, $\vec{M}$, is zero. When placed in an external magnetic field, $B_o$, a torque, $\vec{\tau}$, is exerted to each spinning hydrogen proton as defined by equation (2) causing the proton to move in a gyroscopic motion (also called precession) around the axis of the $B_o$ field (Fig. 4a). This gyroscopic motion happens at a very precise frequency called the Larmor frequency, $\omega$.

$$\vec{\tau} = \vec{\mu} \times \vec{B} \quad (2)$$

$$\omega = \gamma B \quad (3)$$

With respect to the axis of the $B_o$ field, the spins precess at a precise angle, which is proportional to their angular momentum. The spins can precess either aligned or anti-aligned to the external magnetic field $B_o$; however, the aligned state is the lower energy level, hence it is more desirable. Thus, in a strong external magnetic field a higher percentage of spins precess in the aligned state.

Fig. 4. a) Precession of a hydrogen nucleus around the external magnetic field at the Larmor frequency; b) the net magnetization due to the summation of magnetic moments.

Consequently, when the biological tissue, which is composed of many hydrogen nuclei, is placed in a strong $B_o$ field, the longitudinal components of the angular moments are mostly aligned and parallel with the field cancelling out all of the anti-parallel longitudinal components resulting in a vector parallel to the $z$ axis. This vector is the longitudinal component of $\vec{M}$. The transverse components of the angular moments (perpendicular to the $B_o$) cancel out each other setting the transverse component of $\vec{M}$ to zero. As a result, the net magnetization will be a vector parallel and proportional to the $B_o$ field (Fig. 4b). This is considered the equilibrium state of the net magnetization, $\vec{M}_o$.

When net magnetization is momentarily disturbed from its equilibrium state and as it goes back to the equilibrium state, the MRI signal can be measured. To disturb the equilibrium state of
the net magnetization, an electromagnetic radiofrequency (RF) pulse that is in resonance with the
net magnetization is applied in the transverse plane of $B_o$. Application of the RF pulse is
equivalent to introduction of a second magnetic field, $B_1$, which, in contrast to $B_o$, is not static. If
$B_1$ oscillates at the Larmor frequency, then the vector $\vec{B}_{\text{eff}} = \vec{B}_o + \vec{B}_1$ causes the net magnetization
vector to start a spiralling precession around the longitudinal axis at the Larmor frequency (Fig.
5a). Due to this spiralling motion, a component of the net magnetization will appear in the
transverse plane, $M_{xy}$. The changing precession angle, called the flip angle (FA), is $\Theta = \gamma B_1 T$,
where $T$ is the duration of the RF pulse. If the RF pulse is applied long enough the flip angle
reaches 90° and the transverse component of net magnetization reaches its maximum while its
longitudinal component, $M_z$, approaches zero. Then, the RF pulse is stopped and the net magnetization starts returning to its equilibrium state. This process is called relaxation. If a coil
is placed such that its central axis is parallel to the transverse plane, the changing flux created by
the diminishing transverse component of net magnetization can induce a current in the coil (Fig.
5b). The resulting voltage change, called electromotive force (emf), can be measured and is the
basis of the signal used in image formation.

As net magnetization relaxes the spins lose energy to their surrounding environment and go
back to their low energy level, which means that $M_z$ grows back to its maximum value. The
amount of time that is required for $M_z$ to grow back to its equilibrium state is characterized by a
parameter called $T_1$. $T_1$ is typically 0.1-1 s and it is somehow dependent on tissue properties.

Fig. 5. a) Spiralling precession of net magnetization due to application of an RF pulse; and b)
generation of emf in the coil due to the decaying transverse net magnetization.

In addition, in the relaxation phase, $M_{xy}$ diminishes from its maximum value to zero. This
is not only due to energy loss of the individual spins but also the “spin-spin” interactions. In the
presence of the RF pulse, when the net magnetization is tipped into the transverse plane, all the spins are precessing at about the same phase. When the RF pulse is stopped, the interaction between the spins causes them to precess at slightly different frequencies. This causes loss of coherence and the faster decay of the $\vec{M}_{xy}$. The amount of time required for transverse relaxation due to spin-spin interaction is characterized by a parameter called $T_2$. $T_2$ is shorter than $T_1$ and typically on the order of 50-100 ms.

In addition to spin-spin interaction, other factors such as magnetic field inhomogeneity affect the decay of $\vec{M}_{xy}$. As mentioned before the precession frequency of the spins depends on the magnitude of the external magnetic field. Thus, in a slightly inhomogeneous field, the spins at different locations in the tissue precess at slightly different frequencies causing the loss of coherence. The amount of time that characterizes the loss of the transverse component of net magnetization in the relaxation process due to both spin-spin interaction and other factors such as an inhomogeneous magnetic field is called $T_2^*$, which is smaller than $T_2$.

The main significance of $T_1$, $T_2$, and $T_2^*$ is that they can be used to provide signal contrast between different tissue types in MR images. The repetition time between two consecutive RF pulses (TR) and the time between the RF pulse and the data acquisition (TE) can be chosen appropriately such that the image provides a contrast based on the $T_1$, $T_2$, or $T_2^*$ value of different tissues. For example, in a $T_2$-weighted image, TE can be chosen such that there is enough time for the transverse net magnetizations of tissues with short $T_2$ to fully decay, while those with long $T_2$ do not fully decay. Thus, tissues with long $T_2$ values generate more signals and appear brighter in the image compared to tissues with shorter $T_2$ values. In addition, the TR should be long so that the longitudinal net magnetization fully recovers minimizing $T_1$ contrast. A $T_2^*$-weighted image is similar to a $T_2$-weighted image in that a medium TE and a long TR should be used for both. $T_2^*$-weighted images are responsive to deoxygenated hemoglobin.

So far, we discussed how the MRI signal, $S(t)$, is generated, which reflects the summation of the transverse net magnetizations generated from all the volume elements, voxels, within an excited tissue. To form an image, the signals coming from each voxel should be differentiated from the signals collected from other voxels as described below.

As mentioned before, when the net magnetization is tipped out of equilibrium with an RF pulse that is in resonance with it, it starts precessing at the Larmor frequency around the effective external magnetic field. Since the external magnetic field and the Larmor frequency are
proportional to each other, changing the value of the magnetic field over space causes the net magnetization vectors to precess at different frequencies making them distinct from each other according to their location. This localization of net magnetizations is achieved by applying additional magnetic fields to $B_0$ called gradients whose strength is increasing linearly over space. The localization is achieved in a two step process. First, a linear gradient, $G_z(t)$, is applied in the longitudinal, $z$, direction such that only the net magnetizations in a specific slice of tissue precess with the same frequency as the RF pulse and, hence, tip out of equilibrium generating considerable signals. In the second step of specifying the position of a voxel, linear gradients are applied in the $x$ and $y$ directions, $G_x(t)$ and $G_y(t)$ respectively, to encode the spatial location of a voxel within the excited slice. As a result, the measured signal, $S(t)$, is the summation of the net magnetization of all the voxels in that excited slice which only depends on the $x$ and $y$:

$$S(t) = \int_x \int_y M(x, y)e^{-i\gamma \int_0^t (G_x(t)x + G_y(t)y) \delta \tau} \, dx \, dy, \quad (4)$$

where $M(x, y)$ is the net magnetization in each voxel at location $x$ and $y$.

To solve for net magnetization distribution within the excited slice, $M(x, y)$, $k_x(t)$ and $k_y(t)$ are defined as:

$$k_x(t) = \frac{\gamma}{2\pi} \int_0^t G_x(t) \, d\tau \quad (5)$$

$$k_y(t) = \frac{\gamma}{2\pi} \int_0^t G_y(t) \, d\tau, \quad (6)$$

which allow equation (4) to be modified. Therefore,

$$S(t) = \int_x \int_y M(x, y)e^{-i2\pi k_x(t)x} \, e^{-i2\pi k_y(t)y} \, dx \, dy. \quad (7)$$

Here $k_x(t)$ and $k_y(t)$ define the spatial frequency domain (k-space) [33], [34].

Equation (7) shows that collected signal, $S(t)$, is the Fourier transform of the net magnetization as a function of $x$ and $y$, $M(x, y)$. This means that by taking the inverse Fourier transform of $S(t)$ we can construct the image [31].

The combination of changing gradients and RF pulses is called pulse sequence, which allows the acquisition of the k-space signals. There are a variety of pulse sequences and each control the trajectory of k-space signal acquisition differently. In some pulse sequences, multiple
excitation pulses are required to collect signal in the k-space for a given slice; however, there are fast imaging techniques in which a single excitation pulse is required to collect the signal from the entire k-space. Examples of these fast imaging techniques are echo-planar imaging (EPI) (Fig. 6) and the magnetization-prepared rapid gradient echo (MPRAGE). EPI is one of the $T_2^*$ contrast techniques used for acquiring functional MRI data while MPRAGE is $T_1$-contrast-based technique, typically used for collecting structural images.

Fig. 6. Echo-planar imaging a) pulse sequence and b) k-space trajectory.

1.5.2. Basis of fMRI Signal Generation

Oxyhemoglobin (Hb) has zero unpaired electrons and no magnetic moment while deoxyhemoglobin (dHb) is paramagnetic. Therefore, when placed within a magnetic field, the intensity of magnetization (also called magnetic susceptibility) of dHb is greater than Hb. This means that in the presence of dHb the hydrogen nuclei precess at slightly different frequencies, resulting in the faster decay of the transverse net magnetization. Therefore, the voxels containing dHb have a lower intensity signal in a $T_2^*$-weighted image whereas voxels with larger amount of Hb show a stronger MRI signal. This is the basis for generating Blood-Oxygenation-Level Dependent (BOLD) fMRI images [31], [35]. Following the neuron activation in the brain, the blood flow increases in the activated region to provide more oxygen and glucose. As the excess oxygenated blood flows through activated regions of the brain, it reduces the dHb that had been suppressing the MRI signal intensity. Therefore, these areas show greater $T_2^*$ contrast and MRI signal intensity compared to non-active regions [31].

1.5.3. Design and Analysis of fMRI Experiments
The resulting fMRI signal from BOLD contrast has a low intensity. Therefore, repetition of task performance in fMRI experiment is a common way to increase the statistical power. For experiments where the goal is to detect the activated brain regions during task performance, an experimental method called blocked design is used. This technique consists of alternating blocks of baseline condition and task performance, each about 10-30 sec. During these alternating blocks, a $T_2^*$ weighted imaging techniques is used to take a series of images of the brain. The end result is a time series associated with each voxel that represents the BOLD contrast.

It is a common practice to conduct statistical tests on a voxel by voxel basis. Typically, a general linear model (GLM) is fitted to the time series of each voxel while considering a mathematical function for the hemodynamic response of the brain for each task. This mathematical model is chosen based on many factors such as the duration of the task, the predicted response of the brain, and the ultimate goal of performing the test. Fitting a GLM to the times series of each voxel produces a set of coefficients for each voxel. Each coefficient is the representation of the amount of activation in that voxel for a given task. Then, if this coefficient differs significantly from zero (the baseline), that voxel is activated for the task associated with that coefficient. In addition, in the blocked design experiments, the baseline is modeled with a third or a forth order polynomial to take into account the signal drift in the long baseline periods. Determining the active voxels helps to get an activation map of the brain for each task.

In order to generalize the results of an experiment to a population, a group of subjects undergoes the same fMRI experiment. To get an average activation map of each task across a group of subjects, the brain activation of each subject is transformed to a standard Talairach space. Then, a t-test is performed voxel-wise to test the null hypothesis that the mean percent change across all subjects is equal to zero percent change from the baseline. If the null hypothesis is rejected based on a typical $p < 0.05$, that voxel is considered active. However, since the t-test is performed on a voxel-by-voxel basis, it is possible that a voxel is being falsely labelled as active. To correct for this error a multiple comparison test such as clustering can be used. In this method, active voxels that are in clusters smaller than a certain size are excluded. Finally, the active voxels are assigned a color based on their t-test results. Then, each activation map is laid over on the averaged Talairached structural images.
1.5.4. fMRI Studies on Laparoscopic Surgery Training

fMRI allows monitoring of brain activity in response to different stimuli and behavioural tasks producing patterns of activity that are often termed neuroanatomical correlates [31].

To date, only one fMRI study relates to surgical performance, reporting that skilled performance of residents on a spatially complex surgical procedure correlates with visuo-spatial ability to rotate objects mentally in space [36]. Performance on the mental rotation tasks* (MRT) was positively associated with activation in brain regions related to visual imagery and motion processing such as the middle temporal region, the posterior cingulate-precuneus region, and the premotor region [37]. Although it was concluded that the neural correlates associated with MRT can be representative of the activation expected during surgical performance, this study does not directly quantify the interplay between brain regions during the cognitive and sensorimotor components specific to laparoscopic surgery training tasks [38]. Use of fMRI to study tasks that more closely approximate real-world laparoscopic surgical performance would be an important incremental step forward, providing brain activation measurements and behavioural assessments that are less reductionist and more directly applicable to the study and refinement of laparoscopic surgery training protocols.

1.6. Current Research Challenges and General Project Criteria

Despite the attractiveness of this approach, direct use of fMRI to evaluate and monitor surgical performance in surgery faces significant engineering challenges. Given that fMRI must be performed while lying face-up within a confined magnet bore of a typical diameter of about 60 cm, there are limitations on subjects’ visual fields to approximately 10° to 15°. The high

---

* Mental rotation task (MRT) is a test assessing the ability of mentally rotating two- or three-dimensional objects. For example, one of the MRT questions can be if figures a) and b) are the same except for their orientation.
magnetic field (several Tesla) and stringent electromagnetic interference criteria required for fMRI make use of conventional surgical instruments and equipment impossible [38].

These challenges are difficult, but certainly not insurmountable and numerous devices have been specifically engineered for fMRI studies in the past [39], [40]. The objectives of this thesis are to: a) implement an fMRI-compatible training box for monitoring the laparoscopic surgery training task performance in fMRI environment, and b) investigate the neuroanatomical correlates of laparoscopic surgical training tasks using this apparatus. Combining laparoscopic surgical training tools and fMRI compatibility requires that the tools should be non-ferromagnetic and that operation of the device should be unaffected by the magnetic field. Also, the set up should not distort the fMRI images. In addition, the apparatus should not hinder tasks performance and should allow for monitoring and quantifying the behaviour, similar to the actual surgical simulators. A specific fMRI-compatible set of tasks should then be developed to characterize key components of laparoscopic performance from a neuroscience perspective, and then applied to an appropriate group of human volunteers to explore the associated neuroanatomical correlates.

1.7. Thesis Direction and Hypotheses

In relation to the above criteria, this thesis involves development of an fMRI-compatible FLS training set including an fMRI-compatible FLS training box and a surgical tool that is commonly used with this surgical simulator. This training set will be used in representative fMRI experiments, looking at the activated areas of the brain in performing some of the FLS surgical tasks. These tasks include a pointing task, uni-manual transfering of pegs using either left or right hand, bimanual transfer of pegs, and knot tying and will be explained in the next chapter in detail.

It is hypothesized that:
1) the laparoscopic surgical training box and a surgical tool can be modified to meet the criteria of fMRI compatibility;
2) simulation of laparoscopic skills can be achieved during fMRI, that is quantifiably similar to the surgical performance using the training box;
3) brain activation will be observed in the primary and supplementary motor area (planning and executing movement), primary and association somatosensory area (processing and
integrating sensory information), parietal and temporal regions (integrating sensory information, depth perception, and tool manipulation), the prefrontal association area (sustaining attention and working memory), and the cerebellum (executive function).

The procedure for testing these hypotheses, data collection, analysis and description of the results are described in the subsequent chapter.
2. An fMRI-compatible Laparoscopic Surgery Training Simulator*

2.1. Introduction

Learning laparoscopic surgery techniques requires special training and surgical trainees typically start to learn these techniques in simulated sessions to improve the psychomotor skills that are required for laparoscopic task performance. However, there is significant variability between the surgical residents in acquiring complex motor skills and not all trainees can reach an acceptable level of proficiency with the currently used laparoscopic surgery training tools. Studying the brain-behaviour relationships in performing the training tasks can be an important step towards refining the training protocols providing a more efficient training for residents with various psychomotor skills. This will allow efficient use of allocated resources for training and provide more comprehensive assessment strategies. Functional neuroimaging modalities provide an appropriate tool for studying the brain behaviour in performing the surgical training tasks. In the past, few imaging modalities, near infrared spectroscopy in particular, have been used sporadically for such studies. In this study, for the first time, functional magnetic resonance imaging (fMRI) has been used to investigate the brain-behaviour relationships associated with performing some laparoscopic surgical tasks. For this purpose, an fMRI-compatible training box and a surgical tool that is commonly used with this simulator has been developed. First, the development of this apparatus and a set of training tasks followed by the tests performed to ensure its fMRI-compatibility are reported in this chapter. Then, the use of this apparatus in fMRI experiments to explore the neuroanatomical correlates associated with performing laparoscopic surgery training tasks is explained. The results and the subsequent discussion emphasize the feasibility of using this technology for future fMRI studies, such as those to evaluate dynamic changes in brain organization that accompany laparoscopic surgery training, and to optimize laparoscopic surgery training procedures.

2.2. Materials and Methods

* This chapter consists of a manuscript accepted for publication in the journal of Magnetic Resonance in Medicine in September 2010 and a manuscript in preparation for submission to the Annals of Surgery. Part of this work was presented as a poster in the 16th Annual Meeting of the Organization for Human Brain Mapping (June 6-10, 2010).
2.2.1. Experimental Tools

The FLS training box is cheap, widely-used in residency programs and easier to modify compared to a VR simulator, thus it is been used in this study. The training box is made of fiberglass, an fMRI-compatible material that is not subject to attractive force within the magnet bore. All metal screws were replaced with plastic screws and the standard video camera was swapped with a charge-coupled device (CCD) camera system with infrared (IR) capability designed for use in MRI systems (MRC Inc., Heidelberg, Germany). Three specially-designed IR illuminators, designed in the laboratory (Fig. 7), were put around the camera to illuminate the field and to work as a light source for the MRI-compatible infrared CCD camera.

Fig. 7. a) Circuit diagram and b) photograph of the infrared (IR) illuminator. The IR intensity of the diodes is controlled by c) an intensity controller whose circuit diagram is shown in d). The IR illuminator is used as a light source for e) the MRI-compatible infrared CCD camera.

A surgical tool commonly used with the FLS training box (ENDOdissect™ 5 mm, United States Surgical Inc., Mansfield, MA, USA) was modified by substituting aluminum and plastic components to produce two ergonomically and functionally similar fMRI-compatible tools (Fig. 8) permitting uni- and bi-manual manipulations (drawings are shown in Appendix B). Due to budget constraints, no other tools were fabricated. Although this led to reduction and
modification of the tasks that could be implemented inside the training box, use of this tool set was sufficient to study the major task components of laparoscopic surgery.

After using the tools for more than ten task practice sessions, the grasping part of the tools broke. As aluminum proved not to be the best wear and tear resistance material, we remade the grasping portion of the tool from brass, a more durable fMRI-compatible material. This tool was used for the remainder of the study.

![Fig. 8. ENDOdissect™ surgical tool and the fMRI-compatible tool modified in the laboratory.](image)

**2.2.2. fMRI-compatibility**

Before imaging human subjects, a “phantom” test object was imaged using a $T_2^*$-weighted echo planar imaging (EPI) sequence (TR/TE/FA = 2000 ms/30 ms/70°, 30 oblique-axial slices, 130 time points), to assess whether the fabricated surgical tools and the training box influenced fMRI data quality by elevating electromagnetic noise or introducing other artifacts. Three fMRI conditions were tested over six runs: 1) the tools and the box absent from the room with the phantom at magnet isocenter (baseline condition); 2) the box at 100 cm and the tools stationary at 80 cm from the phantom (the approximate device location longitudinally in the magnet bore during the actual fMRI study); and 3) the identical configuration as Condition 2 but with the tools held and moved in each hand by an experienced operator (P.B.) during fMRI with a movement frequency of approximately 1.5 Hz and 10 cm range of motion in a random path. Beyond the static noise assessment of Condition 2, Condition 3 assessed whether tool and limb movement caused magnetic field perturbations of sufficient magnitude to constitute a problematic noise source. Signal-to-noise ratio (SNR) and signal-to-fluctuation-noise ratio (SFNR) were calculated within the phantom in a region of interest (ROI) that was a centered circle with radius 40 mm within an axial slice toward the inferior end of the phantom (closer to
the tools), using Friedman and Glover’s method [41] as follows. After discarding the first ten time points of each run, a “signal” image was calculated as the average of all images in the time series. The odd-numbered and the even-numbered images in the time series were then separately added together and the resulting two images were subtracted to obtain a “noise” image. The SNR was subsequently calculated for the ROI by dividing the mean of the signal image by an appropriate metric from the noise image, taken as the root-mean-square (rms) value. The SFNR was calculated by an analogous procedure except that the noise metric was given by the rms value of the residuals obtained by detrending the image time series by a second order polynomial. In addition, all images were visually examined for image artifacts, such as spatial distortion, potentially caused by the surgical tools or the box. The fMRI-compatibility testing was done on the tool with Aluminum grasping part.

In addition, when a metal is moved in a magnetic field, the change in the magnetic flux induces a current in the conductor. This current may generate some heat in the metal and make it uncomfortable to use in the fMRI environment. Therefore, temperature of the tools was monitored at the beginning and at the end of the phantom imaging as well as the subject scan sessions to ensure that the metal portion of the tools did not heat up substantially.

2.2.3. Task Design

Five tasks were developed for use with the fMRI-compatible training box, modified from the original FLS assessments. Each task was implemented in a block fMRI design consisting of 20 s baseline condition (foveal visual fixation, white cross on a black screen), 2 s of task instruction (white text on a black screen), followed by task performance to an upper time limit per block. The upper time limit in some of the tasks was substantially reduced from that of the original FLS scenarios to provide task performance durations and task repetitions that enabled robust mapping of brain activity, accounting for fMRI signal and noise characteristics. Due to these changes, new metrics were also developed to score behavioural performance. To remove timing effects and quantify performance efficiency, each metric was developed as a rate (performance per unit time) that rewarded correct behaviour and penalized errors.

Task 1- Pointing task to examine depth perception. The subject was required to point to 12 posts on the pegboard in random order using one tool in the right hand. Because this task did not exist in the original set of tasks, a cut-off time (15 s) was chosen after consulting with an
experienced surgeon who is a certified examiner of surgical laparoscopic skills (T.G.). One point was given to the subject for each peg that was pointed to in the given time. The total points earned were divided by the completion time to quantify task performance.

*Tasks 2&3 – Uni-manual pegboard transfers using the right hand (RH) and the left hand (LH).* In these tasks, the subject was required to use the surgical tool to lift two plastic rings, one after the other, from pegs on one side of the pegboard and transfer them to the other side using only one hand. For the right hand, the transfer was performed from right to left; for the left hand, the transfer was performed from left to right. These tasks helped to examine the motor skills associated with each hand, depth perception and hand-eye coordination. For comparison, the original FLS task involves pegboard transfer using both hands with a cut-off time of 300 s for 12 transfers. For fMRI tasks 2 and 3, the cut-off for two transfers was set at 30 s. Each subject could earn one point for successfully picking up the ring and one point for successfully placing the ring on the other side of the pegboard. Half a point was deducted for dropping a ring. The total points were divided by the completion time to quantify task performance.

*Task 4 – Bimanual pegboard transfers using both hands (BH).* This task required use of both the dominant and non-dominant hands to transfer the rings across the pegboard. Specifically, the subjects were required to pick up a ring using the right hand, transfer the ring to the left hand, and then place the ring on a peg at the left side of the pegboard. This task helped to examine the coordination between both hands in addition to the skills required for task 2 and 3. The cut-off time for this task was set at 50 s for 2 transfers. One point was earned for successfully picking up the ring, one point for successfully transferring the ring to the left hand, and one point for successfully placing the ring on the other side of the pegboard. Half a point was deducted each time a ring was dropped. The total points were divided by the completion time to quantify task performance.

*Task 5 - Modified knot tying.* This task involved tying three knots in a piece of string, with the strings pre-inserted in the slit of a Penrose drain (a 2 cm soft rubber tube). Both ends of the string were freely accessible to the subject. The subject could start the first knot with either the left or right hand. For example, if they started the task with their right hand, they were required to pick up the string end on the left side with the tool in their right hand, turn that end around the tool in the left hand twice, pick up the string end on the right side with the tool in the left hand (while holding on to the string in their right hand tool), pass this string through the loops made
around the tool in the left hand, and pull both strings to tighten the knot. Then the subject was required to tie the second knot similar to the first one, with the order of hands reversed. The third knot was tied the same as the first. For the second and third knot, the subject was required to turn the string around the tool only once. The cut-off time for completing this task was set at 60 s. One point was earned for successfully picking up the string, one point for each time the string was successfully turned around the tool, one point for passing the string through the loops, and one point for tightening (finishing) the knot. Half a point was deducted each time the string was dropped. The total points were divided by the completion time to quantify knot tying performance.

In the functional MRI sessions, each subject performed each task four times, in random order, over two runs, each lasting 590 s. The four scores associated with each task were added together to calculate a total score for each subject.

2.2.4. Subjects

Nine young healthy, right-handed adults (average age ± std = 23.2 ± 2.7 years and average education ± std = 16.6 ± 1.9 years) consisting of four females (average age ± std = 23.5 ± 1.7 years and average education ± std = 17.5 ± 1.0 years) and five males (average age ± std = 23.0 ± 3.3 years and average education ± std = 15.8 ± 2.2 years) gave their informed consent to participate in the study, which was approved by the Research Ethics Board at Baycrest Hospital. Handedness was assessed using the Edinburgh scale\(^\ast\) [42]. Exclusion criteria were history of substance abuse, presence of neurological, medical or psychiatric disorders, and MRI contraindications such as claustrophobia and metallic implants. Subjects had no prior experience in performing the laparoscopic surgery tasks.

2.2.5. Experimental Set-up and Data Acquisition

Initially, subjects had a few minutes to familiarize themselves with the tasks and the modified surgical tools, using the modified training box and the modified surgical tools in a standing position. Then, they had a one hour pre-scan training session in an MRI simulator (Psychology Software Tools Inc., Pittsburgh, PA), a mock-up that provides a realistic experience.

\(^\ast\) Edinburgh scale is a measurement scale used to assess the handedness of an individual; that is the dominance in using the right or the left hand in everyday activities.
of undergoing an actual fMRI session. Subjects were familiarized with the tools and the surgical training tasks in the simulator and were instructed on how to minimize their head motion during task performance. Each subject lay supine with their head inside a mock head coil, and interacted with the fMRI-compatible training box that was supported over their lower torso by a custom-built fMRI-compatible table.

Inside the box was an fMRI-compatible video camera with a view of the 10 cm x 10 cm task area. Streaming video was fed back to the subject using a visual display provided by an LCD projector and rear projection screen, viewed through an angled mirror attached to the mock head coil. The subject held an fMRI-compatible surgical tool in each hand and performed the tasks with the tools inserted into holes in the training box (Fig. 9).

Fig. 9. Subject undergoing pre-scan training of laparoscopy tasks using the MRI simulator and fMRI-compatible training box. The subject is not shown within the simulator bore for display purposes.

Following this training session, each subject underwent fMRI with a 3 Tesla MRI scanner (MAGNETOM Tim Trio, VB15A software; Siemens AG, Erlangen, Germany) with the standard 12-channel phased array head coil and an experimental set-up analogous to the training session. The fMRI data were acquired using T$_2^*$-weighted EPI (TR/TE/FA = 2000 ms/30 ms/70°, FOV 200 mm, 64 x 64 matrix, 32 oblique-axial slices, 4.4 mm thick), covering the whole head. A standard T$_1$-weighted anatomical image acquisition provided the grayscale underlay for brain activation maps (3D MPRAGE, TR/TE/FA/TI = 2000 ms/2.63 ms/9°/1100 ms, FOV 256 mm x 192 mm, 256 x 192 matrix, 160 oblique-axial slices, 1.0 mm thick). Task performance video
recordings were saved in time synchrony with the fMRI data using a video capture system specially developed in the laboratory [43].

After the first scan, each subject attended nine practice sessions, on average of three sessions per week. In each practice session, which lasted maximum half an hour, the subject practiced tasks 1 to 5 in the MRI simulator. Following the last practice session, subjects underwent fMRI with exactly the same set up and scan protocol as the first scan.

2.2.6. Data Analysis

Task performance was scored based on the scoring criteria explained in section 2.2.3. A series of t-tests were performed between the scores of each pair of tasks to determine the relative complexity of each task with respect to the other tasks. The last scan’s fMRI data were processed using established freeware, Analysis of Functional Neuroimages (AFNI, revision-2008_07_18_1710) [44]. The first ten time points (20 s) for each run were discarded to eliminate possible head motion caused by the onset of the scan and to discard the initial signal decay associated with the fMRI signal baseline reaching steady state. The remaining time series data were subsequently pre-processed to suppress potential artifacts arising from cardiac and respiratory motion [45], and co-registered to the first remaining time sample to correct for rigid-body head motion. Following this step, the two runs collected for each subject were spatially smoothed using a 5 mm full width at half maximum (FWHM) Gaussian filter, normalized by the run-wise mean within each voxel and concatenated together to form a single dataset. General Linear modelling (GLM) was then performed on a voxel-by-voxel basis with a square wave model for each task and fourth-order Legendre polynomial detrending. As a result, for each participant, a brain activation map, in the form of integrated percent signal change, was generated for each task. To get an average activation map of each task across all nine subjects, each participant's brain activation images were transformed to the standard Talairach atlas space, spatially smoothed using a 6 mm FWHM Gaussian filter and a t-test was then performed on the datasets associated with each task. The resulting group activation images were subsequently superimposed on the average of the nine participants' anatomical brain images which were also transformed to the Talairach atlas space. This yielded a color map of brain activation (percent fMRI signal from baseline), for each task averaged over nine subjects. The activation areas were color coded according to t values that were found to be statistically significant, after correction
for multiple comparisons with a minimum cluster radius of 6.2 mm and family wise error rate of $p = 0.05$.

2.3. Results

2.3.1. fMRI-compatibility

Phantom experiments showed that the fMRI-compatible apparatus had no statistically significant impact on image quality. The SNR and SFNR (mean ± std) values for all three conditions are shown in Table 3. Visual inspection of the fMRI data for all conditions also showed that introducing the simulator and tool manipulation during scanning procedures did not cause noticeable artifacts and distortions.

No temperature elevation was observed in the tools during the fMRI-compatibility testing or any of the subject-scan sessions.

Table 3. Measured SNR and SFNR values showing fMRI-compatibility of the device

<table>
<thead>
<tr>
<th>Condition</th>
<th>SNR (mean ± std)</th>
<th>SFNR (mean ± std)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>311 ± 6</td>
<td>298 ± 1</td>
</tr>
<tr>
<td>Condition 2: the box at 100 cm and the tools stationary at 80 cm from the phantom</td>
<td>307 ± 5</td>
<td>299 ± 7</td>
</tr>
<tr>
<td>Condition 3: the identical configuration as 2) but with the tools manipulated during fMRI</td>
<td>307 ± 2</td>
<td>297 ± 7</td>
</tr>
</tbody>
</table>

2.3.2. Behaviour

All subjects were right handed according to the Edinburgh scale [42]. For the subjects who were larger than normal it was harder to perform the tasks comfortably because they had less room to move their hands. Subjects who were shorter than normal had a similar issue as they could not reach out to perform the tasks. As a result, given the body size, it would take longer to set up the table and the box such that the mounting table was at a lower position and the box was closer to the magnet bore to allow the subjects to perform the tasks comfortably. Fig. 10 shows the mean, maximum, and minimum task performance scores for tasks 1-5. There was a general reduction in performance scores across the tasks from task 1 to 5. The $p$ values associated with the t-tests that were performed between the scores of each pair of tasks are shown in Table 4.
According to this table, subjects performed task 1 significantly better than the other tasks, and completed task 2 significantly better than tasks 3 to 5. However, subjects’ performance of tasks 3 to 5 was not statistically significant different from each other. This is an indication that task 1 was the easiest task, task 2 was easier than tasks 3 to 5, but tasks 3 to 5 are at the same level of complexity.

![Fig. 10. Mean, standard deviation, maximum, and minimum task performance scores for tasks 1-5.](image)

Table 4- p value associated with the t-tests performed between the scores of each pair of tasks

<table>
<thead>
<tr>
<th></th>
<th>Task 1- Pointing</th>
<th>Task 2- RH</th>
<th>Task 3- LH</th>
<th>Task 4- BH</th>
<th>Task 5- Knot tying</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1- Pointing</td>
<td></td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Task 2- RH</td>
<td>0.000</td>
<td></td>
<td>0.008</td>
<td>0.007</td>
<td>0.014</td>
</tr>
<tr>
<td>Task 3- LH</td>
<td>0.000</td>
<td>0.008</td>
<td></td>
<td>0.414</td>
<td>0.512</td>
</tr>
<tr>
<td>Task 4- BH</td>
<td>0.000</td>
<td>0.007</td>
<td>0.414</td>
<td></td>
<td>0.121</td>
</tr>
<tr>
<td>Task 5- Knot tying</td>
<td>0.000</td>
<td>0.014</td>
<td>0.512</td>
<td>0.121</td>
<td></td>
</tr>
</tbody>
</table>
2.3.3. Task Related Activation

**Task 1**: the positive activated areas associated with the pointing task were contralateral to the side of task performance and included premotor cortex (PM) and supplementary motor area (SMA) including BA 6, primary motor cortex (M1) including BA 4, Somatosensory Cortex (S1) including BA 1, BA 2, & BA 3. Negative activation was observed in right insula (INS-R) and parahippocampal gyrus (PHG) (Fig. 11a, Appendix A Table 5).

**Task 2**: transferring pegs using the right hand revealed positive activation contralaterally in the PM and SMA area including BA 6, primary motor cortex including BA 4, somatosensory cortex including BA 1, BA 2, & BA 3, superior parietal lobe including BA 7 and BA 5, inferior parietal lobe (IPL) including BA 40, middle occipital gyrus (MiOG) including BA 19, middle temporal gyrus (MTG) including BA 37. Negative activation was observed in posterior cingulate gyrus (PCing) and right insula (Fig. 11b, Appendix A Table 6).

**Task 3**: positive activation was observed contralaterally in premotor cortex including BA 6, primary motor cortex including BA 4, somatosensory cortex including BA 1, BA 2, & BA 3, and superior parietal lobe including BA 5 (Fig. 11c, Appendix A Table 7).

**Task 4**: the positively activated areas associated with bi-manual pegboard transfers using both hands were left premotor cortex and supplementary motor area including BA 6, primary motor cortex including BA 4, somatosensory cortex including BA 1, BA 2, & BA 3, and superior parietal lobe including BA 7 and BA 5. Negative activation was observed in the right insula including BA 13, superior temporal gyrus (STG), inferior frontal gyrus (IFG), and left and right posterior cingulate gyrus (Fig. 11d, Appendix A Table 8).

**Task 5**: modified knot tying task revealed bilateral positive activation in premotor cortex and supplementary motor area including BA 6, primary motor cortex including BA 4, somatosensory cortex including BA 1, BA 2, & BA 3, superior parietal lobe including BA 7 and BA 5, inferior parietal lobe including BA 40, middle occipital gyrus, Middle temporal gyrus including BA 37, and lingual gyrus (LG) including BA 17 (Fig. 11e, Appendix A Table 9).

The least amount of activation was observed in the pointing, the simplest task, and the most amount of activation was observed in the knot tying task that was the most complex task. Less activation was observed in transferring pegs using the left hand compared to transferring pegs using the right hand.
Fig. 11. fMRI results of the 2nd scan, showing dominant areas of activation vs. Baseline in: a) Pointing task, b) uni-manual pegboard transfers using the right hand (RH), c) uni-manual pegboard transfers using the left hand (LH), d) bi-manual pegboard transfers using the both hands (BH), and e) Knot tying task.
Higher activation in medial frontal gyrus was observed in the knot tying task compared to all the other tasks. However, no activation in medial frontal gyrus was observed in transferring pegs using both hands.

2.4. Discussion

2.4.1. fMRI-compatibility

The results of phantom testing indicated that the apparatus has excellent fMRI-compatibility. As shown by the SNR and SFNR values, the device did not increase spatiotemporal noise during fMRI acquisition. This was expected given the use of non-ferromagnetic material in the box, tools and supporting table, and the distance between the apparatus and the imaging field of view. The lower SFNR values compared to SNR values were expected, as MRI systems typically have larger temporal noise than spatial noise. In addition, robust fMRI data, with no visible image artifacts, were obtained when the subjects used the apparatus without any incidents.

Since brass and aluminum has similar electromagnetic properties and the grasping parts are small and located the furthest from the magnet bore (sitting outside of the magnet bore) compared to the rest of the metal portion of the tool, the difference in SNR and SFNR or electromagnetic noise and other artifacts caused by replacing the grasping part was expected to be negligible. Consequently, the fMRI-compatibility testing was only done on the tool with aluminum grasping part.

No temperature elevation was observed in the surgical tools when used in the fMRI sessions, so from this perspective, the materials used in modifying the surgical tools were suitable in the fMRI environment.

2.4.2. Behaviour

In this study, the subjects practiced the laparoscopic surgery training tasks for about ten sessions before they underwent the second fMRI session. Scanning subjects who have the same level of experience in using the training box insures that the resulting neuroanatomical correlates are a depiction of the task performance rather than large differences in practice effects. In addition, anecdotal reports from the subjects indicated that the fMRI simulator practice sessions
were of substantial benefit in acclimatizing to subsequent imaging procedures. Therefore, practice sessions helped to minimize the effect of anxiety or distraction due to performing complex motor skills in the claustrophobic fMRI environment. However, the body orientation in the fMRI simulator and scanner may influence the task performance compared to performance in standing position. To eliminate this issue, fMRI can be combined with other functional neuroimaging modalities to provide more comprehensive results.

The task performance of the subjects was reported in terms of newly created metrics, developed due to the necessary adaptations of the original FLS scenarios for fMRI procedures. Although these metrics remain to be validated in relation to the original FLS scores, the new metrics are also based on speed and accuracy, suggesting that they should provide similarly useful insight.

As expected, task performance of subjects declined as task difficulty increased (i.e. pointing to knot tying). For pegboard transfers, performance with the right hand was better than with the left hand. This was predictable since all the subjects were right handed and they received the same amount of practice for all tasks. Interestingly, performance with the left hand was as poor as that of the bimanual peg transfer task, which was initially predicted to be more difficult. On inspecting the video recordings, the reason for this effect was that the bimanual transfer task started with picking up a ring with the right hand. Subjects were able to receive points for performing this maneuver more easily than the next component of the task, which required transferring the ring to the surgical tool in the left hand. Transferring pegs with the left hand was the common component of these two tasks which caused the subjects to perform poorly on both of these tasks.

2.4.3. Task Related Activation

The fMRI results showed that activation in some brain regions amplified as the level of task complexity increased from pointing task (task 1) to knot tying task (task 5). For example, BA 5 and BA 7 activations were only observed in tasks 2 to 5. These two areas play a role in visual-motor coordination and the integration of the information coming from the postcentral gyrus and the visual information coming from visual cortex [21]. This implies that the pointing task involves less preprocessing and integration of visual and sensory information compared to the more difficult tasks. Similarly, activation of inferior parietal lobe is observed for tasks 2 and
5 which can be an indication of the high spatiotemporal complexity of limb movements in these tasks [25]. Along the same lines, only the lateral portion of BA 6 was activated in uni-manual tasks (tasks 1 to 3), whereas both the medial and lateral portion of BA 6 were activated in task 5 (a bi-manual task). The lateral and the medial portion of BA 6 include the premotor cortex (PM) and supplementary motor area (SMA), respectively. These findings suggest that PM and SMA are both activated when a motor movement is planned and organized but SMA shows more activation when a bimanual task is coordinated [21]. Similarly, activation of BA 4, which includes the primary motor cortex (M1) and works with BA 6 to plan and execute motor functions, was observed as expected for all the tasks and amplified as task complexity increased. Overall, higher activation in parietal and premotor regions suggest that performing the more complex tasks requires more attention/visuo-spatial ability and movement planning, respectively.

The medial activation of BA 6 was expected, but not observed, in task 4 as this task involves coordinated use of both hands. Performance videos revealed that most of the subjects could not complete task 4 in the given time, meaning they started the task with their right hand but could not start using the left hand in the given time. As a result, the medial part of BA 6 did not show any activation, causing a similar pattern of activation for tasks 2 and 4.

Activation in the middle of the strip of the postcentral gyrus (BA 1, BA 2, and BA 3) was observed for all five tasks. This area is a part of the primary somatosensory cortex and is associated with processing somatosensory information coming from sensory receptors in hands and fingers [21]. This may suggest that the sensory information received from manipulation of surgical tools is directly involved in planning the task execution.

Initially, it was hypothesized that prefrontal area would be activated in tasks 2 to 5 and activation in cerebellum would be observed in tasks 4 and 5. While activation in these areas is not observed in the group results, the brain activation map of some individuals showed prefrontal and cerebellum activation. Considering the variability in brain activation maps between individuals, a larger group of subjects is required to examine the prefrontal and cerebellum activation in performing the laparoscopic surgery tasks.

The results showed a reduction in brain activation, as well as mean score, in performing the uni-manual transfering of pegs using left hand (task 3) compared to uni-manual transfering of pegs using right hand (task 2), despite the identical design and scoring criteria of these two tasks. Since the subjects were right-handed, recruitment of smaller brain regions along with the poorer
performance and lower scores in performing the task with the left hand compared to the right hand suggests a positive correlation between handedness, task performance, and the brain recruitment. The smaller brain recruitment in executing tasks with the non-dominant hand in comparison to the dominant hand has been observed in previous studies [26]. These observations imply that the trainees should receive more training for the non-dominant hand to improve its task performance to the same level of the dominant hand. This is a crucial finding in refining the laparoscopic training curriculum as the more efficient use of the non-dominant hand can improve bimanual tasks performance and the overall outcome of practice and training.

Performing surgical tasks is a complex procedure and previous studies could not capture the complete brain activation patterns associated with surgery by using simple cognitive tasks. For example, the brain activation of the mental rotation task (MRT) was in parietal, premotor, frontal and temporal regions [37]. The activation patterns associated with surgical training tasks, except the knot tying task, were different from MRT. The brain activation in the knot tying task was similar to MRT but the extent of activation, particularly in the cortical regions, was much larger. Therefore, to have more comprehensive brain activity, it is crucial to use realistic laparoscopic training tasks in studying the brain activation associated with performing such tasks.

2.5. Conclusion

An fMRI-compatible FLS training set including an fMRI-compatible FLS training box and a surgical tool that is commonly used with this surgical simulator has been developed. Results of this study showed the fMRI-compatibility of the device. This device provided the possibility of performing and evaluating a laparoscopic surgery training task in the fMRI environment. The fMRI experiment that employed this device confirmed that the apparatus can be used comfortably. It also revealed the neuroanatomical correlates associated with performing a few laparoscopic surgery training tasks in the fMRI environment.
3. Conclusion and Future Directions

3.1. Summary

The first chapter of this thesis explained the motivation behind integration of the laparoscopic surgery training set with fMRI technologies for exploring the brain-behaviour relationships associated with laparoscopic surgery training task performance. The second chapter outlined the experiments that were undertaken to meet the objectives of the thesis through the development and testing of an fMRI-compatible training box and surgical tools and acquiring the brain activation associated with performing some of the laparoscopic surgery training tasks. The results of these experiments confirmed the fMRI-compatibility of this apparatus. The brain activation associated with performing several laparoscopic training tasks was explained within the current framework of knowledge of the neuroanatomy underlying sensorimotor and cognitive behaviours.

The first objective of this thesis was to modify a laparoscopic surgical training device such that the simulation of laparoscopic skills in the fMRI was possible. To meet this objective, the FLS training box and the surgical tools were modified to meet the fMRI compatibility criteria. The imaging experiments on a phantom showed that the device did not affect the electronic noise levels during fMRI and did not produce noticeable image artifacts. Further, it was observed that the subjects could comfortably perform the surgical training tasks using this training set in fMRI environment.

The second objective was to investigate the brain activation related to several laparoscopic surgery training tasks using this set up. For this purpose, nine young healthy, novice right-handed adults were trained to perform five tasks in a simulated fMRI environment for ten sessions. Following the last practice session, they underwent an fMRI scan while performing the tasks. The results showed that the primary and supplementary motor area (planning and executing movement), the primary and association somatosensory area (processing and integrating sensory information), and the parietal and temporal regions (integrating sensory information, depth perception, and tool manipulation) were activated during performance of all five tasks with variable intensity and coverage depending on the task.

The development of this fMRI-compatible training set and the initial experiments on subjects set the basis for future fMRI studies, such as those to evaluate dynamic changes in brain
organization that accompany laparoscopic surgery training, and to optimize laparoscopic surgery training and assessment procedures. The following section outlines some of the future directions that can be envisioned for this work.

3.2. Future Directions

3.2.1. Validation of the fMRI-compatible Training Apparatus

Comparing the fMRI-compatible training set with its original version is beneficial to see if the performance in the fMRI environment is analogous to the performance on the training box in real world. To provide more insight into this issue, it would be interesting to design a study that compares the performance of the subjects while they are performing tasks with the original versus the fMRI-compatible training set (i.e. training box and the tools) in standing position. The subjects should be surgical residents who have some experience in using the training box so any change in performance when using the fMRI-compatible training set can be detected. A similar study can be designed such that the performance of the subjects when using the training set in the standing position can be compared to the performance in the fMRI simulator.

3.2.2. fMRI-compatible Training Apparatus Modifications

Although subjects could perform the laparoscopic surgery training tasks with the fMRI-compatible training apparatus presented in this thesis, there are ways that the testing situation can be improved for future studies. Improving the video signal quality would be beneficial. The noise level in the video images fed back to the user in the fMRI scanner was quite high compared to the fMRI simulator. The noise level can be reduced either by using a better quality camera or using signal processing techniques. Using a better quality camera may be a more expensive option and using signal processing techniques may introduce feedback delays. The pros and cons of each option can be explored in more detail for future usage of the device.

Improving the quality of the fMRI-compatible surgical tool is another potential area for improvement. The basic laparoscopic surgery tools such as the one used in this study are typically intended for one time use in real surgical cases, hence, the breakage-resistance of the device with continuous use is unknown. In addition, the metal portion of these tools is usually made out of a hard metal such as steel.
The dimensions and the design of the modified surgical tool, used in this study, were very close to the dimensions of the original tool (Appendix B). Therefore, the modified surgical tool, the grasping part in particular, had small dimensions and fine cuts. Since these parts in the fMRI-compatible tool were hand-made it was hard to produce them out of a hard metal, such as steel. This issue and the higher cost of an fMRI-compatible steel pushed the use of brass, which is a cheaper fMRI-compatible metal and has enough hardness for multiple use. Although the fabricated tool was successfully used in more than 100 practice and scan sessions, it required service after about every 30 practice sessions. To improve the life time of the tool and prevent the interruption in the practice sessions, production of the laparoscopic surgery tools with a new material and design, or different fabrication methods can be considered for the future fMRI studies.

3.2.3. Future fMRI Experiments with Laparoscopic Task Performance

With the data available from this study, some analysis has been done which is described below and can be continued to a larger study. The images from the first scan were analyzed similar to the procedure explained in section 2.2.6 resulting in the brain activation versus baseline for each task as shown in Fig. 12. Visually comparing Fig. 11 and Fig. 12 showed that the same areas were activated in both the first and the second scan. However, for all the tasks except the pointing task, larger areas of activation were observed in the results of the first scan session compared to the second scan. For instance, activation in cerebellum, which was seen in tasks 5 of the first scan session, was not seen in the results of the second scan session. However, activation intensity in the activated areas was higher in the second scan compared to the first one. This may suggest that smaller regions of the brain are recruited after practice while the areas that are recruited are used more often. This is in agreement with the results of the previous studies showing that the demand on cognitive control resources that support early learning or novel task performance decreases with practice [46], [47] resulting in more automatic task performance. However, performing a t-test comparing the results of the first and the second scan for each task did not reveal any statistically significant difference between the before and after practice brain activity. This may be explained by the variability in subjects’ performance and their improvement with practice and the small pool of subjects. For example, the standard deviation
from the mean performance score in task 3 is about 100% and 60% of the mean score of task 3 in the before-practice and after-practice scan sessions, respectively.

Observing the task performance of individual subjects triggers other interesting questions. For example, the comparison between the before-practice and after-practice brain activation of the group that showed the most improvement in each task would demonstrate if the regions activated early in task performance are different from those showing activation after practice. In addition, it would be interesting to compare the brain activation of those who greatly improved with practice and those who hardly improved with practice, for each task. This comparison would reveal the difference in brain activation patterns between these two groups. For instance, subjects 1 and 3 had the greatest improvement while the least improvement was observed in subjects 7 and 8 during practicing task 2. A 3-factor analysis of variance was performed between these two groups which did not result in any statistically significant result. Similar analysis was performed for other tasks that did not show any significant results either. Due to small number of subjects and the high variability in brain activation in different subjects, recruiting more subjects is required for investigating these and similar questions. For example, the ratio of the standard deviation over the mean number of activated voxels in performing task 1 to 5 is about 97%, 150%, 130%, 115%, and 280%, respectively.

The results show that performance in some subjects does not change with practice. These subjects can be divided into two groups: a) subjects who performed equally poorly; and b) the subjects who performed equally well before and after practice. With a larger pool of subjects the instances of such individuals will increase which allows studying the differences between the brain activation patterns of these two groups and the group that improved with practice. Such studies can provide some insight into how the training methods can be altered to accommodate trainees with different learning and psychomotor abilities.

In the long term, it will be interesting to observe how the resulting activation maps differ from those of highly skilled laparoscopic surgeons, who as a consequence of extensive repeated practice over many years are anticipated to show substantial brain reorganization indicative of highly efficient neuronal activity. Such group studies, particularly involving the detailed analysis of brain activation patterns across the set of fMRI-compatible laparoscopic tasks, alone or in combination with analogous results obtained using other functional neuroimaging modalities,
should provide significant opportunities to improve training protocols for enabling surgeons efficiently to perform laparoscopy surgery.

Fig. 12. fMRI results of the 1st scan, showing dominant areas of activation vs. Baseline in: a) uni-manual pegboard transfers using the right hand (RH), b) uni-manual pegboard transfers using the left hand (LH), c) bi-manual pegboard transfers using the both hands (BH), and d) Knot tying task (No activation was observed in the pointing task).

As the last recommendation for future studies of this kind, it is better to recruit from medical students interested in pursuing a career as a surgeon to insure that all subjects have
enough motivation for attending the practice session and learning the tasks. In this study, we were not successful in recruiting surgical residents or any experts.

3.3. Conclusion

Improving the laparoscopic surgery training and assessment tools is an issue requiring additional research. In recent years, there have been multiple studies looking at the training methods and their effectiveness in laparoscopic surgery [4], [5] and the need for improved or additional training [48]. A better understanding of the brain function in performing this procedure would be a significant step towards improving laparoscopic training and assessment. The integration of a laparoscopic surgery training set with the fMRI technologies, which was the goal of this novel study, provides a platform for understanding the brain-behaviour relationships in performing these training tasks. This thesis involved the development of an fMRI-compatible laparoscopic surgery set, and demonstrated the neuroanatomical correlates associated with some of the real world training tasks. Using this training box, fMRI studies involving surgical residents or complete novices can be developed, providing a framework for improving our understanding of the dynamic changes that occur in cortical networks as a consequence of training, and intensive practice in laparoscopic procedures. Such studies, particularly involving the detailed analysis of brain activation patterns across the set of fMRI-compatible laparoscopic tasks, alone or in combination with analogous results obtained using other functional neuroimaging modalities, should provide significant opportunities to improve training protocols for enabling surgeons efficiently to perform laparoscopy surgery.
References


[45] G.H. Glover, T. Li, and D. Ress, "Image-based method for retrospective correction of


### Appendix A. Brain regions identified for tasks 1-5 vs. baseline in Talairach coordinates

Table 5. Brain regions identified for the contrast task 1 vs. baseline in Talairach coordinate space for all participants (N = 9)

<table>
<thead>
<tr>
<th>Cluster (+ or – activation)</th>
<th>Talairach coordinates of the center of the cluster</th>
<th>Activated areas within the cluster</th>
<th>Side</th>
<th>Number of voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x        y        z</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 ( - )</td>
<td>-34      14       3</td>
<td>Insula (INS-R) including Brodmann Area (BA) 13 Parahippocampal gyrus (PHG)</td>
<td>R</td>
<td>2931</td>
</tr>
<tr>
<td>2 ( + )</td>
<td>29       13       55</td>
<td>Premotor cortex (PM) including BA 6 Supplementary motor area (SMA) including BA 6 Primary motor cortex (M1) including BA 4 Somatosensory Cortex (S1) including BA 1, BA 2, &amp; BA 3</td>
<td>L</td>
<td>1631</td>
</tr>
</tbody>
</table>

Table 6. Brain regions identified for the contrast task 2 vs. baseline in Talairach coordinate space for all participants (N = 9)

<table>
<thead>
<tr>
<th>Cluster (+ or – activation)</th>
<th>Talairach coordinates of the center of the cluster</th>
<th>Activated areas within the cluster</th>
<th>Side</th>
<th>Number of voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x        y        z</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 ( + )</td>
<td>34       43       42</td>
<td>Premotor cortex (PM) including BA 6 Supplementary motor area (SMA) including BA 6 Primary motor cortex (M1) including BA 4 Somatosensory Cortex (S1) including BA 1, BA 2, &amp; BA 3 Superior parietal lobe (SPL ) including BA 7 and BA 5 Inferior parietal lobe (IPL ) including BA 40 Middle occipital gyrus (MiOG ) including BA 19 Middle temporal gyrus (MTG) including BA 37</td>
<td>L</td>
<td>8724</td>
</tr>
<tr>
<td>2 ( - )</td>
<td>-41      3        -4</td>
<td>Insula (INS-R) including BA 13</td>
<td>R</td>
<td>6497</td>
</tr>
<tr>
<td>3 ( - )</td>
<td>0        50       8</td>
<td>Posterior cingulate (PCing)</td>
<td>R,L</td>
<td>4636</td>
</tr>
</tbody>
</table>
Table 7. Brain regions identified for the contrast task 3 vs. baseline in Talairach coordinate space for all participants (N = 9)

<table>
<thead>
<tr>
<th>Cluster (+ or – activation)</th>
<th>Talairach coordinates of the center of the cluster</th>
<th>Activated areas within the cluster</th>
<th>Side</th>
<th>Number of voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (+)</td>
<td>-37 26 56</td>
<td>Premotor cortex (PM) including BA 6, Primary motor cortex (M1) including BA 4, Somatosensory Cortex (S1) including BA 1, BA 2, &amp; BA 3, Superior parietal lobe (SPL) including BA 5</td>
<td>R</td>
<td>2097</td>
</tr>
</tbody>
</table>

Table 8. Brain regions identified for the contrast task 4 vs. baseline in Talairach coordinate space for all participants (N = 9)

<table>
<thead>
<tr>
<th>Cluster (+ or – activation)</th>
<th>Talairach coordinates of the center of the cluster</th>
<th>Activated areas within the cluster</th>
<th>Side</th>
<th>Number of voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (-)</td>
<td>-41 4 -6</td>
<td>Insula (INS-R) including BA 13, Superior temporal gyrus (STG), Inferior frontal gyrus (IFG)</td>
<td>R</td>
<td>5962</td>
</tr>
<tr>
<td>2 (+)</td>
<td>37 31 53</td>
<td>Premotor cortex (PM) including BA 6, Supplementary motor area (SMA) including BA 6, Primary motor cortex (M1) including BA 4, Somatosensory Cortex (S1) including BA 1, BA 2, &amp; BA 3, Superior parietal lobe (SPL) including BA 7 and BA 5</td>
<td>L</td>
<td>3389</td>
</tr>
<tr>
<td>3 (-)</td>
<td>-1 56 11</td>
<td>Posterior caudate (PCaud) including BA 31, Posterior cingulate (PCing) including BA 23 and BA 30</td>
<td>R,L</td>
<td>3163</td>
</tr>
</tbody>
</table>
Table 9. Brain regions identified for the contrast task 5 vs. baseline in Talairach coordinate space for all participants (N = 9)

<table>
<thead>
<tr>
<th>Cluster (+ or – activation)</th>
<th>Talairach coordinates of the center of the cluster</th>
<th>Activated areas within the cluster</th>
<th>Side</th>
<th>Number of voxels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (+)</td>
<td>x 1 y 54 z 33</td>
<td>Premotor cortex (PM) including BA 6&lt;br&gt;Supplementary motor area (SMA) including BA 6&lt;br&gt;Primary motor cortex (M1) including BA 4&lt;br&gt;Somatosensory Cortex (S1) including BA 1, BA 2, &amp; BA 3&lt;br&gt;Superior parietal lobe (SPL) including BA 7 and BA 5&lt;br&gt;Inferior parietal lobe (IPL) including BA 40&lt;br&gt;Middle occipital gyrus (MiOG) &lt;br&gt;Middle temporal gyrus (MTG) including BA 37&lt;br&gt;Lingual gyrus (LG) including BA 17</td>
<td>R, L</td>
<td>15295</td>
</tr>
</tbody>
</table>
Appendix B. Shop drawings of the parts of the surgical tool (ENDOdissect™ 5 mm) that have been modified or redesigned for use in fMRI.

Note: the spring used in the handle was replaced with an O-ring.

File name: central rod
Number of pieces to be made: 1
All dimensions are in mm, unless otherwise specified.
Scale: as specified on the drawing
File name: cover for the central rod
Number of pieces to be made: 1
All dimensions are in mm, unless otherwise specified.
Scale: as specified on the drawing
File name: grasping part (left side)
Number of pieces to be made: 1
All dimensions are in mm, unless otherwise specified.
Scale: 5:1
File name: grasping part (right side)
Number of pieces to be made: 1
All dimensions are in mm, unless otherwise specified.
For dimensions refer to “grasping part (right side)”
Scale: 5:1
File name: square (used in the handle)
Number of pieces to be made: 1
All dimensions are in mm, unless otherwise specified.
Scale: 10:1