LEARNING THROUGH HAPTICS: HAPTIC FEEDBACK IN SURGICAL EDUCATION

by

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ABSTRACT

Touch is one of the most important sensory inputs during the performance of surgery. However, the literature on kinesthetic and tactile feedback—both called haptic—in surgical training remain rudimentary. This rudimentary knowledge is partially due to the fact that haptic feedback is difficult to describe, as well as record and playback. To begin understanding the effect of decreased haptic feedback on task performance an incision performance experiment donning different number of gloves was designed under two separate environments. One of the environments had a simulated vessel underneath a simulated skin, while the other scenario did not have the vessel. Results demonstrated that reduced tactile feedback by the gloves did not affect performance, however, the presence of a vessel change the amount of force applied by the performer. Moreover, to gain insight into the effect of exclusive kinesthetic feedback, novices' muscle memory was tested during performance of movement patterns of increasing complexity. Novices were able to remember and learn movements' direction easier than the length. In a subsequent experiment, an innovative kinesthetic system (SensAble™ PHANTOM® Omni) recorded an expert surgeon's haptic features from both hands and delivered to a surgeon-in-training and compared to a group of novices using self-learning while learning a navigational laparoscopic task. Different metrics were utilized to assess task outcomes, motion, and force performance. Although, the difference between the means for all the three areas of both training methods was not statistically significant, a master-slave kinesthetic-guided platform was developed as an end product of this endeavor. Together, these studies exemplify the potential use of kinesthetic guidance as a complementary teaching paradigm in surgical education.

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LIST OF ABBREVIATIONS

JND	Just Noticeable Difference
MIS	Minimally Invasive Surgery
PHANTOM	Personal Haptic Interface Mechanism
RMIS	Robotic Minimally Invasive Surgery
VR	Virtual Reality
VBLaST	Virtual Basic Laparoscopic Skill Trainer
FLS	Fundamentals of Laparoscopic Surgery
MATLAB	Matrix Laboratory

CHAPTER 1 GENERAL INTRODUCTION

1.1 Perception in Surgery

Imagine yourself as a surgeon reaching deeply inside a patient's body, pushing aside organs and trying to stop bleeding from a ruptured spleen. Your vision to the surgical site is constrained and you have to trust your tactile feedback to guide your movements. Fathom yourself maneuvering organs with a long-shafted instrument via a single incision into a body cavity. Your touch perception is distorted by the intricate tool you are holding, and you have no choice but to depend on the distorted tactile feedback to guide you. These imaginary scenarios highlight the importance of how tactile or haptic feedback affects your surgical performance.

As a surgeon, I understand how important vision is in guiding my performance and building skills, and also realize that haptic feedback plays a vital role when vision cannot prevail. However, our knowledge of haptic feedback and its effect in guiding surgical performance is quite limited, and even less is known about the function of haptics (i.e., those which rely on sensory information) in building surgical skills. I personally like to perform laparoscopic surgery when possible; however, laparoscopy requires a high level of hand-tool interaction. I believe that insight into haptic feedback is important to gain understanding of how a surgeon's brain and body interact with tools, and also how haptics perception improves dexterity, which affects performance in such tasks as tele-operation and in visually unfavorable surgical scenarios.

How do surgeons learn?

Since its beginning, surgery has been an art which was not regulated and was exercised by barbers without any formal training or surveillance. Early in the 1800s, a large number of deaths from this type of practice forced decision-makers to organize themselves and to require that their performance be observed by doctors of the time, making it a more legal and therapeutic act[1]. Among the pioneers of the current surgical education system is William Halsted from the John Hopkins hospital. He developed his system based on a German model of that era, creating the first hospital systems paradigm of residency[2]. This paradigm continued until the end of 1937 where various organizations, including the American College of Surgeons (ACS), American Board of Surgery (ABS) and the American College of Medicine (AMA), set forth a committee on graduate training and surgery that led to the publication of a more structured program in the Minimum Standard for Graduate training in surgery[3]. These residencies finally joined the universities and concomitantly created graduate surgery programs[4]. The new structured system for residents proposed annual goals to attain according their year of training. More emphasis was placed on gradual and systematic training in specific skills and skill development by the surgeon[5]. Unlike clinical medical training, the surgeon requires certain innate dexterity in addition to scientific knowledge, acquired personal skills, and good visuospatial perception for tissue identification[6].

When selecting candidates for surgical training, a few ideal characteristics come to mind for both technical and non-technical skills, for instance a good universal medical knowledge is taken into consideration for entry in most post graduate surgical training programs[6]. It should be clear that having a broad knowledge of this kind is not extrapolated proportionally to the residents' performance as a surgeons, moreover, previous studies have shown that the most important and desired features in a surgical resident are a right attitude and surgical dexterity, both which are not generally assessed in medical knowledge examinations[6]. Another very important asset for surgeons and physicians is mindfulness and the capacity for *making decisions* under pressure and emotional stress tolerance which are non-technical skills [7]. These types of "soft skills" are hard to teach and measure, along with other desirable traits expected from a new surgical resident, such as the ability to identify severely ill patients, empathy towards patients, and knowing at what stage of the natural history of the disease a patient is experiencing [7].

Teaching new surgical techniques requires that the surgeon attains a new level of dexterity [8], especially for situations where visual feedback is not reliable, such as tele-operations or bleeding in the surgical field. In this type of scenarios additional feedback information provided by haptic feedback may be advantageous for recognizing blood vessels, abnormal tissue, and gauging appropriate force for tissue manipulation [9-11]. In the current model, the way surgeons can obtain skills and the perception of the environment to set movement coordination in an anatomical context may develop in three stages[12]. First, during the **cognition stage**, the task to be executed is broken down in simple steps to be understood by the novice and followed. The novice observes and memorizes the steps of the model and possible eventualities including complications. Following that, in the **integration stage**, motor abilities are used to learn the task and eliminate ineffective movements. It is helpful at this stage the use of wet labs, including performance of simple surgical assistantships to accelerate the automation of movements and an increase in cerebral visual-learning integration. In the last stage, **automation**, repeated movement creates neural automatized loops that engage and thus create confidence, speed, plus accuracy. An efficient evolution allows for more complex tasks to develop and ergo a flattening of the learning curve[12].

In this approach, it would seem that surgical learning is more of a manual rather than intellectual ability process. However most of the surgeon's time involves deciding the merit of the surgery rather than performing it[12]. There is also the necessity of automation, during the surgeon's formation, in a series of small events (i.e., incision) as they will be valuable for creating a new procedure or skill[12]. This motor skill's learning curve is different in each individual and type of invasive procedures, and needs to be addressed differently for each procedure [13].

The patient remains central in surgical learning and every patient is different with individualized practices, while the surgeon's experience is rooted in their successes and failures during their practice with different learning curves. However, the most important for assessing learning and patient safety is the experience against complications[13]. Therefore, the ultimate purpose in surgical education is to flatten the learning curve and keep surgical complications to a minimum from the beginning, i.e., when the surgeon begins to learn[12]. It is unacceptable for a surgeon to expose the patient to suffer all the complications that could be avoided with a gradual learning of abilities simply in order to gain experience [8]. It is therefore clear that surgical education has to strengthen cognitive and integration stages allowing the best conditions for them to be reached.

The employment of wet labs for the purpose of gaining dexterity has allowed the reinforcement of certain cognitive aspects and the integration of surgical procedures in order to attain movement automatization before facing the patient. These laboratories have been of great help, especially in the area of laparoscopic surgery and decreasing microvascular complications[14]. Ideally, teaching surgical skills in these labs should follow the educational model as described by Peyton[15, 16] which is divided into four stages following this order: demonstration, fragmentation, development, and implementation. During the demonstration part, the instructor shows the procedure at normal speed so the novice observes its normal evolution.

During the fragmentation, each step of the procedure is taught explaining its purpose. At the development stage the apprentice must verbalize each step while the instructor performs and gives feedback. Finally, the implementation stage is the step where the learner performs the procedure while verbalizing the steps.

Moreover, in the surgical theatre, the two senses most frequently employed are visual and haptic [17], especially when evaluating organ viability and controlling a hemorrhage. For example, a surgeon spends a little less than 40% of the time doing dissection, palpation, and tissue manipulation tasks[18]. Consequently, some educators believe that a combination of visual and kinesthetic methods of learning should be emphasized when instructing surgical trainees[12]. However, individuals use the three varieties of sensory inputs—visual, auditory, and kinesthetic—to learn motor coordination based on their innate sensory preferences [19]. Perception research has demonstrated how humans learn skillful movement through these three sensory inputs, either separately or by combining them over time. Visual learners are people who gain the most from being shown a skill, while kinesthetic learners benefit the most from imitation and obtaining information through movement as well as touch. Although visual feedback is more beneficial, learning can be enhanced further when combining simultaneous feedback from visual and haptic sensory systems [20]. Moreover, a previous study found that in procedures to replicate position where visual information is not reliable, haptic feedback enhances motor learning more than just vision on its own[21].

Open surgery is performed with indirect reduction of haptic feedback through the use of gloves[22]. It was with the increased use of endoscopy that looking into the effect of lacking haptic feedback became important[23]. Haptics in surgery is defined as the tactile sensation perceived by the surgeon both actively and passively[10]. Although there is great hindrance of the haptic feedback in minimally invasive surgery, modern bench-top simulators utilizing actual surgical instruments give a fairly close match to the actual feedback felt in surgery[24]. In conclusion, surgeons are aware of the effects of haptics on performance, however, research in this area has been limited and it is one of the principle points of this paper.

Haptics as an underexplored teaching tool

Haptics, which comes from the Greek word *haptikos (*meaning to perceive), is the term that has been coined to refer to the combination of kinesthetic and tactile sensations humans rely on in order to perceive additional information about their environment [25]. A haptic system consists of kinesthetic information (proprioception), cutaneous system (touch), and the motor system which are perceived by the brain [25]. The pathway that follows from the hand receptors up to the central nervous system begins from the organic stimuli and continues through the autonomous system to the thalamus and then to cerebral cortex. Any stimulus that is imposed in the body is interpreted by the receptors that in turn send the signal to spinal medulla which divides the stimuli into two groups. The first one is in charge of pain and temperature, and forms the spinothalamic tract. The second one forms the medial lemniscus and carries on the information coming from articulations, muscle and tendons The information received by posture and body movement is known as kinesthesia, or the perception on one's self; this ability allows for movement planning, control of motions already in effect, and awareness of the relative location of neighboring body parts[24]. Kinesthesia knows where each articulation is without visual feedback and it is altered in surgery by the distance of the tip of the instrument from the hand of the surgeon. This alteration is compensated with training that develops an extended proprioception through tool interaction[24].

The haptic receptors are in charge of picking up the kinesthetic information via the haptic channel and the receptors are distributed in different areas of the skin. On one hand, kinesthesia is obtained via proprioceptors located on the joints, the muscle spindles that provide information about changes in muscle length, and the Golgi tendon organ that gives information on changes in muscle tension[25]. On the other hand, the cutaneous receptors are Meissner's corpuscles and Merkel's disks which are abundant in the lips and fingertips, thus accounting for the ability for object identification. Even deeper in the dermis, the Ruffini's corpuscles and the hair follicles terminals give information on pressure and changes in shape. Lastly, the Paccini's corpuscles get feedback on rapid movement and vibration [25].

It is through haptic perception that humans recognize objects by a combination of patterns in skin surface and proprioception. Haptic perception occurs through an active strategy of manual exploration to obtain as much information from the object and almost an innate set of probing maneuvers that replicate depending on the type of characteristics sought[25]. For example, hardness is determined by pressure in the surface and weight by unsupported holding. Lederman and Klatzky have developed an extensive research in this area; they explain further that these surveying strategies can be combined in a complementary form, such as grasping and lifting - yet, in surgical training this approach can be limited by space constrains[26]. Likewise, managing tissue in surgery is an important part of training. Human haptic perception follows Weber's law that stipulates the Just Noticeable Difference (JND) of a new stimulus is related to the magnitude of the original stimulus plus a constant[27]. In surgical training, detection of tissue density is hindered by the surgical tools, which pleads for a stronger force input increasing cognitive load and greater tissue differentiation time[26]. Vision research has employed JND to developed video perception metrics by asking participants to subjectively grade videos and correlate those scores to different video qualities [28]. Similar type of metrics could be created in haptics to measure the quality of haptic replication in surgical training.

Motor skill learning is a continuum of innate mechanisms of building movement coordination combined with haptic perception that has different phases in the process of skill acquisition and heavily related to motor skill practice[29]. Part of the surgical skill learning process involves learning through different phases and cycles. These three phases that occur while learning a new surgical skill include cognitive, associative, and autonomous [12, 30]. During the cognitive phase, a trainee recognizes the individual components of a procedural skill. In the associative phase, the trainee links these components into a continuous action using feedback to optimize movement. During the autonomous phase, movements become automatic, requiring little cognitive input. Gallagher describes an attention model that is part of the process when learning a complex motor task in surgery [31]. In this attention model, trainees benefit from separating complex tasks into more simple individual movements, which are more easily mastered prior to contextualizing them as components of a more complex motor task. This is evidenced by research into how people acquire skills when learning to play an instrument. Humans tend to pay more attention during the cognitive phase of the training because, it is believed, more efficient identification of the task components will result in a more rapid associative phase of learning [32]. If trainees are better able to identify the steps, trainees will learn more quickly and efficiently. Despite the fact that most people rely on visual feedback when learning— i.e., they learn based on what they see— haptic feedback is more effective for learning because haptics speeds up the process; haptic is a critical element for creating muscle memory by offering information on body position and how to replicate it [21]. Furthermore, Fitts' law states that difficulty of a task has direct relationship with time execution[33], thus faster task completion with haptic feedback can mean it has become instinctive.

Despite all the previously mentioned benefits of haptics in motor skill learning, skill acquisition using haptics alone has some challenges. One of the limitations of haptic training alone is less effective than visual training to distinguish shapes and position. Moreover, if vision is available after haptic training, vision overrides the haptic information acquired [9]. Surprisingly, relying on visual feedback alone increases the surgeon's workload and the time it takes for him or her to train[18]. Skill transferring between people oftentimes is delivered via visual and verbal channels. When visual information is not reliable (such as during a video signal delay in tele-operation), training with haptic feedback can help complete a task. This is because haptic perception has the advantage of being the only human sense that allows direct manipulation of the environment and aids to demonstrate movements which is not possible through verbal channel. This potential teaching strategy has been displaced in favor of vision for surgical training, despite haptic training having less mental workload since it occurs in a motor loop, unlike visual training which needs to go through complex sensorimotor transformations requiring an increased cognitive load [9]. Considering this, emphasizing haptic feedback in the associative phase of acquiring new surgical skills can decrease the time needed to acquire motor coordination proficiency through kinesthetic learning [32]. Kinesthetic learning takes advantage of kinesthetic memory, or the ability to remember motor patterns. Kinesthetic memory, also known as muscle memory, is employed in kinesthetic training and is created by the kinesthetic sensory and motor information obtained from movement [9]. An example of kinesthetic training is when a professional golfer guides the golf swing of a golfer trainee to teach him or her to hit harder.

There are two types of feedback when developing a motor skills. These can be delivered during or once the task is over and may be inherent to the task on course or extrinsically related[34]. This feedback may be coming from within the body (proprioception) or it may come from the external environment called exteroception or augmented feedback[35]. Exteroception is greatly aided by audition and vision, while proprioception uses the skin receptors, muscles, joints and vestibular system[34]. The two types of augmented feedback are known, knowledge of performance (KP) and knowledge of results (KR)[36]. KP is the kinematic information obtain after completing the task regarding the trace characteristics. On the other hand, KR is the feedback on completion of the task in relation to the undertaking[36]. Even though these feedbacks belong to different mechanisms, they may be considered to work under the same principles[36].

Different roles have been proposed for augmented feedback in the acquisition of motor skills. Kinematic feedback not only provides information about the task performed either by identifying errors made and possible corrections but also works as a motivator as an assessment tool[37]. Schmidt describes the benefits of kinematic feedback in task completion through various forms. One is by giving knowledge of the subject’s motion patterns and the other through providing information no otherwise given by intrinsic sources[34]. However, two main challenges have been found in kinematic feedback, one is that the simplicity of the task at the bench-top level makes enhanced feedback unnecessary, and the second that at the same time it is difficult to extrapolate these results to complex tasks[36].

Having said that, our knowledge on haptic and its role on learning a motor skill remains largely understudied in surgery and skill training. In the next section, we will overview current knowledge of haptics in different fields, some challenges associated with haptic feedback, and explore the possible routes for improving skill training via the haptic feedback guidance.

1.2 Problem Definition

This thesis research begins by laying down the foundations around the mechanism by which human memory perceives haptic information. Specifically, we aim to understand to what degree is kinesthetic information is saved into our memory, and once this kinesthetic information is retrieved, how accurately can it be used to guide our movement. We believe, kinesthetic memory, or "muscle memory," constructs the foundation of skill learning, and it is the main component of proficiency in complex surgical maneuvers. By finding new methods to harness the way in which kinesthetic memory is enhanced by simulated haptic feedback, we may be able to expedite the way we learn certain surgical tasks.

A decrease in the time devoted to skill training, a diminishing case volume for practicing new surgical procedures, and ethical concerns about the use of animal and cadaver models have created a need for new methods and strategies for teaching surgical skills [8]. Haptic sensor technology has been applied to create a common frame of reference for haptic interactions between humans and computers. Specially designed equipment offers haptic interactions in computer simulation or remote guidance manipulation. By using these new haptic interfaces in training, surgical educators may be able to create novel learning strategies. These new haptic interfaces may promote surgical skill training by guiding the movement of surgical trainees. With Minimally Invasive Surgery (MIS) having limited haptic feedback, teaching haptic guidance may increase patient safety by speeding up tissue identification, hastening the transfer process from education to the operating room, and enhancing tele-mentoring (Figure 1-1).

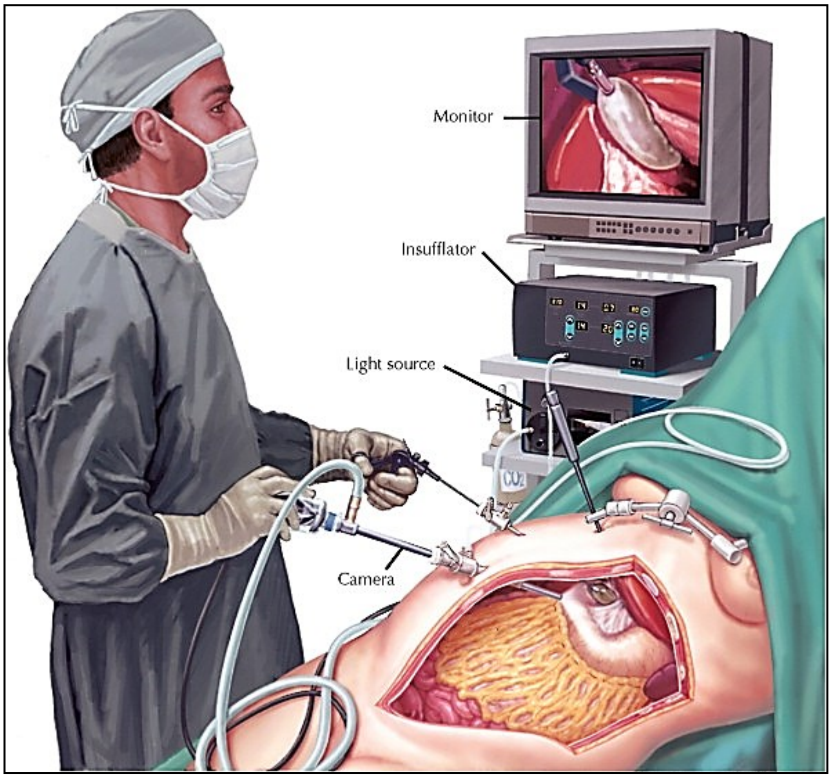

Figure 1-1. Typical laparoscopic setup composed of a light source and a camera that displays the image into a monitor.

An insufflator keeps air in the body cavity to enhance visibility and maneuverability of the organs [38]. Visual feedback is limited to a 2D view and the quality of video feed. Tactile feedback is reduced by the instruments inside the cavity, making it difficult to distinguish different characteristics of the organs.

1.3 Research Questions

The purpose of this thesis is to explore these two research questions: 1) Can we save and retrieve kinesthetic information from our memory to guide our movement? 2) Can we deliver kinesthetic feedback between two operators and use such guidance to enhance proficiency of a trainee in learning laparoscopic skills? Recommendations will be made from the insights acquired from the research.

1.4 Outline of the Thesis

This thesis is divided into six chapters, each focusing on a different part of the research topic. Chapter 2 presents a survey and literature review of the prevailing trends of haptic simulation in MIS. The review helps to clarify the current state of haptic perception simulation and future issues that need to be addressed. In Chapter 3 the effect of decreased tactile sensation on performance is explored. Chapter 4 examines the role that kinesthetic memory plays in learning new skills, with a focus on using passive haptic guidance. Chapter 5 provides information about how kinesthetic guidance can affect perception during laparoscopic tasks and addresses the issue of how kinesthetic guidance influences performance. Chapter 6 offers a general discussion, with conclusions and ideas for future work.

CHAPTER 2 HAPTICS IN SURGERY: PREVAILING TRENDS IN HAPTIC FEEDBACK SIMULATION IN SURGERY

2.1 Introduction

Before presenting our research results, I have completed a literature review in the field of haptic perception, with an emphasis on its role in surgical performance. This literature search was conducted using PubMed to capture articles with the following terms: haptic, force feedback, touch feedback, minimally invasive surgical procedures, minimal invasive surgery, robotic surgical procedures, robotic, virtual reality, surgical training, and surgical education. Reviews, randomized controlled trials and observational studies were included.

Our search strategy identified 198 abstracts relevant to haptic feedback and MIS. A manual review of each of the abstracts by the first author resulted in a selection of 32 studies consistent with the focus of this review. Three major areas of investigation were consistently reported in the literature, including reports on the focused development of one of the four core components of a haptic feedback system, compensation mechanisms and utility of various tool and tissue interactions, as well as novel tools for enhancing haptic feedback in MIS and robotic minimally invasive surgery (RMIS) simulators. I discuss each of these three areas in the sections below.

2.1.1 Loss of haptics in surgery

According to Bholat *et al*. [23], haptics refers to the interaction between the tactile stimulus provided by one's environment, and a combination of cutaneous and kinesthetic sensors in tendons, joints and muscles. The perception of an object's stiffness, or contrarily, its compliance, requires a combination of visual and haptic components that varies depending on the amount and quality of information coming from either sense (e.g., sensory channel) and the ability to integrate this information with previous experience [39]. This suggests that despite the predominance of visual feedback while performing motor tasks, adding haptic feedback significantly accelerates the identification of objects and is vital for learning new motor tasks and improving coordination [21].

Motor coordination is controlled principally by both visual and haptic feedback loops [10]. Zheng and MacKenzie [40] theorized that highly precise movements can overwhelm the bandwidth of the visual sensory channel, and that motor tasks that demand a high degree of accuracy are consequently more dependent on kinesthetic information provided by haptic feedback. They demonstrated that when kinesthetic information is limited or attenuated by the introduction of a tool or instrument, performance deteriorates significantly when subjects are required to perform more accurate motor movements, such as those executed in surgery.

Surgeons have been able to counteract the detrimental effects of attenuated haptic feedback with extensive training and experience as well as by consciously and subconsciously placing more emphasis on visual cues. However, despite advances in imaging technology and high-definition video systems, visual compensation in minimally invasive surgery remains significantly different than that experienced in open surgery [25]. As a consequence, in inexperienced hands, these impediments result in prolonged procedural times and a greater risk for surgical error [10, 25]. Furthermore, in situations where visual feedback is not as reliable, such as tele-operation, or with increased cognitive load, such as in 3-dimensional (3D) camera endoscopy, additional feedback provided by enhanced haptic feedback may be advantageous for improving the recognition of critical structures such as blood vessels and gauging the appropriate force for tissue manipulation [9-11, 41].

Cognizant of the attenuation of haptic feedback in MIS, surgical educators and scientists have designed MIS skills labs to maximize surgical realism by emphasizing haptic cues [24]. This is especially important, since haptic feedback has been found to be beneficial in the early phases of surgical skill acquisition [42]. Bench-top simulators are frequently utilized to create a training environment with similar or identical tissues and instruments, with the ultimate goal of replicating the haptic experience of the real-world operating room [24, 42]. However, the parallel development of virtual simulation environments (virtual reality [VR] simulations) has been hindered by the inability to realistically replicate haptic feedback. This is primarily due to the technological challenge of rendering mechanical properties of instruments and tissues, in addition to a lack of understanding of how haptic feedback should best be delivered to the trainee [10, 43].

VR–based surgical simulation was pioneered in the early 1990s by Delph and Rosen (1990) and by Lanier and Satava (1993) [44]. Subsequently, different models have been developed in a variety of surgical and clinical fields [10]. At the most elementary level, these VR systems consist of a processor unit that registers instrument movement and manipulation. The movement and manipulation are then input into a software program that generates high-fidelity simulated environments for display on a monitor via haptic interfaces.

Haptic interfaces are devices through which the surgeon interacts directly with a variety of real or virtual environments. These are the tools that use actuated joints that sample data and register movement, orientation, and applied forces at a speed of 300 and 500 Hz [45]. However, their availability is still restricted, limited by proprietary development and significant cost. This has resulted in a lack of benchmarks and interoperability with other systems. One possible solution that has been proposed is to simplify the haptic interface model (low fidelity) to decrease the cost and facilitate interoperability [45]. Fortunately, the ability to convey simulated haptic information to the surgeon is improving with haptic interfaces. Haptic playback enables the trainee to follow a pre-recorded force and position trajectories [11]. Using haptic playback may aid in the creation of surgical training trajectories by way of closed loop motor control, which is motor control that requires continuous adjustment of muscle movements based on the integration of perceptual cues [24]. For example, a haptic playback system could demonstrate to a novice the order in which fingers should move when tying a surgical knot.

A variety of both mechanical and electronic haptic compensation mechanisms, as well as augmentation devices, has been developed to compensate for the attenuated feedback experienced in laparoscopic surgery as a means to improve haptic rendering, the ultimate mechanical forces or tactile feedback provided to the operator [11, 45]. From the mechanical perspective, graspers that reduce friction have been developed to reduce the haptic sensory loss that is typical of endoscopic tools. While these devices have not been able to completely restore haptic feedback, they have been able to measurably decrease sensory loss and enhance perceived feedback [46]. Examples of novel mechanical feedback mechanisms include a pneumatic array of 3-mm balloons developed for the da Vinci surgical system [47], and the “SureTouch” device, which, by using 192 high-resolution pressure sensors, possesses four times more sensitivity than a human hand to detect breast tumors [48]. Although vision partially compensates for this haptic deficiency, applying this technology to MIS might improve tissue identification, and would address one of the major limitations of robotic MIS (RMIS).

Haptic feedback is decreased in MIS mainly because of the instruments employed. The distance effect of the long tools to the surgical site plus the friction added by the ports inserted in the abdominal wall add to the fulcrum, alter the forces applied and give imprecise proprioception of the amount of force needed by the surgeon[24, 49]. Despite this, the surgeons have been able to counteract this effect by extensive training (extended proprioception) and heavily weighing in visual cues for size and shape at a cost of time and risk for the patient safety[10]. Yet, this visual compensation cannot differentiate between force exerted and tissue texture [25].

2.1.2 Utility of haptics to teach surgical skills

As described above, new technology continues to improve each of the four key components that comprise a haptic feedback system. At the same time, ongoing research has helped to identify which of these components provide the most benefit at improving a surgeon's perception of the operative field. This portion of the review focuses on the surgeon's perception of and response to artificially generated or augmented haptic feedback [22, 24, 31]. Lamata *et al*. studied the collective set of forces and torques that the surgeon perceives, a collective set referred to as an individual's perceptual boundary. The set of perceived forces deemed useful for carrying out a particular maneuver is known as the utile boundary [50]. Using the utile boundary, Lamata *et al.* tested the ability of several surgeons to perceive differences in tissue stiffness using laparoscopic tools. They then compared their findings with instrument-based measurements of the same tissues [51]. After the surgeon's subjective opinion of stiffness was obtained, the tissues were objectively tested in the laboratory and both stiffness scales were compared. The researchers found that when surgeons held large amounts of tissue in their graspers, the accuracy of their subjective assessment of stiffness increased. Additionally, the following four parameters were correlated with the ability to discriminate among tissue types [51]:

a. Mass of tissue manipulated
b. Mass of tissue held with graspers
c. Tissue stiffness
d. Amount of fixation of the tissue to the abdominal wall.

These findings suggest potential areas to further develop simulators that incorporate haptic feedback. Given that a surgeon spends approximately 40% of operative time performing dissection tasks, a potential system should provide accurate and useful feedback regarding the total magnitude of the forces applied [18]. Wagner and his group investigated haptic feedback during dissection tasks using a Personal Haptic Interface Mechanism (PHANTOM) in a master-slave arrangement. They found that the use of force feedback decreased the amount of force applied as measured at the tip of an instrument, and reduced the overall number of errors. The researchers suggested that the improved performance was a result of the simulated forces imitating natural physical constraints in the tissue [18].

Similarly, the use of master-slave systems and amalgamations of laparoscopic tools with haptic interfaces provides alternate methods for enhancing haptic feedback in MIS. Tholey *et al.* integrated the PHANTOM into a laparoscopic system to investigate the difference between using vision alone or combined with force feedback while learning laparoscopic surgical tasks. Their results demonstrated that force feedback improved the identification of tissues, resulting in superior dexterity, dissection, task time, and overall diagnostic proficiency during MIS [52].

Despite the aforementioned advantages, the benefit of haptic feedback in current VR systems remains controversial [10, 53-55], as demonstrated in a recent experiment by Brinkman *et al.* [56]. Brinkman *et al*. investigated the performance of a peg transfer task in a crossover study comparing a standard laparoscopic box trainer (lap box) with a Lap Mentor (Simbionix USA Corp, Cleveland, OH). The Lap Mentor employs software and a microbot to create force feedback when interacting with tissues, thus improving the tactile experience [57]. The investigators found that although performances in the box trainer and the VR simulator were correlated, participants who began training with the VR simulator required significantly more time to complete the task [56].

There has been previous validation of skill transfer from VR simulators that do not incorporate haptic feedback to the operating room [10], yet there is still significant controversy regarding where haptics should be emphasized during surgical training to hasten skill acquisition [54]. This concept was investigated by Panait *et al*. In their study, 10 medical students (laparoscopic novices) performed a peg transfer and cutting task in the Laparoscopy VR (Immersion Medical, Gaithersburg, MD) both with and without haptic feedback. When force feedback was available, the participants demonstrated improved performance in a cutting task, yet no statistical significance was found in the performance of a peg transfer task [54]. Similarly, Perrenot *et al*. validated the dV-Trainer (MIMIC Technologies, Seattle, WA), a virtual 3D haptic platform, as an assessment tool in robotic surgery. In this study, distance path and total time were significant criteria, with a high reliability scoring ($r = 0.851$), and five clearly differentiated levels of dexterity ($p = 0.822$)[58].

Another important contribution was made by Chmarra *et al.*, in which residents completed three separate laparoscopic tasks, each requiring different levels of force application in both a conventional box trainer and a VR trainer. The authors found that in tasks where force application was essential, trainees completing the task with non-attenuated haptic feedback performed better [59]. This crossover study also demonstrated that those who trained with the VR model prior to completing a task using a box trainer did not perform as well, suggesting that haptic feedback only has a significant advantage when introduced early in the motor skill acquisition process. Conversely, this effect may have been exacerbated by poor haptic rendering.

Cao *et al*. explored the effect of haptic feedback on experience and cognitive load, the latter of which is the relative amount of mental attention required by a given task. In this experiment, the cognitive load was measured by comparing the performance of a primary task in addition to a less demanding secondary task [60]. Participants were asked to perform mental arithmetic while completing a "TransferPlace" task using the MIST VR (without haptic feedback) versus the ProMIS (with haptic feedback). Not only did the haptic feedback cohort improve performance (36% faster, 97% more precise) but these participants demonstrated reduced cognitive load [60]. One compelling finding was that the performance improvement was greatest for experienced surgeons in the no-cognitive-load subgroup, implying that experts use spare cognitive capacity to focus on indirect haptic cues [60]. These results are congruent with those obtained by Botden *et al.*, in which 90 participants, 30 for each level of expertise (expert, intermediate, and novice), completed a suturing task and a basic skill task in both a ProMIS AR (Haptica, Dublin, Ireland) and the LapSim VR. Those aided by haptic feedback outperformed the haptic-deficient cohort in all tasks [61].

Zhou *et al*. studied the effect of haptic feedback on the learning curve of novices while performing laparoscopic suturing and knot-tying tasks in a haptic-equipped simulator, the ProMIS, or alternatively in the MIST-VR without feedback [62]. The investigators found that complex tasks were learned more efficiently when haptic feedback was available during the early phases of surgical training. The participants were able to reach the first performance plateau more quickly and experienced the greatest benefit when learning suturing compared to knot-tying alone. One limitation of this study is that post-training evaluation was not completed; thus, the effects of haptics on skill retention and transfer to the operating room were not evaluated [62]. However, similar to previous investigations, this study again identified the early phases of surgical skill acquisition as the key point in time for emphasizing haptic cues.

Other contemporary studies have illustrated an improvement in precision and accuracy with force skill training in simulated environments [41], as well as no negative effects on task time [63]. An example of this is the work developed by Chellali *et al.* with the Virtual Basic Laparoscopic Skill Trainer (VBLaST) (Rensselaer Polytechnic Institute, Troy, NY). In this study, 30 subjects performed the peg transfer task on both the VBLaST and FLS trainers, and their results were compared. The participants performed better on the VBLaST than on the FLS ($p < 0.05$), but levels of expertise were not discernible[64]. Since experts performed well only on the FLS trainer, the authors surmised that this phenomenon was perhaps due to the novelty of the technology.

Trejos *et al*. developed a force-position metric of performance which demonstrated an ability to discriminate between six levels of experience during a complex procedure consisting of five tasks. The procedure was composed of palpation, cutting, tissue-handling, suturing, and knot-tying tasks. The force-based metrics are more clearly associated with skill and expertise than position-based metrics or task completion time ($p < 0.05$)[65]. This study offers an innovative method using force-based metrics as an avenue for skill training and an outcome measure for surgical procedures.

Finally, the effect of haptics on the user has been examined with qualitative measurements. The qualitative measurements applied are subjective ratings of mental workload assessment of performance, such as the National Aeronautics and Space Administration Task Load Index (NASA-TXL) [66]. These subjective measurements are very limited and can only offer a conceptual framework in which to base future designs [66].

In summary, despite plenty of advancement in haptic technology to replicate the feeling for both force and tissue sensation, there is still room for innovation. Further studies are needed in the area of the quality of haptic feeling being rendered in surgery. From an experts and novices point of view, learning how haptic knowledge is implicitly acquired during training, what is the type of skill that is learned, and how it is attained will be of great benefit to expedite skill learning.

2.1.3 Previous research of motor skill training using haptic feedback

Finally, there are other areas in which haptic feedback has been used to teach motor skills. For one, haptic guidance emphasizing position control has been suggested as the first stimulus needed in the course of motor learning [67]. Although position control did not show any learning advantage in training in novices, it is thought to be beneficial specifically in individuals whose perception of position has been altered, such as patients with stroke. This points at rehabilitation as the optimal environment for this type of motor training; current studies explore the benefit of robot-assisted therapy [67].

Haptic guidance is successful teaching simple motor tasks, however, few studies have looked into the effect of haptic training using guidance in complex motor tasks. Haptic feedback in complex tasks has shown to reduce the user's perceived workload and increase cooperation and mindfulness [67]. A few instances of complex motor tasks in which haptic feedback has been applied successfully are: learning of a steering task, wheelchair driving, and piano playing[67]. Both steering task and wheelchair driving through a maze were performed faster and more precisely with haptic guidance, however, performers in both experiments became dependent on the guidance if kept constant[67]. In a similar manner, the piano playing experiments have demonstrated the benefit of haptic guidance on retention tests for motor-auditory short-term tasks[67].

In the absence of reliable haptic cues, the main compensation mechanism utilized by surgical experts is visual-haptics. Salkini *et al.* addressed the issue of *visual haptics* in VR simulator originally quoted by Lamata[51, 57]. Their premise explained that the lack of significant increase in performance with haptic feedback was given by a "visual" sense of density and texture (visual-haptics) associated with surgical experience; and also why novices learning robotics may not necessarily miss it once accustomed to not have it during surgery[57].

2.2 Conclusion

Even though novel investigations incorporate haptic feedback in surgery, new research must be directed toward decoding the ways in which haptic training in surgical education may help make patients safer and decrease training times for new surgical techniques in our new duty-restricted work-hour era. This might involve deciphering the effect of haptic guidance on motor skill acquisition at a more detailed level as well as evaluating the effect of haptic feedback on skill retention mechanisms for skill transfer to the operating room. Parallel to these developments, future studies will need to focus on enhancing and standardizing tissue sensation through force feedback in surgical training as well as qualitative studies.

Finally, elucidating haptic feedback on motor skill learning at different stages of skill acquisition will aid in the development of customized curricula where haptic feedback might be used to provide tailored guidance to each individual based on his or her level of training.

CHAPTER 3 FORCE ADJUSTMENT OF AN INCISION TASK: EFFECTS OF DECREASED TACTILE SENSATION ON PERFORMANCE

3.1 Introduction

In this chapter, I am presenting a study on the effect of decreasing tactile sensation during a surgical incision task. In surgery, making an incision on the patient's body is completed with a surgical scalpel. When performing this basic task, a surgeon needs to control the scalpel to make a precise amount of force from the surgeon's hands to the tip of the scalpel. However, a light force delivery may not be sufficient to incise the skin. On the other hand, a strong force application may create a deep incision which can damage internal organs beneath, causing internal breeding, bowel perforation, and other unwanted consequences. Therefore, precise force control is a critical skill young surgeons need to learn before entering the operating room[23].

Applying appropriate force during the incision of a procedure is not just about the interaction between the hands and the scalpel, this interaction also requires the surgeon's own knowledge about the anatomy and tissue behaviors around the incision. The total force applied to the tip of the scalpel is the surgeons' end output after taking all these aforementioned factors into consideration to make a final judgment based on their past experience [40, 68]. Considering this, we decided to study how surgeons precisely regulate their force output based on their judgment on different tissues while making an incision. We predict that, when making an incision over the site with a vessel beneath it, a surgeon will generate different forces to the scalpel compared to making an identical incision over a site without such a dedicate anatomy structure below. There is no question that a senior surgeon can take the incision's site anatomy into consideration during the procedure, but we are uncertain whether a novice trainee can also precisely make a force adjustment according to different anatomies. This is the first research question we aim to answer in this project.

Precision force adjustment of a human operator's hand requires intense involvement of subcutaneous sensors beneath the skin of the hands. However, when surgeons perform an incision in the operating room, surgeons are required to wear surgical gloves to create a sterile condition; sometimes, double gloves are worn to protect against the two-way transmission of blood-borne pathogens between patients and surgeons [69]. Unfortunately, double-gloving can create an uneven pressure on the hands that can disturb the natural perception of tactile sensation [70]. Therefore, several researchers have examined the effects of gloves on hand dexterity and tactile sensitivity [71, 72]. There is a chance that double-gloving can affect hand dexterity and tactile sensitivity [22, 73]. The second objective of this study is to examine whether the precise force adjustment in making a skin incision will be affected by wearing gloves.

In this controlled laboratory study employing simulation, we measured force and task outcomes while participants (trainees) perform incisions on the same surgical site but with two different types of tissues underneath, one with an elastic band that simulates a vessel and the other without it. This task was repeated by asking the participants to wear double gloves and compared to wearing single gloves or no gloves at all. It was our hypothesis that different force profiles will be recorded between incisions with and without the simulated vessel underneath since the ability to offer force control over different tissue types will decrease and as the number of gloves increases the surgical task performance will decrease.

3.2 Methods

3.2.1 Participants

Twenty university students without surgical experience at the University of Alberta in Edmonton, Alberta were recruited for this study. Exclusion criteria included any individual with a history of musculoskeletal problems. The University of Alberta Health Ethics Review Board approved the study's purpose and objectives. Information and objectives were explained to the participants prior to them giving consent.

Task

The experiment was conducted at the Surgical Simulation Research Lab (SSRL) at the University of Alberta. Participants were asked to make 2.2cm long incisions through two layers of custom-made synthetic tissue (Michaels Inc., Irving TX. Figure 3-1). Each cutting was performed under two incision scenarios. The first scenario was identical to the trial period where each participant made a 2.2cm long incision with constant force through the two layers of synthetic tissue. The second scenario had an elastic band (Staples the Office Superstore, Framingham MA), which resembled a vessel, underneath the synthetic tissue.

In the second scenario the participant had to use haptic feedback (tactile) to determine how much force they should apply to cut through the two layers of synthetic tissue without severing or damaging the elastic. The elastic was completely covered to ensure the participants solely used haptic feedback rather than visual feedback to determine the location of it. This elastic band scenario was implemented so that the participants did not apply an unneeded amount of force for each incision through the synthetic tissue, simulating a more realistic surgical task.

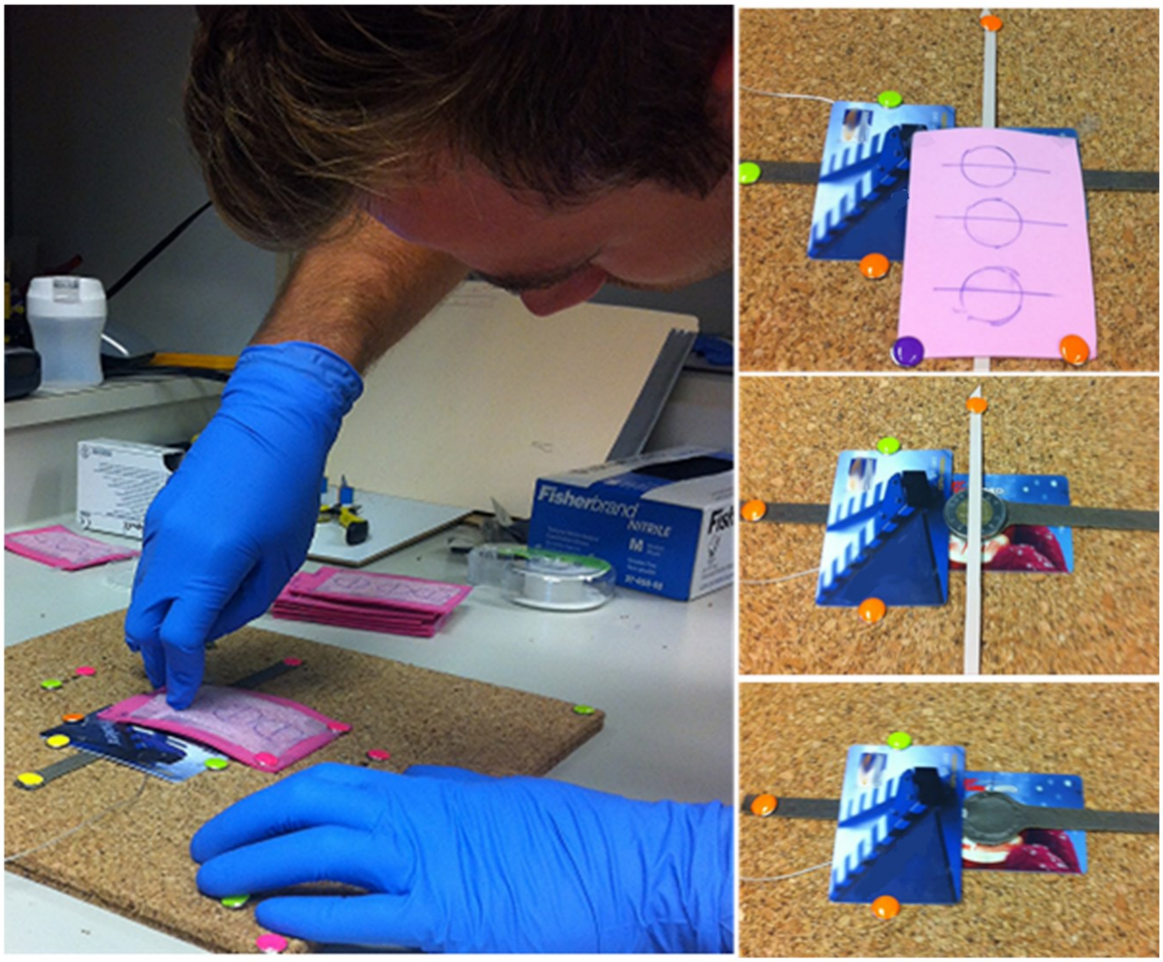

Figure 3-1. Simulation scenarios on incision task.

Incision is performed on a piece of pink synthetic tissue (right, upper panel). Beneath the synthetic tissue is a force sensor which record force applied to the tissue (right middle panel). The force sensor is protected by a coin. In the condition with increase task requirement, a rubber band is placed on top of the coin (right, lower panel).

Before beginning the experiment the participants were shown a proper technique for a scalpel, this technique included a 90° entry position, 45° cutting movement, and a 90° exit position. After the demonstration, a trial period occurred, where each participant made three incisions to practice grasping the scalpel and feeling the depth and texture of the synthetic tissue.

When starting the cutting tasks, each subject needed to repeat three trials in two scenarios while wearing no gloves, one pair of gloves (*Fischerbrand Nitrile* gloves, Fischer Scientific, Ottawa ON), and two pairs of gloves. The starting glove condition was counterbalanced for each participant and all participants. Each individual was able to choose his or her preferred glove size (small, medium, or large) and depending on the participant's comfort they were allowed to mix and match glove sizes during the double glove condition. The procedures were standardized for each individual and each participant was read a set of instructions.

3.2.2 Force Profiles

The *FingerTPS* (Pressure Profile Systems, Inc., Los Angeles, CA) sensor system was used to measure the force application and it was calibrated before each participant to ensure the data was being collected in a standardized manner. For each incision the force profile was created by MATLAB (Figure 3-2, force profile).

The starting of the trial was defined by the moment when the force exceed 0.2 N and ending at the moment when the force dropped to 0.0 N. On each profile, we report the peak force, time to peak force, and the total area of force. Considering different subjects had different force application strategies, we calculated area of force profile to estimated total force given by a participant during entire cutting task. Dividing the area by the total time it took to make the incision, which was determined through *MATLAB* (Mathworks, Palo Alto, CA.)

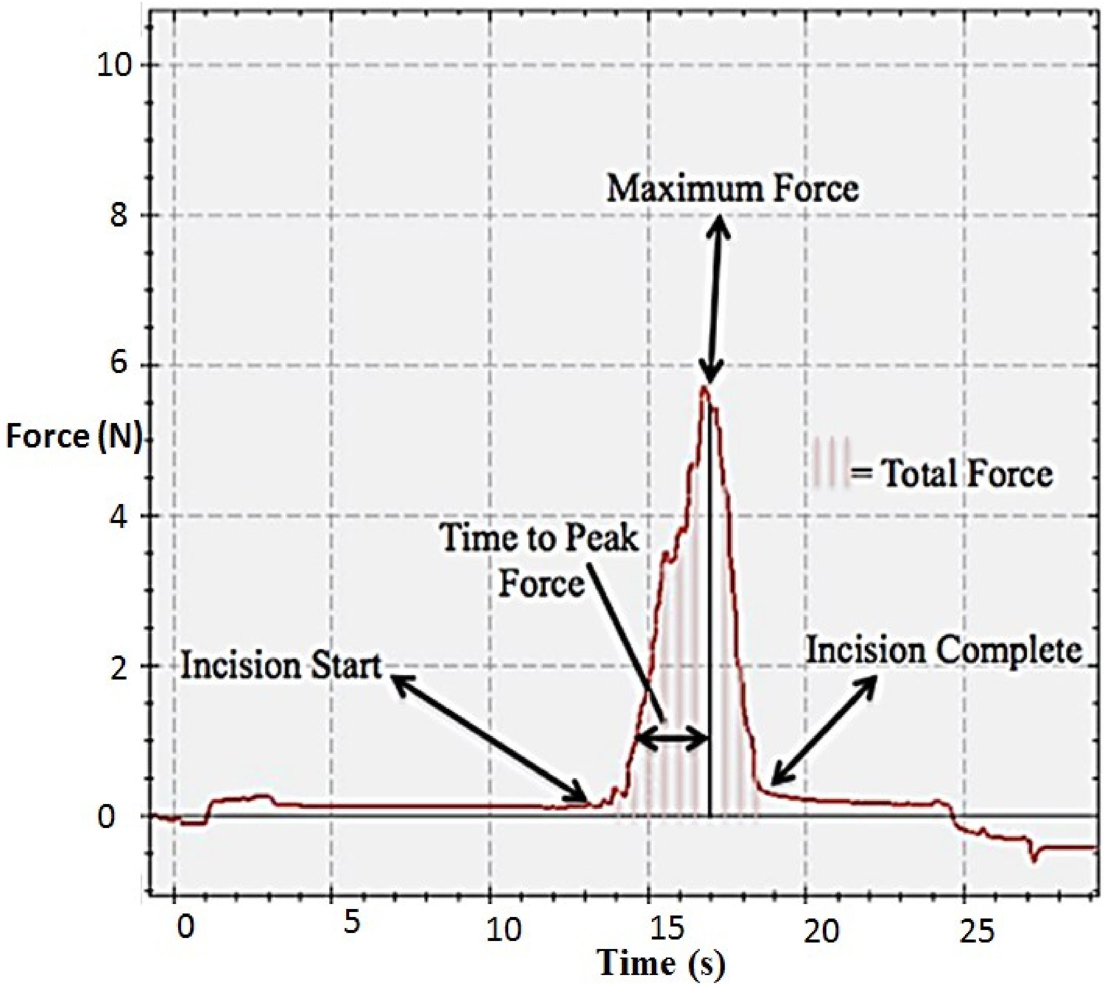

Figure 3-2. A typical force profile for an incision task.

3.2.3 Incision Performance

Surgical task performance was defined as the score each participant received for every incision made. Each time the participant damaged or severed the elastic band they received a score of zero. On the other hand, if the participant did not apply enough force to make at least a 1cm long incision through the two layers of synthetic tissue they received a score of two. If the participant created an incision of 1cm or greater, along with no damage to the elastic band (if present) they received a score of one, which was considered a perfect score.

3.2.4 Statistical Analysis

Variables on force profiles (peak force, time to peak force, and total force) and incision performance score were analyzed applying the *SPSS 22.0* (Chicago, IL) using a 2 (incision condition: without and with elastic band underneath) X 3 (glove condition: wearing no gloves, one pair of gloves, and two pairs of gloves) within-subject ANOVA; $p < 0.05$ was considered statistically significant in this study. Post-hoc analysis was also completed (*Bonferroni*) when needed.

3.3 Results

Of the 20 participants, 11 were male. The mean age was 24.1 years of age and the range was 19-38 years of age. There were 3 individuals that were left-handed and 17 that were right handed. Participants were randomly assigned to one of three different starting glove condition, therefore seven began with no gloves, six with one pair, and the last six began with two pairs of gloves. Each glove condition had two scenarios: cutting with an elastic band under the synthetic tissue and cutting the synthetic tissue with no elastic band. The order of elastic band presentation was counterbalanced (random) between subjects.

Table 3-1: Effect of task requirement on force profiles and task performance

	No-Elastic	**Elastic**	***p*-value**	**Effect Size**
Total Time	7.0 ± 2.1	8.9 ± 2.8	<0.001	0.56
Score	1.3 ± 0.3	1.4 ± 0.5	0.111	0.14
Max. Force	3.1 ± 1.6	2.4 ± 1.0	<0.001	0.60
Time to Max. Force	2.8 ± 1.1	3.9 ± 1.8	<0.001	0.58
Total Force	10.3 ± 4.2	10.3 ± 5.1	0.876	0.10

As shown in Table 3-1, the presence of an elastic band underneath the synthetic tissue had a significant effect on the task time ($p < 0.001$), the peak force ($p < 0.001$), and time to peak force ($p < 0.001$). Subjects decreased their maximum force application when a simulated vessel was present, and increased the task time to perform in a more careful way.

As shown in Table 3-2, wearing gloves did not significantly affect the force profiles of the subjects' cutting performance. However, it seemed that subjects tended to prolong the task performance time by cautiously generating the cutting force when wearing the double gloves.

Table 3-2: Effect of gloves on force profiles and task performance

	0 Gloves	**1 Glove**	**2 Gloves**	***p*-value**	**Effect Size**
Total Time (s)	7.7 ± 2.6	8.1 ± 2.4	8.2 ± 2.9	0.285	0.07
Score	1.4 ± 0.4	1.4 ± 0.5	1.4 ± 0.4	0.808	0.12
Max. Force (N)	2.8 ± 1.5	2.8 ± 1.4	2.7 ± 1.3	0.724	0.16
Time to Max. Force (s)	3.3 ± 1.7	3.3 ± 1.4	3.4 ± 1.6	0.818	0.06
Total Force (N)	9.7 ± 4.1	10.5 ± 4.7	10.7 ± 5.0	0.145	0.11

Lastly, there was an interaction between gloves and elastic for task time ($p = 0.048$) that is depicted in Figure 3-3. Specifically, cutting tissue with presence of an elastic band increased the task time compared to without elastic band. The prolonged task time was more prominent when subjects were wearing two gloves. There was no interaction between gloves and the elastic band for any of the other variables (maximum force, time to maximum force, total force, and performance score)

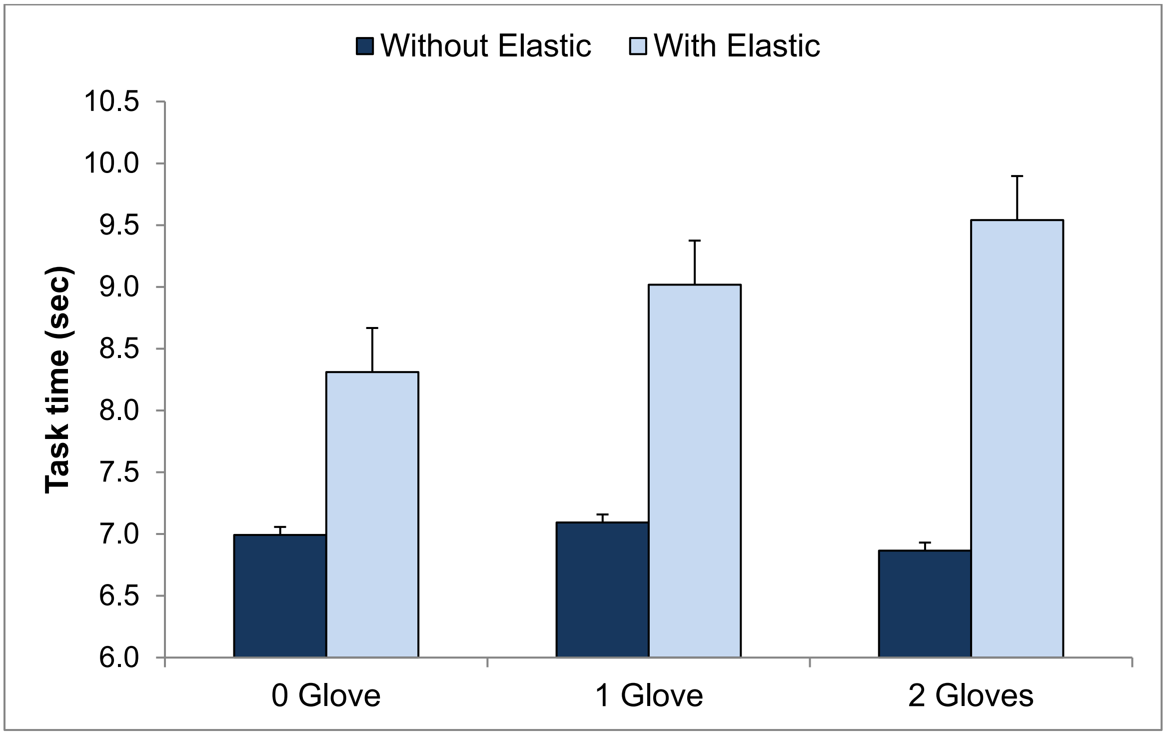

Figure 3-3. Interaction between gloving and elastic conditions.

Measure of force application time.

3.4 Discussion

Our first research hypothesis was supported by our results. Participants adjusted their force output delicately between incisions of two different tissues. With the simulated vessel under the synthetic tissue (increasing the task requirement), participants tended to decrease their maximal force application, as well as use longer task time and time to force peak (Table 3-2). By prolonging the task time participants were able to better control force application when sensory feedback was hindered while wearing gloves.

Wearing gloves did not significantly affect any of the force profiles or the surgical task performance of any of the performers (Table 3-2). It was interesting to note that wearing gloves slightly increased task time but decreased force application. This means, when the gloves blocked direct sensory inputs, participants tended to apply smaller amounts of force. This could be due to a safety concern of applying too much force due a decrease in sensory input with glove donning.

The presence of an interaction between task requirement and glove donning on the measure of task time provides further evidence on how human operators respond to the increased task workload. While making incisions with a higher level of safety requirements, participants needed more time to process sensory feedback. In the cases where sensory feedback was hindered by wearing a double pair of gloves, time increments became more significant (Figure 3-3). Several participants stated that they were worried about applying too much force that could have resulted in severing the 'artery' and therefore they decreased their force application, which was seen in our results. When wearing the two-pair of gloves, trainees hesitated considerably when apply the force to the simulated vessel below.

In brief, participants demonstrated a certain level of dexterity to control the incision force while interacting with simulated tissue with a higher level of safety concern. Since the task scores were maintained equally between the two simulated vessel conditions, we believe that the "safety first" strategy was implemented and necessary. Results gained from this study have implications for surgical education. Sufficient practice need to provide to our trainees when they start to learn surgical manipulation with tools in hands and when the hands wearing the gloves. They need time to control extra degrees of freedoms introduced by the tools, and adopt for the twisted tactile feedback received from the hands wearing the gloves. We believe that such a training should perform in the simulation setting without involving patients.

There were a few limitations in this study. First we did not design the study to examine the performance of expert surgeons. The results described in this paper are the behaviors of the general population. Thus, results do not necessarily describe the patterns of surgeons during their training. We will further extend this project to different levels of surgical training, to get a deeper insight into the learning behaviors of surgeons during the process of gaining dexterity. Secondly, the sample size was relatively small; our partial eta value was around 0.1- 0.6, which was sufficient, but not powerful. Lastly, in a future study, we plan to design a skill learning study and examine a surgical resident's learning curve on force control of more complex surgical procedures.

To further study the role of tactile feedback on surgical performance, we need to be clear that the hand is not just an important motion output device of a human operator, but also a sensory intake organ. When those sensory inputs are blocked by gloves and by holding a surgical tool, special training is needed for the surgeons to get used to the indirect and remote manipulation condition [23]. Although the results in this project did not find wearing gloves to have a significant effect on the surgical dexterity congruent with clinical procedures [74], subjects still believe that double gloving can negatively impact surgical performance [22, 73]. To ensure patient safety, we believe a certain amount of training time is required to help surgeons regain control of their hands' sensory feedback from the manipulation with gloves and surgical tools. To further our understanding of subjective tactile changes during surgical tasks, a haptic performance metric can be developed to assess the quality of force performed by participants with distinct levels of surgical experience[75].

3.5 Conclusion

The results in this study provided evidence that increasing task requirement (by adding a simulated vessel underneath the wound) had a significant effect on force application. These results may have occurred due to participants being wary of the safety of the patient while making a cutting task. The precise force regulation was not directly affected by wearing surgical gloves, however, subjects needed longer time to process tactile feedback and adjust it for task performance. Nevertheless, interpretations of these results are limited as the surgical tasks were performed by non-surgeon participants. Therefore, future research should incorporate surgeons on more complex surgical procedures (e.g. intraoperative knot tying) to determine if the results would be generalized to different levels of surgical training.

CHAPTER 4 GUIDING KINESTHETIC MEMORY FOR SKILL TRAINING: SKILL LEARNING FROM KINESTHETIC FEEDBACK

4.1 Introduction

In the next two chapters, we are focusing more on the role of proprioceptive pathways in building motor skills. I start here by examining kinesthetic memory before presenting outcomes from haptic training.

Motor tasks demand a haptic memory system with a matching mental model [76]. Kinesthetic memory is the ability to memorize and recall which of one's movements and body part positions are necessary to perform a task. Continuously practicing a motion makes it more automatic, thus creating "muscle memory" [77]. Hand dexterity requires a high level of integration between motion execution and sensory perception. In surgery, skillful performance is constantly regulated by movement schema saved to memory and instantly adjusted via sensory feedback loops, mainly via visual and kinesthetic pathways [78]. Ernst and Banks[20] demonstrated how humans learn skillful movement through vision and kinesthetic feedback loops, either separately or by integrating vision and feedback loops over time. Individuals benefit most from visual feedback, but learning can be enhanced further when simultaneous feedback from visual and kinesthetic sensory systems is combined [20].

Guided kinesthetic training allows a trainee to attempt to reproduce the movement patterns of an expert[9]. For surgical skill training, the major advantage of kinesthetic training over vision is that the former is body-centered. Feygin *et al*.[9] compared three types of guidance training: visual, kinesthetic, and a combination of the two. Kinesthetic guidance was the most efficient type of training because subjects completed the task more quickly. However, kinesthetic guidance was less efficient than visual training in helping subjects to determine position and shape [9]. Kinesthetic guidance relies on mostly kinesthetic (force) feedback that a subject obtains from interacting with a 3-D system replicating a motion with and without the aid of visual feedback [9, 79]. Additionally, kinesthetic guidance aims to decrease the amount of mistakes during motor performance, especially during high risk and time-dependent tasks; as well as illustrate a specific sequence of movements while offering a novice feedback on the accurate motion [80]. Nevertheless, kinesthetic guidance is considered a great tool for motor skills training; although, there is conflicting evidence on the type of task for which it is useful and on the extent of the benefits offered by this paradigm under different conditions [79].

In addition, kinesthetic guidance shows greater advantage during dynamic motions, which in turn proposes a weak relationship with visual information [79, 81]. Greater benefits may arise from emphasizing externally induced kinesthetic feedback (augmented feedback) on tasks to improve skill retention given the benefits received from dynamic motions [81]. Augmented feedback may be classified as Knowledge of Results (KR) and Knowledge of Performance (KP), in which the former refers to the feedback on the outcome [81]. In fact, most of the studies until now have demonstrated the benefit of kinesthetic guidance using KR, since end-result information is easier to obtain in the research environment. However, the majority have been regarding short-term outcomes, but none on the long-term learning. Moreover, several of these models work by giving augmented feedback during a task, as long as the participant does not become guidance-dependent for task completion [81].

One special benefit of guided kinesthetic training offers the novice direct information on the position of body parts, improving kinesthetic memory by decreasing the number of errors while completing a task [76]. Kinesthetic memory obtained through motor guidance training helps a person to actively learn complex 3D motor skills such as surgical maneuvers by directly performing a movement [82]. For instance, a cholecystectomy procedure is a complex task that can be broken down into smaller simpler surgical tasks, maneuvers and gestures to be remembered easier in the OR and when offering focused feedback to trainees [83]. Continuously practicing a motion makes it more automatic, thus creating "muscle memory[77]." Moreover, this guided kinesthetic training offers the novice direct information on the position of body parts, improving kinesthetic memory by decreasing the number of errors while completing a task [76]. In this manner, surgical trainees may increase confidence and task performance by tapping into their muscle memory and not utilize vision alone during training[84].

Guided kinesthetic training reduces movement errors that may be common during early skill acquisition. Hand dexterity requires a high level of integration between motion execution and sensory perception. In surgery, skillful performance is constantly regulated by movement schema saved to memory and instantly adjusted via sensory feedback loops, mainly via visual and kinesthetic pathways. If applied during the motor learning acquisition stages, kinesthetic training has been associated with decreased performance errors and more effective learning [78]. Although numerous studies have examined the effect of guided kinesthetic training in skill acquisition, none have explored the behavior of kinesthetic memory [76, 85].

The purpose of this study is two-fold. First, we examined the natural ability of human operators to store movement information in their muscle memory through the kinesthetic feedback loop. Second, we intend to investigate the effectiveness of learning a motor skill purely from kinesthetic feedback. Specifically in Phase 1, we asked a group of participants to perceive movement through a master-slave delivery system through kinesthetic feedback. When the complexity of the task raised with incrementing number of movement steps, we analyzed the accuracy of kinesthetic memory, i.e., the participants' ability to duplicate the movement. In a following Phase 2 of the study, participants were required to perform the same task over 9 trials. We explored the learning process of the participants in performing the movement acquired purely from kinesthetic feedback. We hypothesized that: a) increasing complexity of a movement pattern will challenge the human capacity to store in the kinesthetic memory (i.e., accuracy recall will significantly drop to a certain degree when movement complexity increases); b) repeated practice will facilitate skill learning as human operators will develop strategies to optimize memory information storage with practice.

4.2 Methods

4.2.1 Participants

The controlled laboratory study was performed in the Surgical Simulation Research Lab at the University of Alberta. Twenty volunteers (n = 20; 45% female; 95% right-handed; age range: 18–39 years old, median age = 26 years) participated in the experiment. Any individual with a history of musculoskeletal problems was excluded and the participants had no previous exposure to surgical training. Written ethical approval for this research study was provided by the University of Alberta's Health Research Ethics Board – Biomedical panel (study ID: Pro00052894). Information and objectives were explained to the participants prior to asking for consent.

4.2.2 Protocol

Task and Procedure

On the first day of the study, each participant perceived the movement of the five pre-determined patterns via kinesthetic feedback in the master-slave system (Figure 4-1 and 4-2). The order in which the patterns were presented to the subjects was counterbalanced, that is, each participant replicated the movement pattern in a different order. All the patterns were repeated six times and at the end of each movement, the participants duplicated the movement on a piece of plain paper with a pen. The accuracy of the participant's kinesthetic memory was assessed by comparing the outcome recorded on the paper (illustration) to the trainer's patterns. In this way, each movement of the pattern is represented on the paper in the form of a line and each was participant was his or her own control.

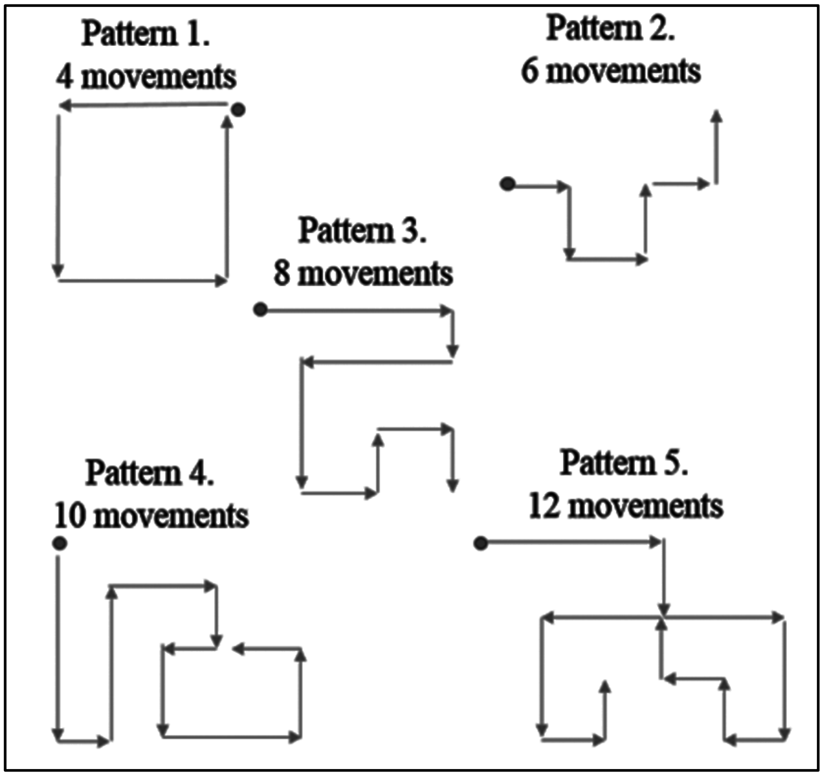

Figure 4-1. The five movement patterns of this experiment.

The arrows show the direction of the movement (lines), and the dot indicates the starting point of the movement pattern.

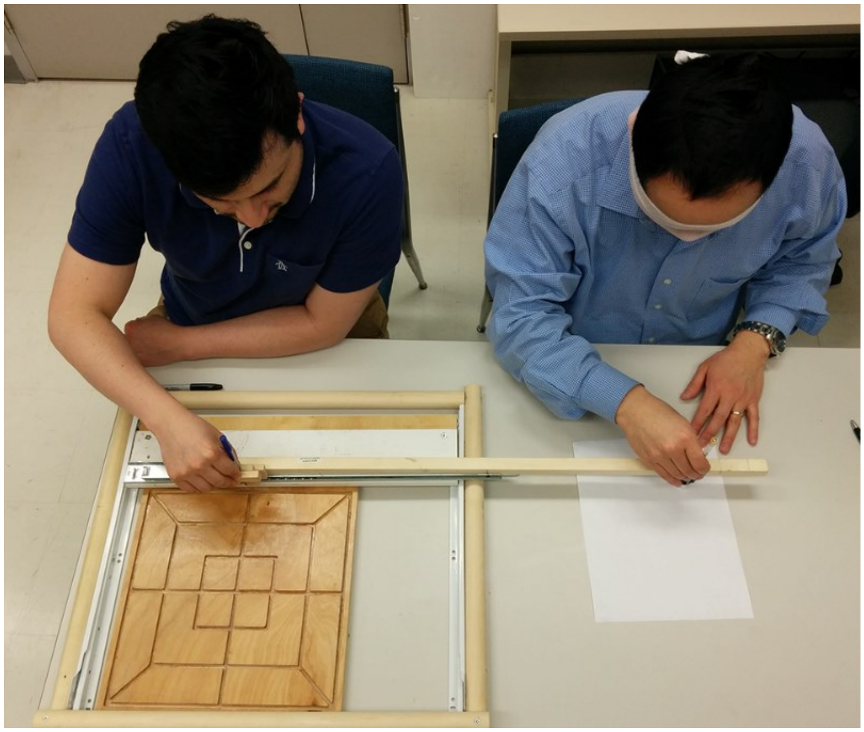

Figure 4-2. Experimental setup: The kinesthetic guidance device shares the kinesthetic information between the master and the trainee.

Note that the trainee's vision is blocked. The participants (right) experienced the movement of the trainer (left) by grasping the guide.

Five participants (n = 5), selected at random, were called back to repeat the performance for a total of nine trials. All nine practice trials were arranged over a period of three weeks, three times per week. During the entire phase of the experiment, participants did not receive any visual feedback nor auditory instruction on their performance. Sample size selected for this experiment is congruent with previous experiments on motor skill learning. No control group was employed for the two parts of the experiment since the participants were their own control.

Measures

Time of task completion is a typical performance measure. Since we recorded the time that every participant took to reproduce every pattern, we could analyze the time relationship with the number of lines in each pattern. However, performance measurement can also be complemented by analyzing the number of errors for each participant in each movement pattern.

Movement duplication accuracy was assessed by recording the number of errors in direction and length recall for each of the lines in the illustrations. Each movement pattern had the possibility of being comprised of movement in eight directions (N, S, E, W, NE, NW, SE, SW) and three different line lengths (short: 5 cm, medium: 10 cm, and long: 15 cm). Errors could occur when attempting to duplicate the movement's direction and length.

4.2.3 Data collection

Since the patterns were hand-crafted, they were scanned, digitized, and then analyzed in MATLAB (Mathworks, Palo Alto, CA.). To determine the accuracy in duplicating movement direction, the angle of each line stroke was compared to the master pattern. If the angle fell within a 30 degrees range to the master direction, a correct matching was recorded.

It was challenging to attempt to measure the length accuracy of the lines drawn. Although participants had knowledge that each line could only be one of three measurements (short: 5 cm, medium: 10 cm, and long: 15 cm), when duplicating the pattern on a piece of paper, they did not make an effort to draw the lines with any extra length. However, we noticed that the participants all tried to make the lines as close to the three different lengths as possible. To detect the accuracy in length duplication, we created a special algorithm by using the longest line recorded on the each pattern as the trial-specific ruler. Specifically, the length of the longest line in each duplicated pattern was detected and measured. The short line should be proportionally equal to one third of the longest line while the middle line equals to two thirds of it. If the line drawn fell within ± 25% range of the calculated line length, an accurate match was recorded; otherwise, a mismatch error in the line length was recorded. As an example, in duplicating a movement in Pattern 3 (which includes one long line of 15 cm, five short lines of 5 cm, and two middle lines of 10 cm), a subject made a longest line of 12 cm. When the subject made a short line that fell within ± 25% range of 4 cm (i.e., 3 ~ 5 cm) we recorded an accuracy match; outside this range, an error was recorded.

For each trial, the overall error of duplicating the movement from the master pattern was calculated by adding the movement errors in direction and length.

4.2.4 Data analysis

MATLAB was utilized to compute a part of the data analysis. Three features were relevant for the comparison measurements: length of the lines, direction of the lines, and coordinates of the pixels in the pattern. These features required the decomposition of the patterns at two levels—line-wise and pixel-wise. At the line-wise level, the length (in pixels) and direction (N, S, E, W, NE, NW, SE, SW) of every line were computed. On a pixel-wise level, taking the start point of a pattern as the origin in a Cartesian coordinate system, the coordinates of every pixel in the pattern were extracted.

To account for the probability of making errors increase with the number of lines in the pattern, we normalized the total number of errors over the number of lines. The error vector would have different entries because all the patterns have at least four lines, but only four patterns have lines five and six, three patterns have lines seven and eight, and so forth. As in the previous case, one can normalize the error vector by the total number of lines that were created.

4.2.5 *Statistical analysis*

Task times and accuracy variables in duplicating the movement through kinesthetic feedback were compared over 5 different movement patterns using a one-way between-subject ANOVA (SPSS 22.0, Chicago, IL). A 5 (movement pattern) x 9 (training session) between-subject ANOVA was employed to examine the learning process of training purely from kinesthetic feedback. Mean and Standard Deviation (SD) are presented. $p < 0.05$ was considered statistically significant in this study. Post-hoc analysis was also completed (*Bonferroni*) when needed.

4.3 Results

4.3.1 *Duplication performance on the first day*

When asked to duplicate a pattern with 4 movements, the 20 subjects did not make any mistakes. All the participants (100%) accurately recalled the movement pattern from their kinesthetic memory. However, recall accuracy decreased as the movement complexity increased (pattern 2 with 6 movements: 90%; pattern 3 with 8 movements: 70%; pattern 4 with 10 movements: 80%; pattern 5 with 12 movements: 60%).

To analyze the data, the number of errors for both direction and length were normalized over the total number of movements performed for each pattern for the first trial. As the complexity of the movement patterns incremented, the duplication errors increased significantly ($p_{\text{direction}} = 0.038$; $p_{\text{line length}} < 0.001$; $p_{\text{sum errors}} < 0.001$). As displayed in Figure 4-3, errors constantly incremented until duplicating pattern 3 with 8 movement, then showed a reduction in pattern 4, followed by an increase in pattern 5 with 12 movements.

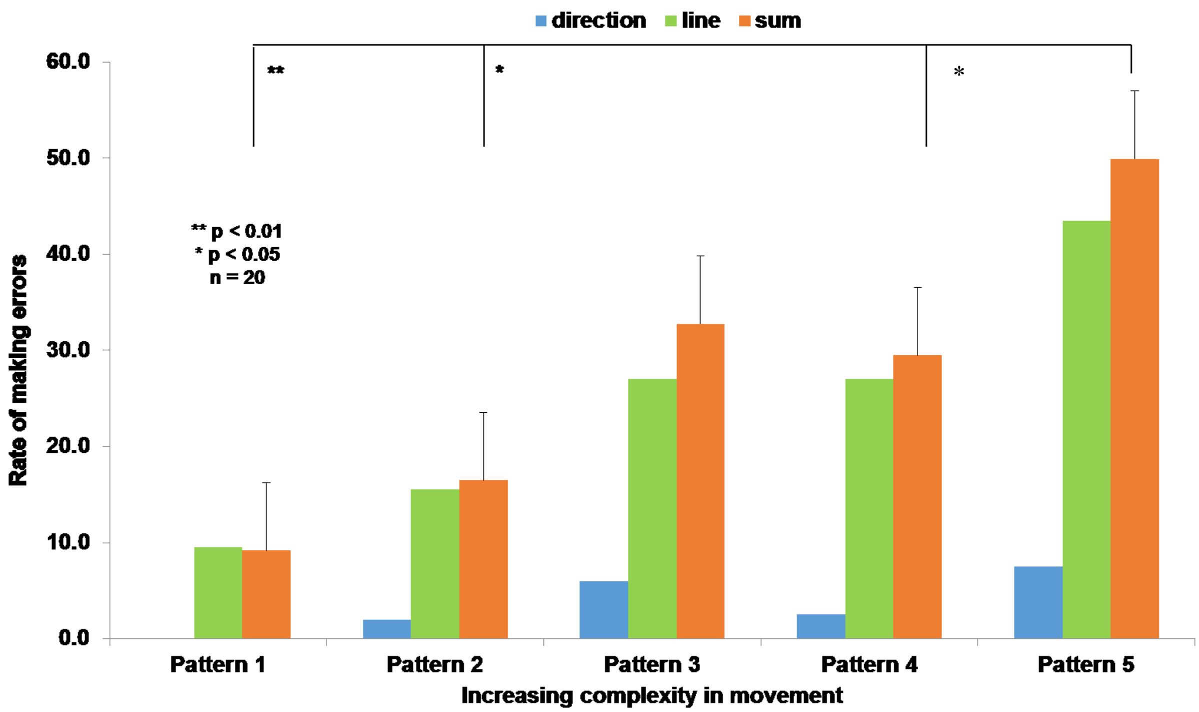

Figure 4-3. Duplication accuracy for the first training session.

Each bar represents the average rate of errors in direction and length on the performance of all subject during the first day.

4.3.2 Duplication performance over the 9 sessions

A 5 x 9 ANOVA analysis between subjects was conducted to determine whether or not the sum of errors in both direction and length decreased over the collective of the nine sessions. Results showed that as guided kinesthetic training continues, the sum of errors decreased ($p <$ 0.001). The error drop varied to different degrees among the five movement patterns ($p < 0.001$) compared over the nine sessions. As shown in Figure 4-4, for training Pattern 5 with the highest level of complexity, errors decreased from 74% to 7% from the first to the last sessions. In contrast, for training Pattern 1, errors dropped from 35% to 0%. Moreover, there was a significant effect of kinesthetic guided training on direction and length remembered at the $p <$

0.05 level for the nine sessions ($p < 0.001$). Post-hoc comparisons using the Bonferroni test indicated that the mean score for the error direction (M = 0.160, SD = 0.176) and error length (M = 0.376, SD = 0.139) were significantly different after the guided training (M = 0.004, SD = 0.020) and (M = 0.100, SD = 0.156) respectively. Taken together, these results suggest that kinesthetic guidance training really has an effect on muscle memory. Specifically, our results suggest that when individual performers employ kinesthetic guided training, they remember movement direction and length.

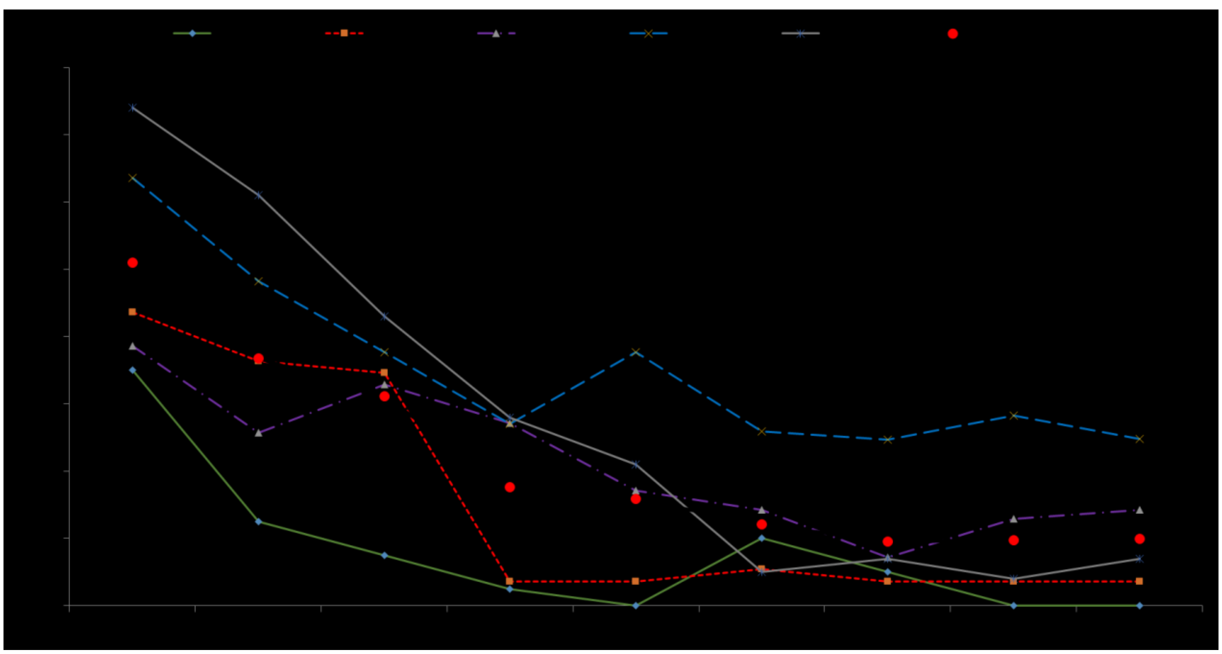

Figure 4-4. Sum of errors rate for each of the movement patterns over the nine training sessions.

Each line represents the sum of the average rate of errors in direction and length on the performance of all subject during the nine sessions.

We also found that the learning curve for each pattern displayed different turning points which became significant in the later sessions of kinesthetic training for complex patterns. It was possible to observe the motor learning effect because of haptics alone after several weeks. Specifically, when training Pattern 1, subjects achieved a significant error reduction in Session 2, but when training Pattern 3, the significant error reduction occurred in Session 4. For all patterns, the error reduction reached to the lowest level in Session 6.

Regarding the efficacy of direction recall, it was easier to identify left and down directions than right and up ($p < 0.05$). After the fifth trial, the left and down directions were remembered in all of the consecutive trials, and the rest of the mistakes in direction were distributed equally between the right and up directions. Unfortunately, remembering lengths was more difficult than direction ($p < 0.05$). Of the three lengths measured, the small length (5 cm) was less difficult to recall than the other two lengths—medium (10 cm) and large (15 cm). Recall of the small length dropped significantly after the sixth trial and only by five times for the medium length. The large length error recall, however, declined after the second trial but remained constant thereafter. There were higher scores for length recall for the first 11 lines. Post-hoc analysis shows significant changes after the fifth trial ($p < 0.05$) for several subjects, especially for the first 10 movements (lines) but with similar difficulty to recall in line 17.

4.4 Discussion

The purpose of this study was to determine the effect of guided kinesthetic training on muscle memory and the building of foundations for skill acquisition. As surgeons are a group of performers that truly depend on kinesthetic feedback, knowledge gained from this project will provide direct benefits by complementing typical visual methods of surgical skills acquisition.

An example of this is teaching knot tying, breaking this task into smaller segments with a kinesthetic guidance can increase the trainees' performance when compared to those employing the typical method [86].

Essentially, our research hypothesis was supported by our results. Results showed that a subject can receive significant information exclusively via kinesthetic feedback and improve the performance of a task. Our findings indicate muscle memory behaves in a similar manner than our declarative memory. All of the 20 subjects were able to recall the kinesthetic information in the same day to optimize their task performance. Direction and length information were perceived and recalled by all participants solely through kinesthetic perception. As shown in Figure 4-3, memory of kinesthetic information (represented by the movement direction and length) reached a saturation point around 8 movements. After the 8 movements, accuracy for duplicating the movements learned from the kinesthetic feedback loop drops significantly. This experiment shows that working memory capacity for kinesthetic information behaves similarly than for visual or language information from other studies [87]. Recent research suggests that the underlying limit for working memory is a single digit around 5; and this limited central working memory capacity may facilitate simultaneous ideas to be associated with each other[87].

We were surprised to see that Pattern 4, comprised of 10 movements, did not follow the expected projection. The error rate only dropped slightly. After revising the movement patterns, we noticed that the last 5 movements of Pattern 4 formed a square. This square in Pattern 4 made it easy to memorize the movements in groups (*chunks*) into a sub-unit. By using this chunking strategy, performers may feel it is easier to replicate more complex patterns, like Pattern 4, with less mental effort than patterns with less movements such as Pattern 3. These are congruent with previously found results regarding short-term memory of kinesthetic enactment [88]. This chunking behavior is similar to the one observed in working memory and it seems to be reflected in kinesthetic memory. In other words, the subjects in this experiment can remember how the movement patterns started and how the patterns ended, but had trouble recalling the intermediate steps. These findings on the nature of muscle memory can be translated for training difficult motor skill tasks like in surgical training. Adding kinesthetic guidance to a surgical training task as groups of chunks can expedite muscle memory and skill acquisition.

Previous work on this area of research have demonstrated that teaching surgical skills delivered in small portions over a long time is more efficient than massed delivery training. In this one particular study, 41 novices underwent training on MIST VR surgical trainer. Participant ho trained in 5 minute blocks performed better than the individuals who did massed delivery training ($p = 0.002$)[89]. This efficiency in training is believed to be associated to a decreased cognitive load when giving small amounts of information per training session. In another prior report on memorizing 2-D maneuvers of an industrial task, 48 participants were divided into 4 groups of training: vision, vision + haptic enactment, vision + haptic guidance, and vision + haptic disturbance. In this study, researchers discovered that vision alone was best for short term memory, however, adding haptic feedback was the most effective for long-term memory ($p < 0.001$)[88].

In psychological theory, there are three types of memory storage: sensory memory, working memory, and long-term memory [88, 90]. While sensory memory is instantaneous and working memory only stores a limited number of items for up to a minute—long-term memory preserves an extensive amount of information that can last a lifetime[88, 90]. When abundant kinesthetic information is received in a short time, kinesthetic memory behaves in a manner similar to that of working memory [78, 88]. An illustration of this is when learning long numbers, such as phone numbers. The working memory has no difficulty learning the first seven digits of the number, but when longer numbers such as the area code are added, a merging strategy of grouping numbers into sets of three guarantees increased success in recalling the number afterwards. The high accuracy in our participants' length-recall scores suggests a strong ability to remember the first movements performed (primacy effect). Similarly, subjects had difficulty remembering the most recent movement performed (recency effect), similar to the findings of Allen *et al.* on enactment and working memory [90].

It is the first time for us to examine kinesthetic skill learning purely from the kinesthetic feedback loop. Our investigation on kinesthetic skills learning yielded encouraging results (Figure 4-4). Human performers can reduce errors in duplicating movements, indicating that kinesthetic memory can be optimized through solely kinesthetic training. This study is evidence that human working memory capacity, perceiving via the haptic loop, stores information similarly than any of the other senses such as vision. This adaptation process builds the foundation of skill learning. Kinesthetic guidance has been widely employed in motor training for several years in other arenas such as stroke rehabilitation and tennis coaching[76]. Guidance has the benefit of offering restriction of movement error that may be used during early acquisition of skills. If applied during kinesthetic skill acquisition stages, kinesthetic guidance has been associated with decreased performance errors and therefore learning [78]. Although numerous studies have looked into the effect of kinesthetic guidance in kinesthetic training, none have explored the behavior on kinesthetic memory[76, 85].

The progress that computing technology has made to recreate kinesthetic feedback via robotic haptic interfaces has intensified research into how recording and playing back motion help kinesthetic learning. Examples of these robotic interfaces are robotic surgical systems and military drones [82, 91]. A haptic interface employs sensors that transmit an electrical signal to a computer where the signal is translated to perform an action or apply a directional force. These interfaces are capable of replicating force and tactile feedback, offering ample sensory information, making kinesthetic training a useful method for skill acquisition [82]. By employing kinesthetic training via these robotic interfaces in surgery it is possible to record an expert surgeon's movement and play them back. Moreover, surgical programs could project training expectations based on pattern complexity and training schedule, as well as create maneuver evaluations for surgical trainees.

Our study has several limitations. For one, it is limited only to a 2D scenario and we are not able to determine the effect of the depth component in kinesthetic memory. We surmise that it would be more difficult to recall lengths rather than direction, as seen in the work of Allen *et al*[88]. Another limitation is the small number of subjects for the retention part of the experiment. Had we had more participants, we may have gained a richer understanding of length characteristics of kinesthetic memory.

4.5 Conclusions

We revealed that kinesthetic information obtained from passive kinesthetic guidance can be stored in the kinesthetic memory span. Our results suggest a chunking effect in the muscle memory for both direction and length recall that can be used for movement duplication. Finally, after repeated kinesthetic training, human performers can optimize their kinesthetic memory.

This can provide the basis of learning kinesthetic skills, like those used in surgery, through a kinesthetic feedback loop. Future work in this field should employ more complex surgical tasks to assess the generalizability of kinesthetic guidance. Also, it is necessary to determine the effect of kinesthetic guidance on surgical trainee's depending on their year of training and develop a learning curve.

CHAPTER 5 HAPTIC SIMULATION FOR SURGICAL TRAINING: KINESTHETIC GUIDANCE EXPEDITES LAPAROSCOPIC TASK PROFICIENCY

5.1 Introduction

In the previous section, we demonstrated that kinesthetic information can be stored in memory; once retrieved, it can be used to guide movement with reliable accuracy. In this study, we are investigating how kinesthetic guidance, delivered from an expert to a novice, can help the novice learn a laparoscopic skill more efficiently.

Kinesthetic sensation makes the surgeon aware, during an operation, of the position of his or her joints and limbs as he or she performs surgical maneuvers. After many repetitions, these maneuvers are committed to memory, improving muscle memory and performance, which are characteristics of an expert surgeon. Novices often spend countless hours doing unstructured training attempting to attain this level of dexterity. Novices' training could be expedited if they were exposed to a system which guides the technique by which they perform the movement, fostering kinesthetic information for muscle memory so that the next time, the movement becomes instinctive [9].

For years, it has been difficult to implement computer-simulated skill training emphasizing kinesthetic feedback because technology was not advanced enough to allow for recording and "playing back" kinesthetic information from a human performer. New computer haptic interfaces are capable of recording this kinesthetic information and playing it back as kinesthetic guidance, as well as quantitatively characterize performance through several metrics[92]. Several recent studies on kinesthetic feedback have captured our attention. In these studies, engineers have found innovative applications for kinesthetic interfaces such as the

SensAble™ PHANTOM® Omni (SensAble Technologies, Inc., Woburn, MA)[93-95]. The PHANTOM is a bench-top device that can apply motorized force feedback in the X, Y, and Z directions to users during object manipulation and can be used in concert with six degrees of freedom of movement with a position resolution of 0.055 mm and reaches peak forces of 3.3 N [96]. An instance of this, is the "what-you-feel-is-what-I-feel" model. In this model, a novice can track the expert's movements during training of a complex motor skill by receiving kinesthetic guidance via a computer master-slave system employing two PHANTOMs [97]. With the PHANTOM, kinesthetic information can be captured from an expert surgeon and delivered instantly via software to a novice surgeon, allowing the trainee to learn a surgical task. It is analogous to golf swing training and providing kinesthetic guidance, but the PHANTOM is able to provide guidance through a computer with laparoscopic instruments. Moreover, the PHANTOM is able to provide force and position feedback during training that can be customized to different tasks and level of skill of the performer.

5.1.1 Performance metrics

Quantitative performance assessment of novices and experts in surgery is difficult. In this section we will briefly review the most frequently used motor performance metrics that can be applied in surgical training namely: temporal, outcome-based, motion-based, and force-based.

Firstly, task completion time has been employed in various studies to determine skill level and the amount of time between subtasks as a predictor of cognitive load [65, 98]. Similarly, outcome metrics evaluate the results specific to the task and the end result of the performance and cognitive load [65, 99]. Another different type of measurements are motion-based metrics. Both path length and economy of movements are associated to level of expertise, as novices tend to exaggerate motions and perform unnecessary movements [65, 98]. Likewise, average and peak velocity are calculated as the derivatives from the path length and its completion time. Velocity can also compute the uncertainty observed in novices' movement, which are changes in velocity that come close to zero [65, 100]. Average and number of accelerations are calculated as the second derivative from the motion profile and employed to tease out target oriented behavior [65, 100]. Akin to acceleration, another metric derived from motion features is the *jerk* metric. This metric is the third derivative of the motion data and describes changes in acceleration or movement smoothness. The jerk metric can describe progress during motor learning, since as we learn the jerk in movement decreases and the movement becomes smoother [65, 100, 101]. Finally, research done in force control of surgical trainees has found that novices have difficulty maintain stable forces and handling tissue gently [102] as opposed to experts who apply gentle force on tissue [65].

In this last project we examined the role of guided kinesthetic feedback in teaching laparoscopic tasks. The tasks selected were validated to teach skills in managing long-shafted instruments, bimanual coordination, and navigation [103]. We hypothesize that learners in the kinesthetic-guided group would learn laparoscopic skills in less time and exhibit fewer performance errors measured with the metrics aforementioned. Also, we expected that aided by this additional source of kinesthetic feedback, subjects in the kinesthetic-guided group would exhibit fewer performance errors than the self-directed group when asked to repeat the exercise over a set of performance blocks.

5.2 Methods

The proposed kinesthetic guidance system (Figure 5-1) is composed of an Arduino UNO (Arduino, Italy) electronic board, a computer, two computer screens, and four haptic interfaces

(Phantom Omni). The Phantom Omni interfaces are connected in parallel, as a master-slave system, to the computer for both left and right hand via Simulink (Mathworks, Palo Alto, CA.), which is a graphical programming environment for simulation that runs on MATLAB (Figure 5-2). The forces generated by the expert at the master-end of the system are recorded by the 3 encoders and played back in the slave-end as forces in three actuated joints in mN/m. The changes in position of the actuators on the slave-end create angles that can track motion from the device in radians (Figure 5-3). The amount of guided kinesthetic feedback given to the novice is managed by Simulink's proportional-integral-derivative controller (PID) and it was set for this experiment to a proportional gain of 5. The movements replicated by the master-slave system did not include movements of the instrument tip or handle.

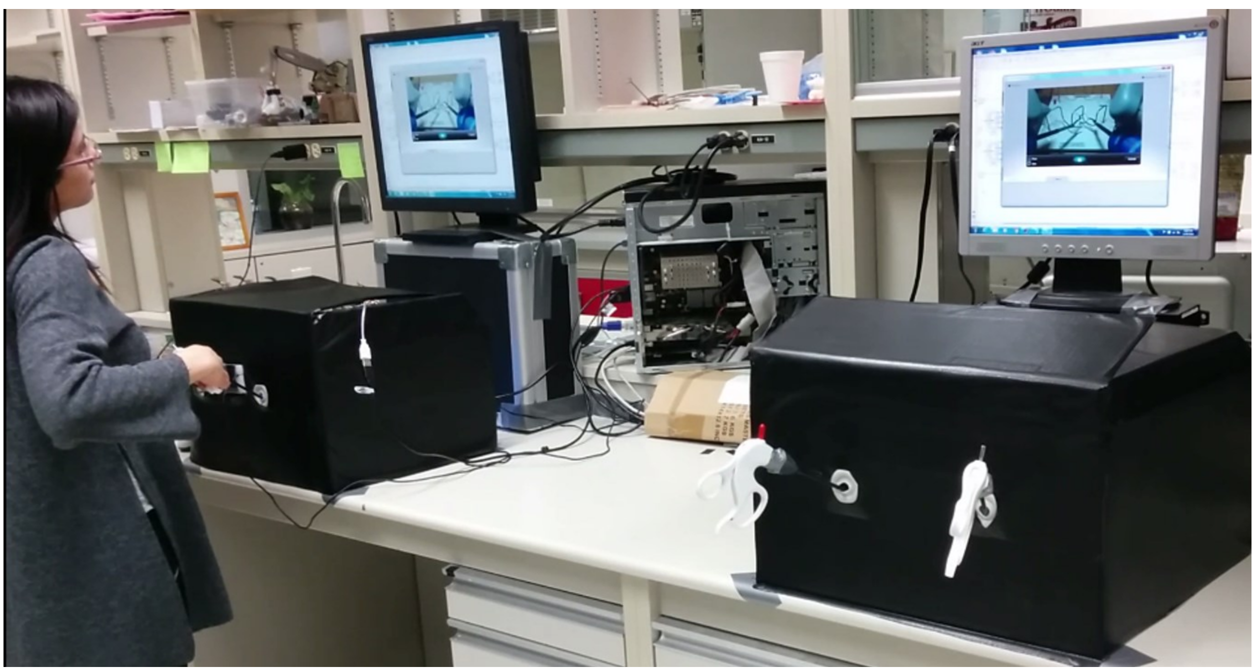

Figure 5-1. Overall setup of the kinesthetic master-slave system.

It allows for guidance of movements during a task in a customized laparoscopic box.

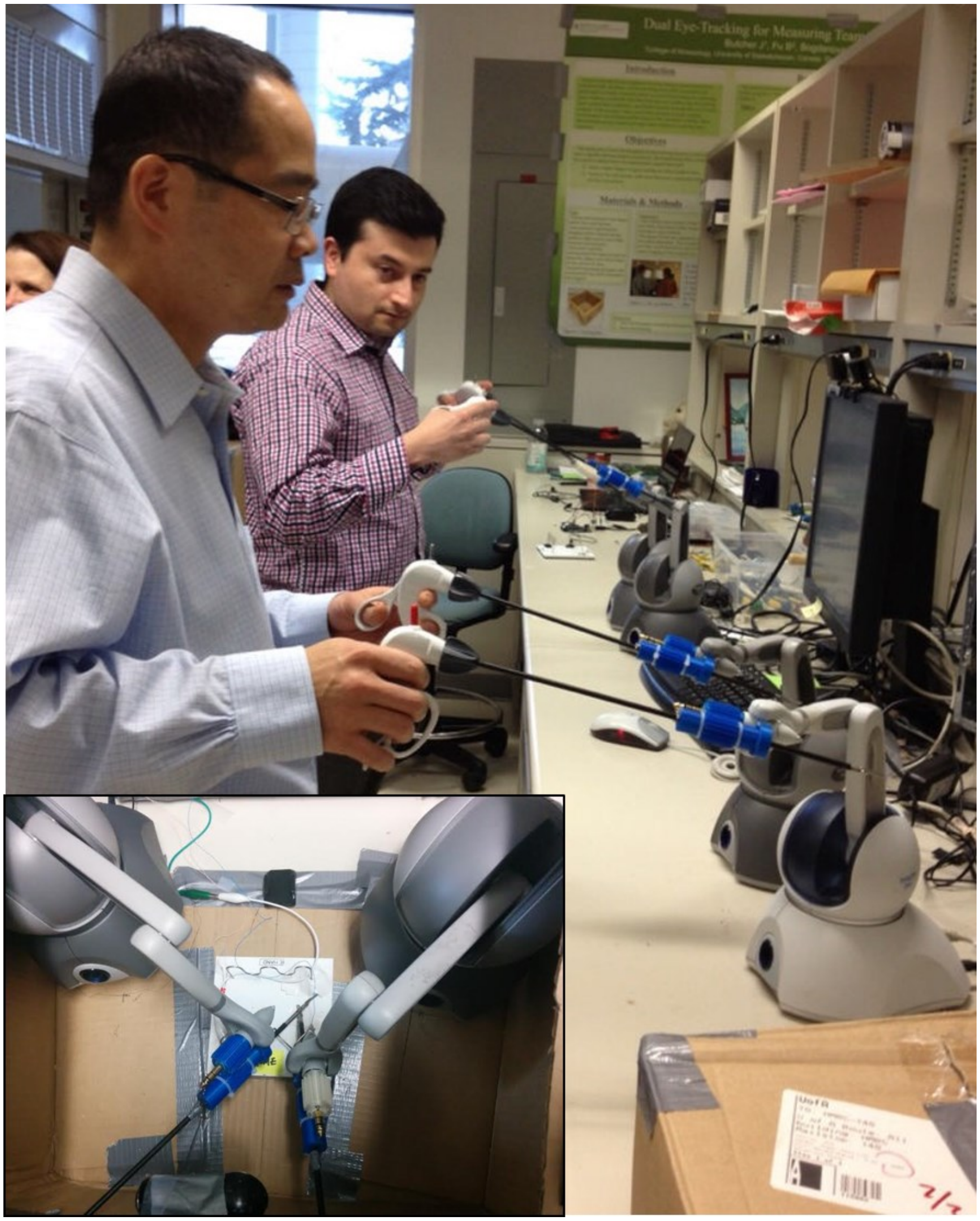

Figure 5-2. Haptic interface setup.

Top: The four haptic interfaces adapted to laparoscopic graspers. Lower corner: Task and tool setup inside the customized laparoscopic box.

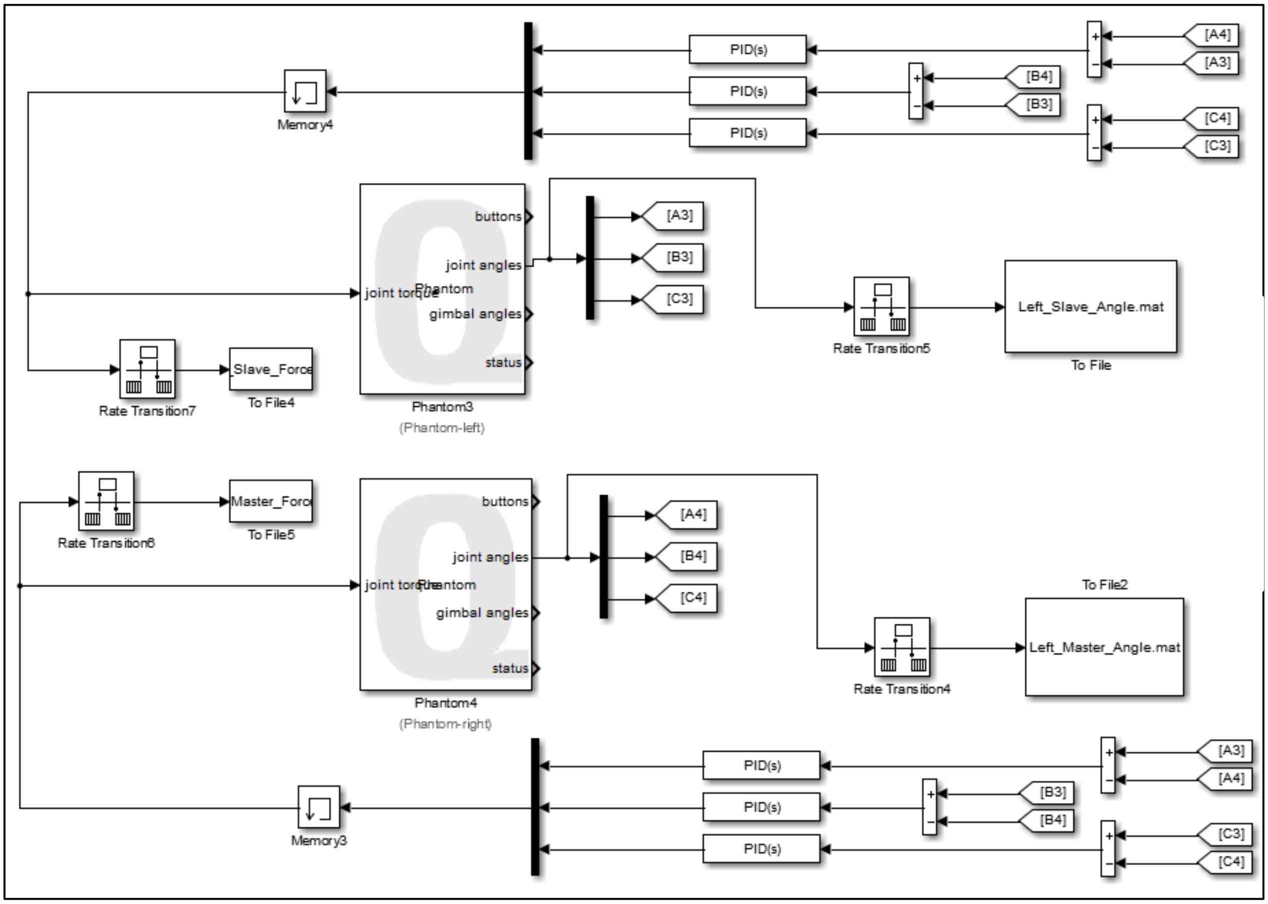

Figure 5-3. Simulink setup of the PHANTOM.

This system also features an Arduino board (Figure 5-4) that is connected to a single metal ring and a twisted metal wire which measures the number of times and duration of contact between the ring and the twisted wire sending the data through MATLAB to the computer.

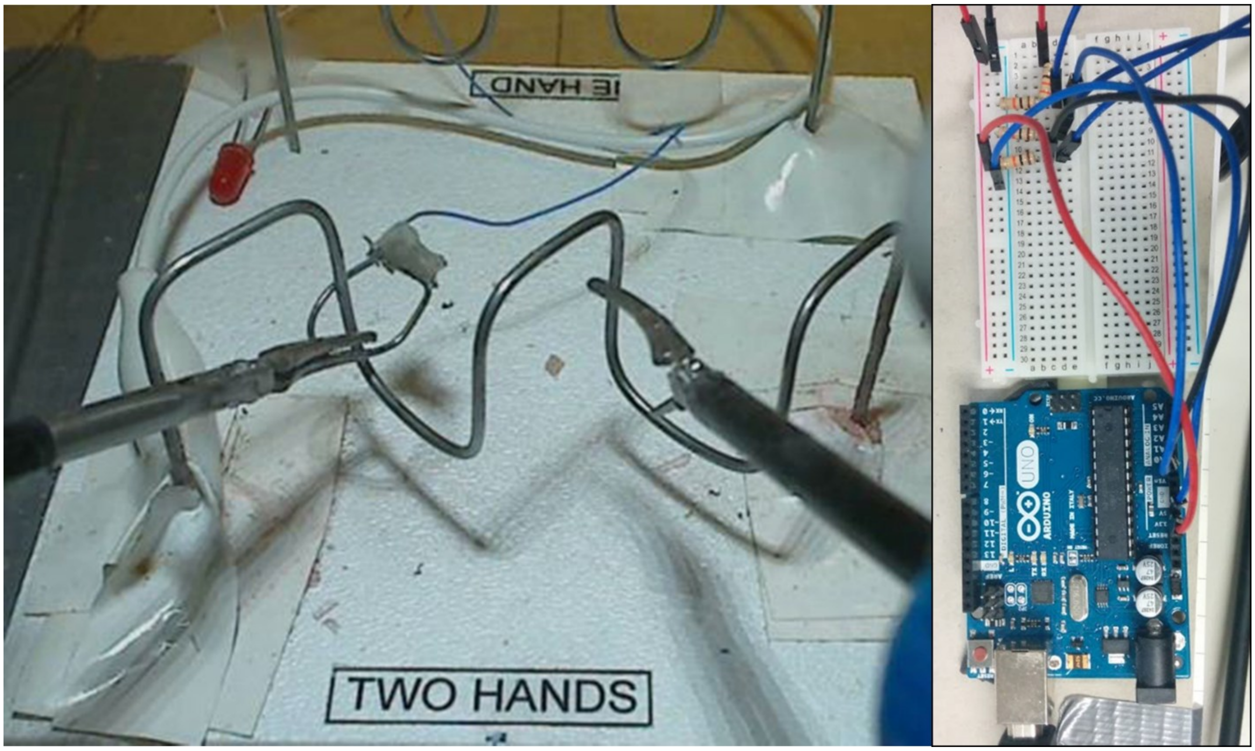

Figure 5-4. Navigational laparoscopic task and Arduino board setup.

5.2.1 Participants

Twenty volunteers (n = 20; 50% female; 95% right-handed; age range: 18–39 years old, mean age = 25 years) were part of the experiment. Individuals with a history of sensory motor problems were excluded and the participants had no previous exposure to surgical training. The University of Alberta Health Ethics Review Board approved the study's purpose and objectives. Information and objectives were explained to the participants before they gave consent.

Task

Of the 20 participants, half (n = 10) were randomly assigned to be kinesthetically guided with the Phantom Omni to complete a laparoscopic task (Figure 5-5). The other half (n = 10) of the participants composed the self-directed learning group who trained without the assistance of the PHANTOM. The task, shown in Figure 5-4, was to move a ring along a twisted wire from one side to the other. In the self-directed learning group, subjects performed 5 trials of moving the ring from one side to the other, which is the equivalent of one training block. After each of the training blocks, the participants of the self-directed learning group observed two trials performed by the expert. In the kinesthetic-guided group, subjects repeated the same task of the self-directed learning group but were presented with two kinesthetic guided trials after every 5 self-directed learning trials from an expert surgeon in person. Both groups repeated the trials during 4 training blocks, 20 trials total, without receiving any kinesthetic guidance from the expert surgeon. Several metrics were recorded and evaluated between the two training groups, among them: outcome-based, motion-based, and force-based metrics. For each one of the blocks the outcome based metrics were the total task time, number of ring drops, number of times the ring came into contact with the twisted wire (number of errors), and the amount of time the ring was in contact with the wire (error duration) during each trial. Moreover, the resultant velocity in the three movement axes was captured for each hand; the average acceleration and average jerk values were derived from this resultant velocity. Finally, the resultant torque force for each of the hands was recorded for each training session to analyze for variances.

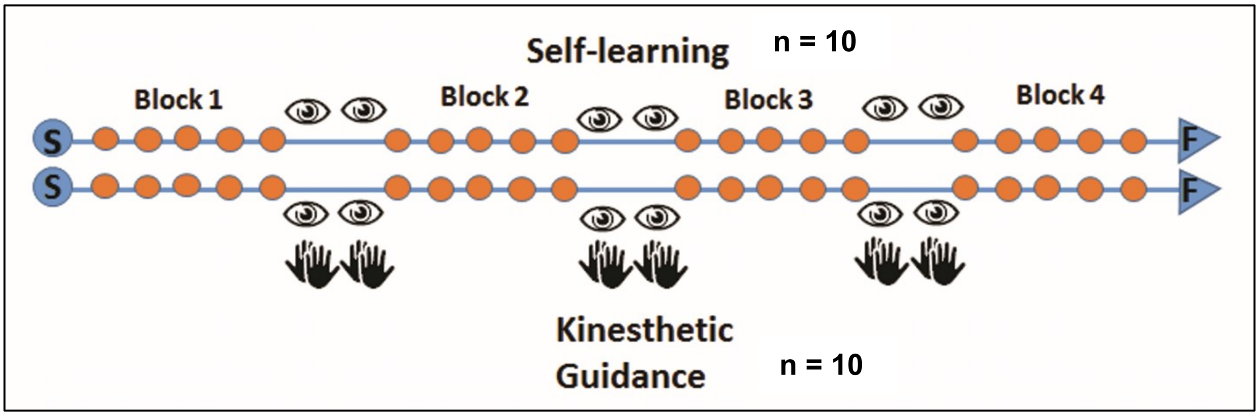

Figure 5-5. Experimental design of the study.

Participants received two trials of feedback, either visual or visual plus kinesthetic.

5.2.2 Statistical Analysis

The four task outcome metrics (time completion, number of drop, number of errors, and error duration,), the three motion-based metrics (velocity, acceleration, and jerk), and force metric were analyzed applying the *SPSS 22.0* (Chicago, IL); using a 2 (training condition: with and without haptic guidance) X 4 (Training block) mixed ANOVA with repeated measure on the second factor. In this study, $p < 0.05$ was considered statistically significant. Post-hoc analysis was also completed (*Bonferroni*) when needed.

5.3 Results

The effect of the two groups' performances over the four training blocks is summarized in Figures 5-6, 5-7, and 5-8 for all the metrics. Both kinesthetic-guidance and self-directed learning groups participants show a learning effect within blocks for the four task outcome metrics ($p < 0.001$). However, there were no significant differences in training type for time completion ($p = 0.074$), error duration ($p = 0.526$), number of errors ($p = 0.632$), and drops ($p =$

0.693). In Figure 5-6, we can observe that for the first block performance of both groups, task completion for the guidance group took 24% longer than the no guidance group, however, both groups finished with no significant differences in time for the last block. Likewise, the guidance group had on average more drops at the beginning but both groups had similar number of drops at the end. An analogous behavior was observed for the two groups in the number of errors performed and duration of the error; error duration and number was higher for the first block but were similar for the last block.

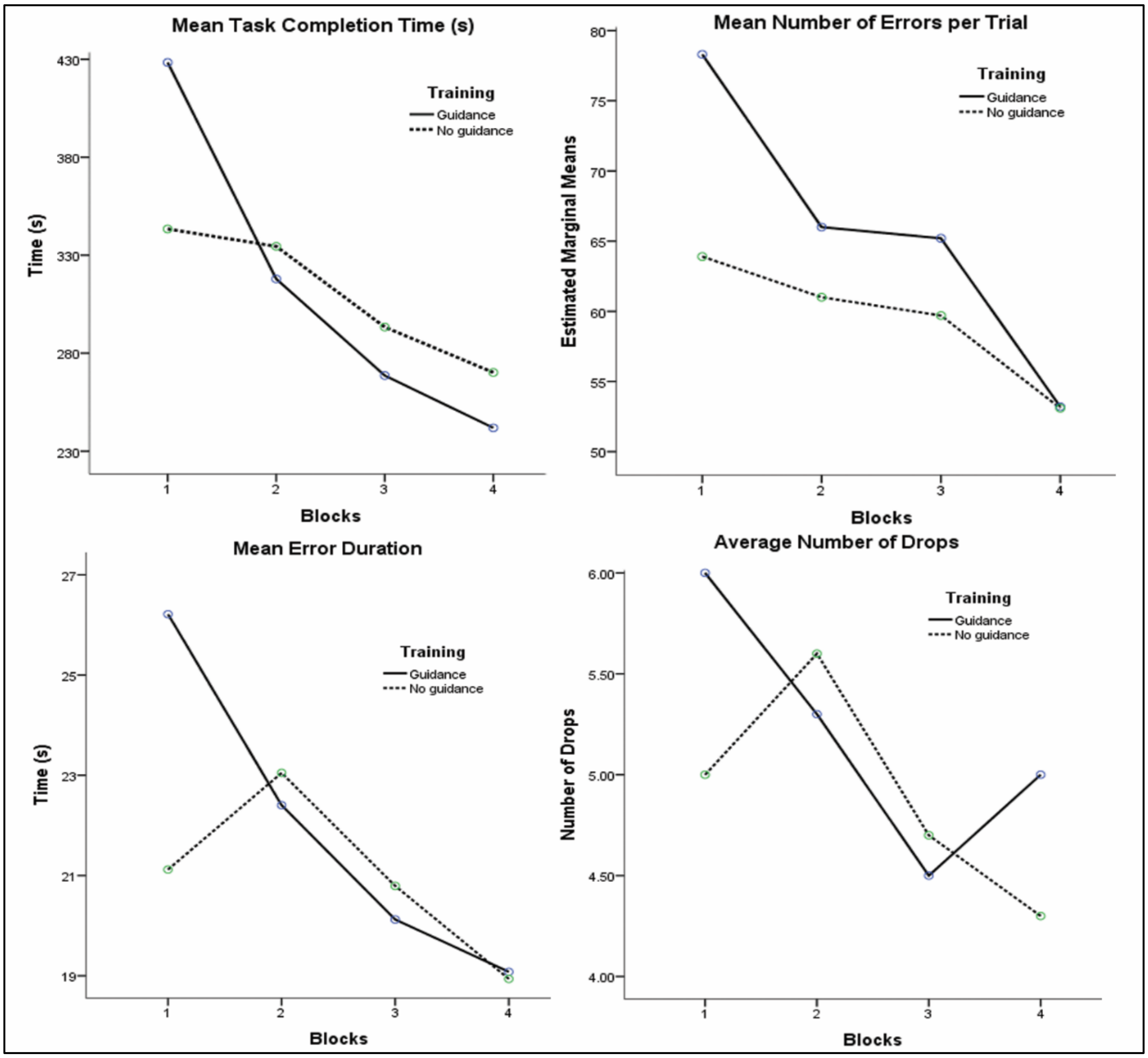

Figure 5-6. Performance results of kinesthetic guidance during the laparoscopic task.

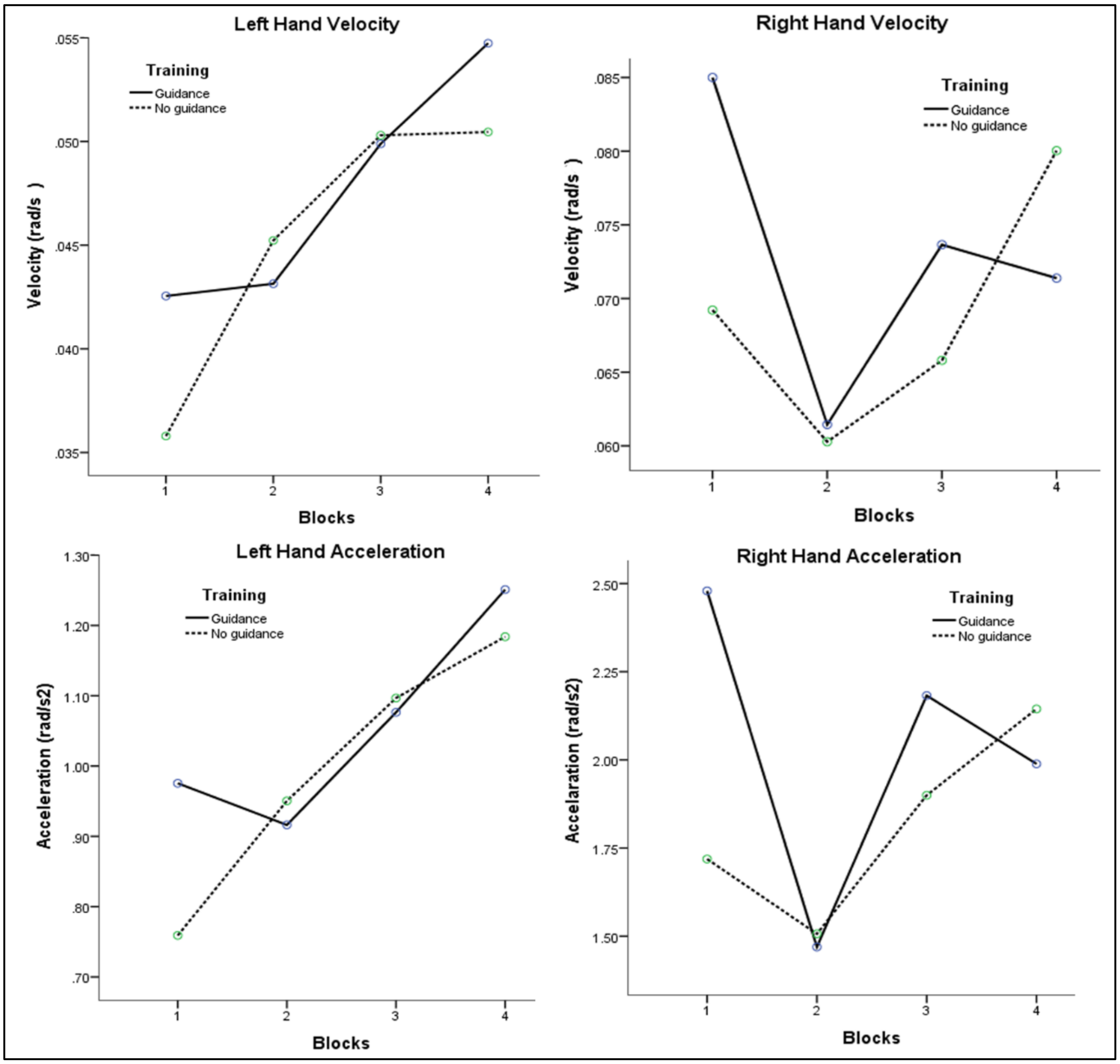

Figure 5-7. Velocity and acceleration of both training groups during the laparoscopic task.

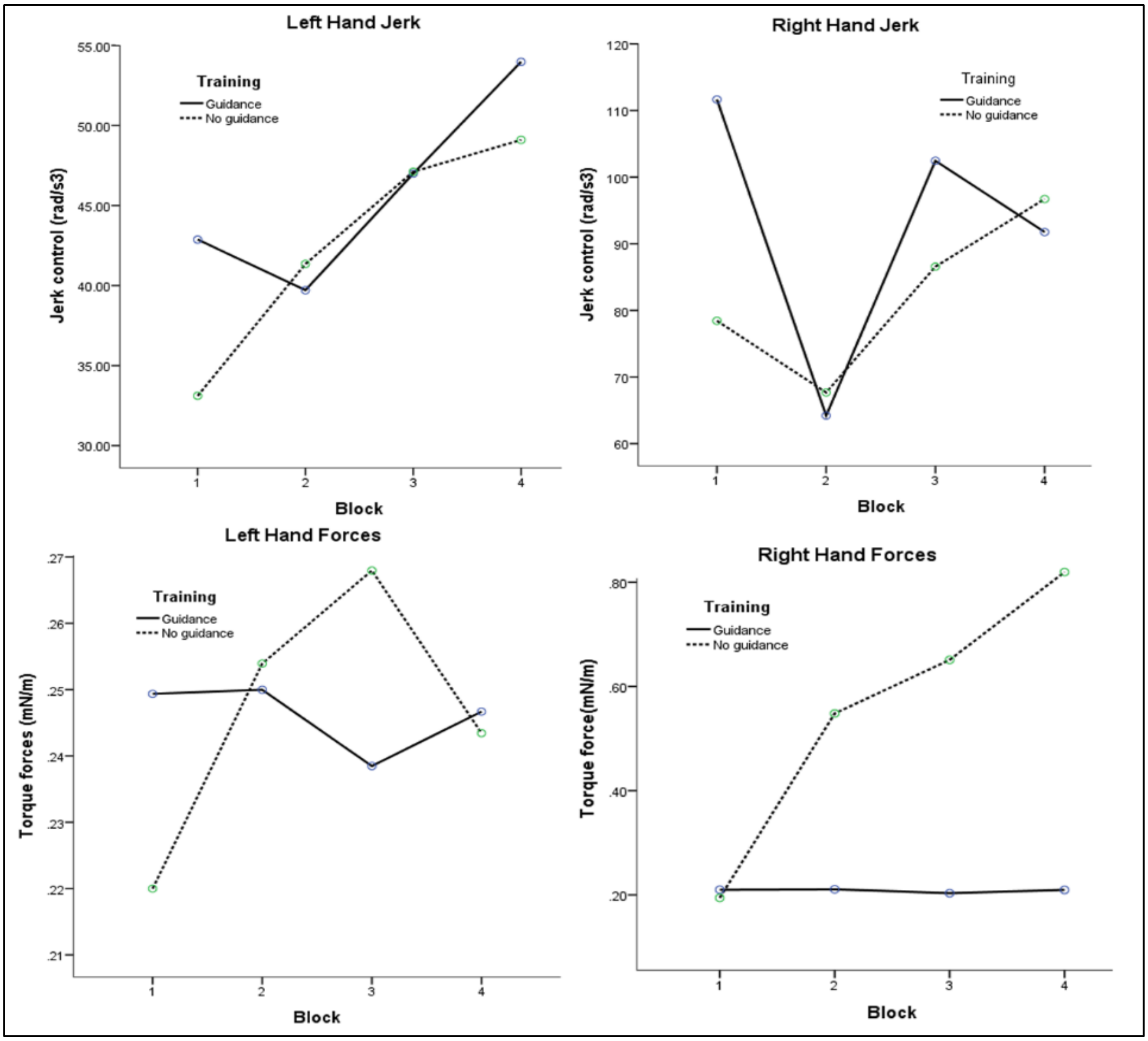

Figure 5-8. Jerk and Force metrics of the groups during the task.

As seen in Figure 5-7, there were no significant differences in either right or left hand's velocity (p = 0.807), acceleration (p = 0.098), between the two training methods. The results from the first block of velocity suggests the two groups were uneven; moreover, for the right hand velocity, although the guidance group was faster for the first block, it decreased by 16% for the last block, whereas in the no guidance group increased by 13%. The acceleration for both hands in the two training groups had a similar pattern to the one observed for the velocity.

Table 5-1: Summary of task outcome metrics

Metric	Block	No Guidance		Guidance	
		Mean	SD	Mean	SD
Time completion	1	202.8	98.76	239.3	123.2
	2	204.8	118.6	173.6	47.19
	3	158.0	68.12	141.4	54.75
	4	153.5	65.15	129.4	32.67
Drops	1	7.87	5.03	7.17	5.52
	2	6.90	5.06	6.33	4.48
	3	5.67	4.15	5.80	3.37
	4	6.53	5.18	5.00	2.77
Number of errors	1	95.5	45.1	91.1	66.7
	2	81.7	36.6	74.5	27.7
	3	73.5	26.5	66.9	36.1
	4	67.3	13.4	59.9	25.8
Error duration	1	35.23	19.76	31.75	20.74
	2	32.26	20.66	26.86	15.94
	3	24.81	14.85	24.34	12.99
	4	27.72	19.47	21.26	11.42

If we observe closely, in Figure 5-8, although there were no significant differences in jerk ($p = 0.415$), and force ($p = 0.099$) applied between the groups, there are some important differences in the first and fourth block for both left and right hand. Forces of the left hand for the guidance group remained almost unchanged throughout the four blocks of training, nevertheless, the no guidance group presented changing force values for the four blocks. For the other hand, the right one, the guidance group had no changing forces in any of the blocks but the no guidance group presented increasing forces for the rest of the blocks (Table 5-2).

A post-hoc multiple comparison of the training blocks ($p < 0.005$) showed a major change after the first trials. There were differences between the kinesthetic-guided and self-directed groups ($p < 0.005$) in the post-hoc multiple comparisons (Bonferroni). Interaction effects were uncovered between the training blocks and learning groups in task time ($p < 0.001$), drops ($p < 0.001$), error count ($p < 0.001$), and error duration ($p < 0.001$). No significant differences were observed for velocity, acceleration, and jerk movement. Forces for the left and right hand were not significantly different for block 2, 3 and 4 ($p > 0.05$) and ($p > 0.05$).

Table 5-2: Summary of performance motion and force metrics for the left and right hands

Metric	Block	Left Hand				Right Hand			
		No Guidance		Guidance		No Guidance		Guidance	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Velocity	1	0.036	0.009	0.043	0.012	0.069	0.037	0.085	0.073
	2	0.045	0.008	0.043	0.012	0.060	0.035	0.061	0.020
	3	0.050	0.014	0.049	0.013	0.066	0.023	0.074	0.049
	4	0.051	0.018	0.055	0.018	0.080	0.061	0.071	0.032
Acceleration	1	0.759	0.166	0.975	0.305	1.719	1.449	2.479	2.925
	2	0.950	0.144	0.916	0.197	1.507	1.161	1.470	0.618
	3	1.097	0.168	1.076	0.287	1.899	1.377	2.182	2.338
	4	1.184	0.628	1.251	0.503	2.144	2.092	1.990	1.426
Jerk	1	33.11	7.250	42.87	13.46	78.44	75.43	111.7	14.7
	2	41.35	6.449	39.71	8.431	67.68	56.39	64.20	27.24
	3	47.11	7.293	46.99	12.93	86.57	67.33	102.4	117.8
	4	49.10	19.94	53.97	21.33	96.71	100.4	91.76	72.34
Force	1	0.220	0.115	0.249	0.206	0.194	0.026	0.210	0.025
	2	0.254	0.147	0.250	0.061	0.055	1.110	0.211	0.028
	3	0.268	0.150	0.239	0.044	0.651	1.389	0.203	0.031
	4	0.243	0.077	0.247	0.036	0.819	1.494	0.209	0.031

5.4 Discussion

Our research hypothesis was not supported by the results. Specifically, adding haptic guidance to a laparoscopic training coursed failed to show benefit to facilitate skill learning. Factors that contribute to this insignificant outcome can be multiple. The first can due to the relative small sample size. A sample size of n = 10 per group, on for task performance and n = 10 for the skill learning are moderate size groups. Within them, the average performance was affected greatly with one participant creating outliers. One possible solution is to redesign the experiment so that the subjects need to perform more trials and thus average out the outlying values.

In our experimental design, participants perceived the information coming from the expert in person through the haptic interface and integrated it into their learning process for two trials. However, both groups of participants received visual training from the expert that they were able to practice on for the same number of trials. We believe this type of design gave the self-learning group the opportunity to employ haptic feedback as part of their training but with no guidance which could explain the interference effect.

Moreover, the number of guidance trials performed were not sufficient to overcome the training effect of the control group. Interestingly, despite that subjects from both groups declared no previous experience on laparoscopic surgery, both groups of participants had different results from the first performance block suggesting an uneven population even before the guidance training started. Both groups at the end of all the blocks had no statistically significant difference in the amount of time to complete the task, number of errors, number of drops, and error duration. Although not statistically significant, the graph suggests that the participants from the kinesthetic guidance group was less dexterous from the beginning and improve on their completion time 35% more than the control one. Another reason that explains why the task outcome metrics were not significantly different for both groups, besides the guided training not being beneficial for this type of experimental design, is the simplicity of the navigational task. A task with more eye-hand coordination demand could benefit from the guidance.

Having encountered with somewhat disappointing outcome, we are still interested in study role of haptic in surgical skill training. The literature is brimming with reports demonstrating that haptic guidance can, in the early stages of training, be a useful teaching paradigm for surgical skills [104]. Offering kinesthetic guidance in the early stages of learning may provide insight and help novices develop accurate motor coordination. Moreover, researchers have supported the introduction of haptics in the early stages of learning as a way to expedite the acquisition of dexterity [12, 59]. We believe this is the case for our experiment. An example of kinesthetic guidance in action is golf swing training from a coach. The novice golfer follows the expert's motion during training, gaining insight into the movement pattern.

Demonstrating in how to attain economy of movement with kinesthetic guidance can expedite acquisition of muscle memory and increase movement accuracy during motor learning [105]. Basically, subjects in the guided group started with the worst performance than the control ones; but their performance significantly improved over the training session to be equal to the control one. In this experiment, the learning benefit in the early stages and performance was not obvious perhaps given the design.

Regarding the motion metrics of velocity, acceleration, and jerk between the both groups there were no significant difference between the means per performance block. Concurrently, non-guided participants increased their manipulation forces as the number of blocks increased, suggesting a possible way of how they sustain their performance with the guided group. Surprisingly, albeit there was no significant difference in force application between the training methods because of interactions, Figure 5-8 demonstrates how forces in the left hand with kinesthetic guidance remained stable as opposed to those without the guidance. This behavior is especially seen for the right hand. For this hand, as the number of training blocks incremented, the right hand forces remained stable, as opposed to the self-directed learning in which the forces incremented. The last block of the no guidance group had a force 4 times stronger than the first block, although a lack of significant difference could be secondary to the outliers in the group. This increase in forces for the right hand in the self-directed group could be secondary to the participants overusing force to compensate for their underperformance. This excessive use of force may be translated in real life situations to excessive force applied to tissues when operating and consequently patient safety. Although until now there is no specific research done on kinesthetic guided training in surgical tasks, Trejos *et al.* explored the employing force metric to differentiate novices (n = 17) from experts (n = 13)[65]. These researchers surmised increased variability in novices force control given their inexperience, however, they found that force measurement by itself was not as sensitive as the combination of the position-force metric.

5.5 Conclusion

The results of this study showed that kinesthetic guidance did not enhance task performance for experimental design. Our future studies will focus on the effect of guidance in different surgical tasks, under distractions, various degrees of surgical training, and stressful environments. Another area of future study is the effect of guidance in telementoring surgery.

CHAPTER 6 CONCLUSION

6.1 General Discussion

In typical surgical training, a novice surgeon learns new techniques after several hours of self-directed training [12]. Surgical self-directed training is composed of box trainers and hybrid animal models. Once the novice is competent in a technique, he or she is able, under the supervision of an expert surgeon, to perform surgery on a human patient [24]. In the same manner, the development of new minimally invasive surgical techniques will results in more training times. Unfortunately, new restricted duty hours limit the amount of practice time [12], and new surgical instruments decrease haptic feedback making it difficult for novices to interact with the surgical field [10, 23, 24].

This restricted number of training hours makes it difficult to introduce complementary training strategies, as their time is already limited. One possible way is by employing kinesthetic-based curriculum to equalize groups of trainers with different levels of dexterity. Researchers have already developed a method for using a kinesthetic-based curriculum to teach surgical knot-tying. This method has proven to be more successful than the traditional self-directed method to make even separate groups of training, similar to our experiment [106]. Another instance can be found in traditional laparoscopic box trainers. Although these laparoscopic box trainers offer metrics useful for criteria-based proficiency assessment, such as economy of movement, these box trainers do not explain how to train to be more efficient in movement performance [107]. Instead of developing optimal motor skills through hours of unregulated practice laparoscopic trainers, learners can become proficient more efficiently by observing experts' underlying motor skill patterns, taking less acquisition time. Another benefit of employing simulated kinesthetic guidance is that can be adapted to the novice's own learning curve. If needed, we can adjust the strength of feedback and choose the parts of the task that require more practice from the subject. This makes simulated kinesthetic guidance a valuable complementary tool for surgical training programs, with the potential to record experts' movements and save faculty teaching time [92].

In chapter 2 we performed a literature review of the current role of haptic in surgical training [10, 60, 62, 108]. The advancement of computer technology, such as haptic interfaces, has made it possible to record and replicate human movement. Being able to record and replicate an expert surgeon's performance has benefits for novice surgeons, whose training can now include an opportunity to mimic an expert's movements with no risk to a patient [92]. Moreover, the expert's recorded performance can be adjusted to different proficiency levels in surgical programs, and thus customized to each learner [92]. Another advantage of using an expert surgeon's movements to train novices is that this method makes it possible to describe how the movements are performed, which is not possible with surgical box trainers. Typical box trainers offer statistics in performance, such as task time completion, but no feedback in how to improve those statistics [24, 104].

As tactile sensation decreases performance of an incision task did not change in chapter 3. When participants were asked to do an incision with various number of gloves on, their time and force performance did not change. However, when an elastic was utilized as a simulated vessel underneath the incision area, subject changed their time and force accordingly.

The motor training experiment in Chapter 4 demonstrated that kinesthetic memory behaved in a chunking pattern after eight movements [79, 87]. This effect was most prominent when the learner was attempting to remember the lengths of movements as opposed to their direction. Remembering lengths seemed to follow a subtler chunking pattern because of more room for perception error. The kinesthetic memory chunking behavior results were compared to the motor training sequential effect after three weeks. After the sixth session of training for all patterns, regardless of their complexity, a learning effect was noticeable.

Chapter 5 focused on testing how kinesthetic guidance can facilitate the learning process for laparoscopic skills like it has been shown in other motor skill training [67, 80, 109]. We make a great effort to implement a novel system to record the hand movement of an expert surgeon and deliver the actions to leaners through haptic feedback loop. Maybe due to the conservative sample size and the interaction of visual learning, in this current stage of the study, we did not reveal benefits of using kinesthetic-guidance for improving skill learning in the laparoscopic ring transportation task. However, we will modify our study design and further test effect of kinesthetic training for more complex surgical tasks.

6.2 Limitations of the Kinesthetic Feedback and Future Directions

Our studies encountered several limitations. The research presented in this paper had two primary goals: to determine if kinesthetic memory can be created exclusively by kinesthetic feedback and to define if kinesthetic guidance can enhance performance in laparoscopic tasks. We have demonstrated that kinesthetic memory can be transmitted from an expert through a haptic guidance system. Moreover, we observed that this kinesthetic information alone can increase performance and learning of motor tasks. We also discovered that when applied in a navigational laparoscopic task, this paradigm was not successful expediting proficiency on the performance of the task when compared to the typical self-directed learning method.

For the kinesthetic memory experiment, the major limitation is that the experiment was performed in a 2D scenario. Future studies will focus on testing the limits of kinesthetic memory in a 3D scenario for both direction and length of movements.

Regarding our laparoscopic haptic guidance experiment, the major limitation was that our experimental design involved some degree of haptic feedback since the control group employed the device to practice but without the guidance. Similarly, the use of a navigational laparoscopic task makes it difficult to apply the results to a surgical laparoscopic procedure which are more intricate. Eventually, we plan to study this effect in hybrid animal models.

Haptics is a difficult skill to describe to trainees with words once it becomes automatic in expert surgeons. In our study, novices with no previous surgical felt the expert's movement guiding the novices during the task. In the future, we plan to integrate and study the effect of kinesthetic guidance in different levels of residency training and with experienced surgeons. Moreover, future research will be performed in stressful situations and over several weeks to evaluate skill retention.

Although our participants had never experienced laparoscopic surgery before, some of them demonstrated more proficiency during the task than others. This effect can be explain by an increased eye-hand coordination secondary to other motor activities such as sports training, videogames, or instrument playing. In the future, a research objective will be to characterize the different amount of time invested in other motor training that affect surgical training and performance. Furthermore, we will also need to look into qualitative or mixed-methods approaches to study touch and learn how residents with diverse degrees of training feel haptic discrimination is acquired developing a *haptic perception metric*.

Lastly, our research will look into the effect of guidance for surgical telementoring and recognizing changes in eye-tracking behavior under kinesthetic guidance to obtain a deeper quantitative understating of the eye-hand coordination during surgical training and how to integrate it in VR surgical training.

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