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A Novel Haptic Simulator for Evaluating and Training Salient Force-Based Skills for Laparoscopic Surgery

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A NOVEL HAPTIC SIMULATOR FOR EVALUATING AND TRAINING SALIENT FORCE-BASED SKILLS FOR LAPAROSCOPIC SURGERY

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by
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ABSTRACT

Laparoscopic surgery has evolved from an "alternative" surgical technique to currently being considered as a mainstream surgical technique. However, learning this complex technique holds unique challenges to novice surgeons due to their "distance" from the surgical site. One of the main challenges in acquiring laparoscopic skills is the acquisition of force-based or haptic skills. The neglect of popular training methods (e.g., the Fundamentals of Laparoscopic Surgery, i.e. FLS, curriculum) in addressing this aspect of skills training has led many medical skills professionals to research new, efficient methods for haptic skills training.

The overarching goal of this research was to demonstrate that a set of simple, simulator-based haptic exercises can be developed and used to train users for skilled application of forces with surgical tools. A set of salient or core haptic skills that underlie proficient laparoscopic surgery were identified, based on published time-motion studies. Low-cost, computer-based haptic training simulators were prototyped to simulate each of the identified salient haptic skills. All simulators were tested for construct validity by comparing surgeons' performance on the simulators with the performance of novices with no previous laparoscopic experience. An integrated, "core haptic skills" simulator capable of rendering the three validated haptic skills was built. To examine the efficacy of this novel salient haptic skills training simulator, novice participants were tested for training improvements in a detailed study. Results from the study demonstrated that simulator training enabled users to significantly improve force application for all three

haptic tasks. Research outcomes from this project could greatly influence surgical skills simulator design, resulting in more efficient training.

DEDICATION

This work is dedicated to the most important people in my life:

Jesus Christ of Nazareth: Lord, you made me, you know me and still chose me for yourself and died in my place. I cannot fathom your faithfulness and love!

My parents, Vijay and Sukanya, for their abundant and sacrificial love, support and prayers throughout my life. Words cannot do justice to express my heartfelt gratitude to them.

My brother and sister, Samuel and Deepika, for their constant love, affirmation and prayers.

My wife, Rachel, for her love, patience and willingness to walk this path with me. I could not have done this without you!

My children Kiran and Asha, for refreshing me daily with joy.

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TABLE OF CONTENTS

LIST OF TABLES

Table Page

List of Tables (Continued)

LIST OF FIGURES

Figure Page

List of Figures (Continued)

CHAPTER ONE

INTRODUCTION

This work details the development and validation of a novel haptic simulator for teaching force-based laparoscopic skills to novice surgical residents. Laparoscopic surgery is an increasingly popular endoscopic surgical technique that involves skilled surgeons using long surgical tools inserted through the abdominal wall of patients to manipulate and operate on tissues, while viewing corresponding images from the surgical site via video feedback. In Chapter Two, the reader is introduced to the variety of complex and non-intuitive skills that a novice surgeon is required to learn to gain proficiency in this technique. The motivation for using inexpensive, objective and ethically desirable simulators to teach surgical skills is then presented, along with an overview of the types of surgical training simulators available to today's residents.

Though surgical simulators have been remarkably efficient in teaching some aspects of basic surgical skills to residents, a key missing feature is lack of force-based or haptic skills instruction. Incorporation of this skill set is crucial since studies show that a majority of surgical errors are caused due to misapplication of force. A haptic device is described in Chapter Three that artificially simulates a force stimulus to train users to perceive certain rendered object properties. The concept of perceptual salience is used in rendering only those force components that are useful for accurate and efficient human perception. A manuscript describing this work was accepted for publication in *Virtual Reality* in 2012.

Several feasibility studies are described in Chapter Four that were undertaken to examine various aspects of the research question—what are the important salient haptic skills that a novice needs to learn to exhibit skilled force behavior in the operating room? One of the studies demonstrates that haptic feedback may not be critical to performing hand-eye coordination tasks, skills that are most basic to laparoscopic surgery. However, in another study, expert surgeon and novice force data were objectively examined when performing a surgery-like task with a haptic simulator. Results show that surgeons significantly differed from novices in the magnitude of forces applied using the simulator. Results from another study comparing surgeon and novice performance in a physical "box" trainer are presented as evidence for presence of a surgical haptic skill set that can be objectively tested on simulators. The above studies were presented at the *Medicine Meets Virtual Reality* (MMVR) conferences in 2011 and 2012.

Based on these pilot studies and results from published literature, the case for salient haptic skills is presented in Chapter Five. Three surgical skills—grasping, probing and sweeping—are identified as part of the salient haptic skill set, based on evidence that surgeons differ from novices in how they apply controlled forces for these surgical tasks. Consequently, prototypical simulators were developed and tested by simulating force-based tasks on the three simulators, one for each task. Results revealed that the simulator tasks and metrics could objectively differentiate between surgeons and novices based on the forces they applied using the simulator. These results were presented at the *Association for Program Directors in Surgery* (APDS) meeting in 2012 and point to the (construct) validity of the three skills as a means to discern skill level on laparoscopic tasks.

The three simulator prototypes were later integrated in one, easy-to-use "Core Haptic Skills" simulator, capable of simulating each of the three salient haptic tasks. Chapter Six describes the study that was devised to test the hypothesis that haptic skills training on the simulator for the three salient force-based tasks improved the force skill of users. Novice participants with no prior experience in laparoscopic surgery were recruited for the study, using a baseline—training—post-test experiment model. Results from the study revealed that, for all three haptic skills, training on the simulator improved participant performance, particularly at lower force ranges. These experiments support the training validity of the three proposed core haptic skills and complete support for the overarching theme that haptic simulators that render salient haptic skills may hold great promise in efficient teaching of critical force-based surgical skills.

Information presented in Appendices A and B pertains to methods used in haptic rendering as well as an experiment demonstrating the efficiency of perceptual salience-based rendering. The standard questionnaire completed by most participants is contained in Appendix C; the required informed consent form for the Institutional Review Board (IRB)-approved study is presented in Appendix D. A schematic overviewing the integration of the dissertation research components is presented below.

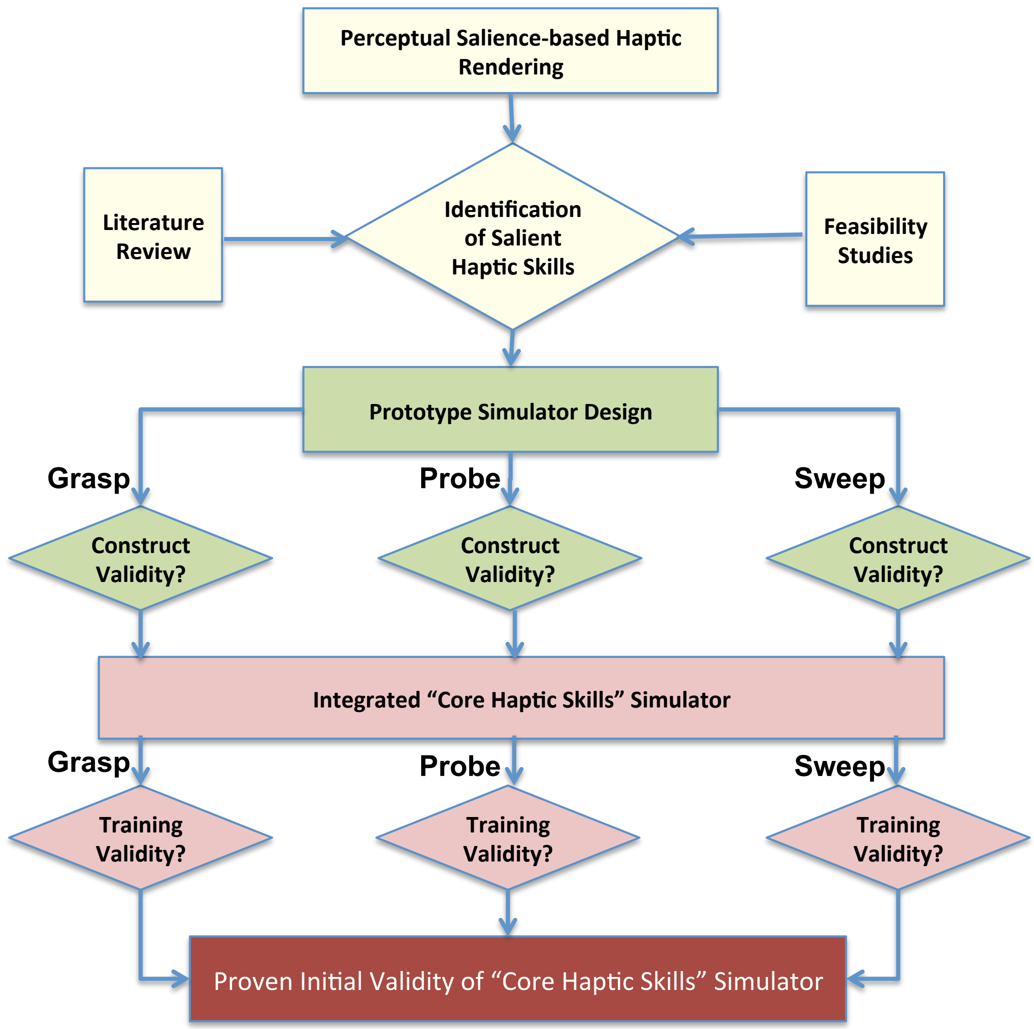

Figure 1: Flowchart of research design for the dissertation project, "A Novel Haptic Simulator for Evaluating and Training Salient Force-Based Skills for Laparoscopic Surgery"

CHAPTER TWO

HAPTIC FEEDBACK IN LAPAROSCOPIC SKILLS TRAINING: LITERATURE REVIEW

2.1 Introduction to Laparoscopic Surgery

Endoscopy can be broadly defined as the tools, techniques and methods of looking and operating inside the human body with minimal incisions. The earliest known effort in endoscopy dates to the Hippocratic period, when a rectal speculum was used to examine organs inside the body. Pioneers that have developed techniques in the field include Philipp Bozzini, Pierre Salomon Segalas and Antonin Jean Désormeaux [1], three physicians who developed technology that enabled the surgeon to look inside the patient's body to detect disease. With the invention of the camera and fiber-optic light pipes, surgeons could insert miniature cameras inside a patient's body through a rigid or flexible tool and view an area of interest [1]. Endoscopy was traditionally associated with diagnostics; that is, inspecting and analyzing rather than treating or performing surgical operations. Laparoscopy is a branch of endoscopy that focuses on inspection of the abdominal cavity [2]. The field of endoscopy has evolved to include tools with the inspection instrumentation that allow the clinician to act on their observations [3]. Laparoscopic surgery, also called Minimally Invasive Surgery (MIS), involves the treatment of abdominal disease or injury using long, rigid tools and camera inserted into the patient's body for observation and surgical manipulation [4]. Approximately two million laparoscopic surgeries were performed annually in the United States at the start of this decade [5-7]. The rapid advancement of laparoscopic surgery as a viable surgical technique is attributed to the desire and push toward patient-centric surgical procedures and the advancement in related technological fields. Indeed, patients that have undergone laparoscopic procedures enjoy the benefits of smaller incisions, less scarring, less post-operative pain, minimal hospital stay, and greater mobility after the operation [2]. As technology continues to progress, new tools and techniques are continually being designed and tested for surgical purposes. A current trend is to reduce the number of incisions from three or four to a single port surgery, where surgeon operate through a single, small incision. This method requires a new range of tools, some of which are flexible [8],[9]. A North Carolina company, TransEnterix Inc., designed the technology that makes single port surgery possible [10], and results were recently reported from the first surgery performed on humans using this technology [9].

Another evolving surgical technique is NOTES, i.e. Natural Orifice Translumenal Endoscopic Surgery [11-19], in which no incision is made on the exterior of the patient. Rather, entry is made through natural anatomical "orifices": the mouth, urethra, vagina or anus. Incisions are then made through internal organs like the stomach or colon to access the required surgical location [2]. Promising results have recently been reported for transgastric NOTES surgeries ([20]) as well as transvaginal cholecystectomies [21-24],[19]. New tools and techniques require a new set of skills for competent surgical performance.

Haptic perception is the human ability to detect properties of objects either through touch or manipulation of the object. The fact that the tool end effector, e.g. the cutting end of the laparoscopic tool, is hidden from direct view of the surgeon suggests that haptic perception of the operating site is important [25]. Haptic perception, like any other skill can be refined through practice [26]. Hence this literature review will focus on laparoscopic surgery and the skills required as well as training methods for achieving competent laparoscopic performance.

2.2 Introduction to Haptics

Haptics (the word derived from the Greek for "to touch" [27]) can be broadly defined to encompass the study of natural and simulated (artificial) touch. The human body's ability to sense touch is one of the earliest senses to develop in a fetus. As the body develops, more complex touch based sensory capabilities are developed. There are three kinds of haptic sensory classifications. The ability to detect properties of objects, such as texture, temperature, softness, based on skin contact is termed *tactile* haptics. An example is using the hand to feel the texture of a fabric. Skin serves, in this case, as the medium through which haptic information is perceived. Another form of touch is when one holds or manipulates objects with limbs; for example, swinging a baseball bat or holding a coffee cup. The body is able to sense properties such as the length, weight, and position of the object as it is being held or manipulated. This kind of haptic sensation is termed as *kinesthetic* haptics. Sensors in the body's muscles and tendons convey information about object properties that relate to efficient grasping and manipulation. Another kind of haptic sensation pertaining to the sense of balance is harder to illustrate. In order to keep the body upright (balanced) while walking, running, etc., the body needs to sense the relative location of organs within itself. This kind of haptic information, used the in organization of organ/limb position for efficient weight distribution, is called *proprioception*. Researchers have long sought to understand the different facets of the human haptic system from a psychophysical perspective. In fact, the coining of the term haptics is attributed to early 19^{th} century psychophysical researchers studying human and animal touch mechanisms [28],[27].

While early haptic studies were confined to the realm of biological and psychophysical sciences, engineers started to look to the field of haptics for answers to questions in remote robot control in the post-World War II era. With the development of nuclear technology, there arose a need for machines that could handle nuclear material that was hazardous for humans to handle. It is in this context that "tele-operators" were built. A tele-operator is a system that has two mechanically coupled machines, commonly referred to the "leader" and the "follower". In most cases the leader and the follower are mechanically very similar, but are not co-located. In other words, the follower system is located at the remote site where the actions (work) need to be performed whereas the leader is located at a safe location for the human operator. Using visual input from the remote site, the human operator performs skilled motions on the "leader" machine. The "follower" mimics the motions of the leader, ideally being regulated by safety mechanical limits. The human operator, thus, uses a machine to remotely perform tasks. This type of remote operation presents some serious challenges to the operator. Because of the operating site being remote, there is limited sensory information available to the operator; vision, haptic, sound and smell cues are limited if not completely absent. Engineers and designers of these machines noted the importance of haptic information for the efficient use of these machines by humans. Sensory information like the texture of materials (tactile) as well as mass-based information like weight and inertia (kinesthetic) were found be crucial for certain tasks. As a result, engineers looked to the field of haptics for ways to incorporate touch information into machines.

A new appreciation for the design and function of the human haptic system was gained while seeking to replicate it in machines. The technology and application areas related to teleoperated haptics were limited and specialized until the early 1990's. During this decade, with the development of inexpensive, small haptic devices and increases in computing power, computer haptics was born. "Computer haptics" refers to *simulated* touch based on the interaction of a haptic device with virtual objects. The user holds and manipulates a haptic device, whose positions are tracked and translated into a virtual "world" containing programmed haptic objects and parameters. When the user encounters objects in the virtual world, the haptic device applies calculated forces on the user's hand, resulting in the illusion of touching or manipulating an object. Figure 2 illustrates users holding and manipulates haptic devices to feel virtual models of the heart.

Figure 2: Haptic devices used for medical applications

Currently there are several commercially available haptic devices ranging in price from a few hundred to several thousands of dollars. The most popular haptic device is called the PHANToM, manufactured by Sensable Inc. (MA, USA). The basic PHANToM Omni features a desktop device which senses movements in all three Cartesian directions and renders forces in 3D (no torques). More advanced devices from Sensable like the PHANToM Premium are capable of rendering forces and torques. Other popular haptic devices include the less expensive Novint *Falcon*, marketed as a gaming device, the Force Dimension (Switzerland) *Omega* and Quanser Inc.'s *Haptic Wand*.

The availability of affordable haptic devices has spawned several fields of study with diverse applications. Haptics has been used to study learning [29-33], children's education [34], in CAD/CAM manufacturing (computer aided design) [35-38], motor skills training and rehabilitation [39-42], surgical robotics [43], surgical skills training [44], and gaming [45]. A majority of these studies suggest or demonstrate benefits to performance with haptic feedback.

Computer haptic systems have two primary components: the haptic device (hardware) and the haptic rendering algorithms (software). The last two decades has seen a great interest in the field of haptic devices, concentrating on the hardware and mechanical aspects of devices. Concurrently, research has also focused on the software and rendering aspects of haptics (algorithms for force/torque). Salisbury and coworkers defined haptic rendering as a "process by which desired sensory stimuli are imposed on the user to convey information about a virtual haptic object [or haptic parameter]" [27]. That is, the software controls the forces (and torques) output to the user through the haptic device using a set of algorithms that check if the device avatar has touched the virtual object (collision detection), how far has the device avatar penetrated into the virtual object and consequently, how much force should be rendered to the haptic device (collision response). Rendering dynamic properties of a virtual object, such as swinging of a bat or wielding a stick, requires constant position input and force/torque output. One of the complexities associated with haptic rendering is the high frequency of rendering. Visual output updated faster than 30 Hz is typically considered suitable for communicating the simulated environment to the user; for quality haptics to be rendered, higher frequencies are necessary (approximately 1KHz servo rate [27]).

The combination of efficient rendering algorithms with mechanically transparent devices produces high quality haptic feel. Limitations in device constructions, such as “backlash” from the mechanical components of the device, may mask and interfere with the values of forces determined by the rendering engine. The haptic device may also have inherent inertia and mass that can impede producing accurate feeling. In an ideal simulation of a physical environment, such as a surgical procedure, the forces computed by the rendering engine will be calculated to mimic the physical world and then these forces will be transmitted by the device to produce a realistic feeling to the user, achieving both of these goals has been elusive in current haptic systems.

Design of haptic devices draws on expertise from many fields including engineering, psychology, physiology, and computer science. One important dimension is understanding the capabilities, limits and thresholds of the human haptic system. As humans, our haptic system is capable of sensing object properties and controlling object motion using sensed information to perform skilled tasks. For example, for the last two decades the Dynamic Touch laboratory at the University of Connecticut has performed various experiments to investigate human perception in haptic wielding. In most of their experiments, human subjects wielded common objects like wooden sticks without looking at them or having any visual feedback, then estimated properties such as length or weight. Quite counter-intuitively, results showed that humans can judge the length of unseen rods very efficiently just based on the haptic feeling from wielding [46-50]. Similar experiments showed that subjects could also estimate weight [51-53], orientation [54],[55],[47], and hand grasp [56]. The results suggest the crucial role of haptic information when objects are held and manipulated. Haptic devices and methods for computer-based rendering of dynamic objects should account for the perceptual aspects of human haptics. Similarly, Lederman and Klastzky performed studies of haptic perception of shape, texture, size of objects perceived with fingers or probes [57-61]. Their results also show key perceptual quantitative and qualitative aspects of the haptic systems in recognizing object properties.

Force and tactile parameters should be rendered within perception thresholds of humans. The Just-Noticeable-Difference (JND) parameter measures the smallest noticeable change in stimulus that can be perceived by a person normalized by the specific stimulus level. This parameter is used as a device- and rendering system; sensitivity of the user to device and the rendering algorithms is measured at varying magnitudes of stimuli [62]. A well designed computer haptic system would match the device performance to the human capabilities. That is, human haptic perception must be considered in the design and rendering stages of haptic systems. Dr. Tan's lab at Purdue University has pioneered the use of psychophysical metrics and methods for device evaluation. Device and rendering methods should be put to perceptual tests for efficient communication of sensory input.

To effectively teach laparoscopic skills outside the operating room, a skills simulator is necessary. For a simulator to be effective it should render aspects of the skill to be taught clearly and efficiently. Some simulators, called high fidelity simulators, aim for simulator "realism" to be as close to reality as possible. Other simulators aim to recreate salient or key features necessary for learning the task on the simulator. This approach can greatly reduce the cost of the simulator while focusing on the skill. The laparoscopic box trainer is an example of a "low fidelity" simulator. For haptic rendering, researchers are turning their attention to determine the required level of fidelity for simulators and salient parameters that must be rendered for skill learning. For example, Kuchenbecker and coworkers demonstrate the perceptual effectiveness of "event-based haptic feedback" for contacting surfaces [63]. Edmunds and coworkers similarly introduce the concept of perceptual rendering, optimizing the user's haptic experience. Previous work by Singapogu and coworkers focused on determining the key (salient) mechanical parameters required to render object properties that are being wielded [64]. The availability of haptic technology holds unique promise to teach surgical skills in an independent and timely manner.

2.3 Skills Required for Laparoscopic Surgery

Between two to four small incisions about 1 cm thick are made on the abdominal wall of the patient [65]. A trocar is inserted into the incision and the abdominal cavity is insufflated with carbon-dioxide gas. The function of the trocar is to keep the CO_2 gas as well as body fluids within the body. Trocars are hollow and have a sealing mechanism allowing laparoscopic instruments to be inserted through the trocar into the body but preventing body fluids from escaping. There are various types of laparoscopic instruments with different functions. One port is usually used to insert a laparoscope, the camera. Lighting for the camera's field-of view is provided through a remote light source like xenon or halogen lamps [65], and the camera's image is viewed on a monitor.

The tools used for performing surgical operations in conventional laparoscopy are long, approximately 50 cm, and rigid [66]. At the proximal end, a handle is designed to control the instrument and the distal end contains the mechanisms for surgical operations. Graspers, dissectors, shears, and electrocautery tools are all available for laparoscopic surgery. The internal mechanisms of the tools consist of levers and other mechanical joints and the sensitivity of a tool to reflect the forces and torques measured at the distal end to the handle to the operator is called the force transmission ratio [67]. Several researchers have investigated the force transmission ratios of commercially available tools with differing results [68-70]. As of yet, standardization of laparoscopic tool design based on force transmission ratios has not been achieved. It is commonly noted that laparoscopic tools suffer from poor ergonomic design and cause hand fatigue for the operating surgeon [66]. As a result, research has also been conducted to provide ergonomic improvements of instruments [71-75].

Given the different setup and tools used for laparoscopic surgery, the question can be asked: will skills in "open" surgery transfer to laparoscopic surgery? When Figert and coworkers compared senior residents with open surgery experience but limited laparoscopic experience, with junior residents with recent open as well as laparoscopic experience, results showed that the junior resident group had fewer performance errors than the senior group. The study concluded that proficiency in open surgery did not translate into laparoscopic skills [76]. Therefore, a new skill set is required to be proficient in laparoscopic surgery. The reviewed literature on this topic has been categorized into the following five areas.

1. *Presentation of Visual Information*: Tendick and coworkers noted that laparoscopic surgery is akin to remote teleoperation; i.e., even though the surgeon is co-located with the operation site, there is a loss of "direct" perception [77]. Unlike open surgery where the surgeon looks directly at the surgical site, in laparoscopic surgery, visual information is obtained by a two-dimensional image on a monitor. The loss of information when presenting a 3D environment via a 2D image is substantial. A human is known to estimate depth through stereoscopic vision in a three dimensional environment. When a 2D image is presented, minimal depth cues are embedded, making depth perception of elements in the image relatively difficult. Specific to laparoscopic surgery, Tendick and coworkers demonstrated that viewing through a camera/display laparoscope is more difficult than monocular direct viewing, increasing the time for successful discerning and

performance of a vision-based task [77]. Several researchers have designed 3D vision systems for displaying information and speculated that surgical efficiency will improve as a result [78-81]. The efficacy of these systems is not clear, as results from these studies are contradictory, likely indicating under-developed and primitive 3D vision technology [82].

2. *The "Fulcrum Effect"*: This term is used to describe the effect of the abdominal wall on the instrument in defining a point rotation that constrains the tool to limited motion in four of the six Euclidean axes [83],[84]. Hand motion in one (linear) direction causes magnified tip motion in the opposite direction, depending on the fraction of the instrument length above the abdominal wall. This "lever effect" not only magnifies motion but also magnifies tool tip forces that are reflected to the user [85],[86]. To test the effect of antipodal hand and tip motions due to the fulcrum effect, Gallagher and coworkers devised an experiment comparing visual feedback under normal conditions and "y-axis inverted" conditions [87]. Under "normal" conditions, the tool tip on the monitor was shown to move in the opposite direction to the hand motion. In "y-axis" inverted condition, however, a visual "correction" was applied (by inverting the vertical axis) so that the tool tip on the monitor appeared to move in the direction of the hand motion. When novice subjects who had no experience in laparoscopic surgery were asked to perform a laparoscopic task, subjects in the "y-axis inverted" group had better incision making performance [87]. This observation illustrates that operation of the tool with the "fulcrum effect" requires intentional learning and is not "intuitively" obvious. In a second experiment, experienced surgeons were compared with novices on both conditions, the

“y-axis inverted” condition was shown to have a detrimental effect on the performance of experienced surgeons [88]. In keeping with previous results, this condition facilitated learning for novices. Experienced surgeons, interestingly, adapted to this new condition rapidly [88].

3. *Eye-hand Coordination*: The laparoscopic surgeon uses the presented visual information to make movements using a tool. The process of using visual information to affect movements with the hand is called eye-hand coordination [83]. Usually, when using one’s hand for making gestures, etc. proprioceptive feedback mechanisms in the body sense position and balance of the hand. When using a tool, however, this information about the hand alone is not enough to specify the tool tip motion [89]. Tool-users need to learn the “kinematic” and “dynamic” transformation of a tool [90]. Users of tools learn to correlate hand motion with tool tip motion through visual feedback. Hanna and coworkers studied the influence of the location of the image (on the monitor) on task performance [91]. Results from the study showed that subjects performed better (time, score of performance) when the image was placed in front of the subject rather than to one side. Further, when the monitor was placed at hand-level with the subjects looking down on the image, performance was further increased [91]. Law and coworkers applied eye gaze analysis to study differences between expert surgeons and novices for a laparoscopic task [92]. Analysis showed that experts tended to maintain their gaze while manipulating the tool, whereas novices tended to track their instruments’ motion during manipulation. Novices needed more visual feedback regarding tool tip position than experts. Consequently, experts performed tasks with shorter times and fewer errors [92].

Efficient laparoscopic tool use requires the learning of the kinematics and dynamics of the tool [55,56]. A study by Zheng and coworkers suggests that in remote manipulation involving tools, “indirect and incomplete proprioception and sensorimotor integration with tool use are the main problems for movement control” [93]. So far, virtual reality simulators have been shown to have some degree of success in teaching eye-hand co-ordination skills to novices [94]. However, most VR trainers lack haptic feedback. The addition of haptic feedback, accurately rendering tool kinematics and dynamics may reduce the learning curve for eye-hand coordination by delivering needed haptic information during tool use.

4. *Reduced and Distorted Haptics*: The sense of touch is another important modality during surgery, with haptic sensation gathered via long, rigid tools. Tactile sensation through the tool is greatly diminished compared to that present during open surgery. Surgeons resort to techniques like gentle tapping to differentiate diseased tissue from healthy tissue. Forces and torques are felt by the surgeon during tissue manipulation and surgical tasks like dissection. The magnitude of forces felt depend on the task at hand as well as the skill of the surgeon [95]. As noted earlier, the fulcrum effect magnifies tip forces depending upon the length of the inserted portion of the tool. Gupta and coworkers noted that tip forces were significantly smaller than handle forces in conventional laparoscopic tools [86]. The forces applied to the tip are distorted due to three interfering components. First, trocar friction, caused by the sealing mechanism between trocar and tool shaft during tool motion, has been shown to be capable of masking tip forces [85] [96]. Second, the reaction torque produced by the abdominal wall at the pivot point is

added to the torque felt by the user and may mask the tissue forces exerted on the tool tip [85]. Third, there are force transmission losses due to instrument mechanisms and backlash [68].

2.4 Laparoscopic Surgery Education

In the United States, after completing four years of graduate education, medical students enter a period of further training called residency. During this period, "residents" choose a medical specialty area and gain the didactic, clinical and technical skills required to become proficient surgeons. It is during this residency period that laparoscopic didactic and technical skills are imparted to trainees. Surgical education in the United States has been primarily based on a mentorship model. The famous American pioneer surgeon William Halsted believed and taught the approach of "See one, do one and teach one", stressing that surgical skills are learned by doing [2],[97]. This was the standard pedagogical method for surgical skills education for over a century [97]. However, the introduction of new surgical techniques has called for new surgical skills to be taught. Concurrently, there has been a shift in teaching philosophy away from the Halstedean approach. There have been a number of factors that have influenced this shift. An expert surgeon training a resident while performing an operation on a human patient has serious ethical and legal issues. Training in the operating room also slows down the surgery, increasing associated costs and increasing the chance for complications. Another main reason is the new restrictions on resident work hours. The Accreditation Council for Graduate Medical Education (ACGME) has mandated that residents work no more than 80 hours per week [98]. In this reduced timeframe and with increased expectations, residents need to learn skills for both open as well as laparoscopic surgery, surgical techniques with different skill sets.

These new requirements have driven interest in devising faster and more efficient training methods, preferably outside the operating room. Of course, operating room (OR) training cannot be entirely eliminated; however, the new goal is that residents will attain a reasonable level of skills outside the operating room and will be better *prepared* when they enter the OR. Valuable OR experience can thus be optimized, lowering the risk to patients and reducing costs. To acquaint surgeons with basic surgical skills outside the OR, various simulators have been devised and tested. The use of simulators is not new in medical education. As technology has developed, so has the range of simulators. Laparoscopic simulators have been devised and tested, ranging from simple physical trainers to sophisticated virtual reality trainers.

In the 1990's, a group of surgeons and engineers at McGill University in Canada recognized the need for simulator-based training for laparoscopic skills [99]. The group worked on a simple pedagogical tool, called the "box" trainer, consisting of a simple wooden box that had ports for inserting trocars and laparoscopic instruments. A small camera, placed within the box, was positioned to capture the motion of the tool tips. The images from the camera were displayed on a video monitor. Concurrently, surgeons in the group identified the basic skills necessary for proficient laparoscopy. The skill domains identified were depth perception, visual-spatial perception, bimanual, complementary use of tools, the endoloop skill (where a suture loop is secured), precise cutting using the dominant hand, intracorporeal suturing, and extracorporeal suturing

[99]. The next step was to model these skills using physical materials and the operating environment approximated by the box. Consequently, five tasks were chosen and modeled using physical materials that covered the identified skill domains [99]. The box trainer, the five exercises and the evaluation metrics used to assess user's performance came to be known as FLS (Fundamentals of Laparoscopic Skills) skills. FLS skills have been widely adopted since their introduction, recently being mandated as the screening exam for residents in American Medical programs to demonstrate competency in laparoscopic skills [100].

The five FLS tasks are peg transfer, pattern cutting, ligating loop, intracorporeal suturing and extracorporeal suturing (Figure 3). These tasks were designed to increase in difficulty from the first to the last task. To measure performance of trainees on tasks, two metrics were devised. All tasks are timed, the time taken to complete the task reflecting the *efficiency* of task performance. Each task also has an associated *accuracy* metric that indicates the precision with which the task was performed. In the first task, known as *peg transfer*, a peg board with six plastic peg pieces is placed on the floor of the box. The user is required to transfer the pegs from one side of the board to the other and back using two laparoscopic tools. Pegs are grasped with a laparoscopic tool in one hand, transferred in mid-air to the other tool in the other hand and placed on the peg board pins. This task is considered the most basic of the five, teaching depth perception and bimanual use of tools and eye-hand coordination. Time to completion measures proficiency in this task and penalty is imputed if the pegs fall out of the field-of-view of the camera.

In the next task, *pattern cutting*, two tools are used to cut the shape of a circle on a gauze pad marked with two concentric circles, staying within the bounds of the outer circle. This task teaches the use of one tool for cutting and the other for providing traction. Users are timed to measure efficiency and deviations from the outer circle are penalized in the accuracy score. In the *ligating loop* task, a pre-tied endoloop must be placed around a marked foam appendage. Users are required to first place the loop around the appendage and then secure it by sliding the pusher rod. A penalty in the accuracy score is scored if the loop is not placed and secured satisfactorily. In the *extracorporeal suturing* task, a Penrose drain, slit longitudinally, is placed on a foam block and used for suturing. Suture (3-0, 75 cm) is introduced through the trocar using a laparoscopic needle driver and the suture is run through both sides of the slit. The suture is then brought outside the trocar and is tied externally using at least three throws to ensure knot tension. After the knot is tied externally, a knot-pushing tool is used to place it on the Penrose drain. Penalties are scored if knots are placed away from marked spots on either side of the slit, for inadequately fastening the slit and for slips of the knot-pushing tool during pushing.

The *intracorporeal suturing* task uses most of the material from the previous task; the knot, however, is tied internally using two laparoscopic needle drivers. First, shorter suture (3-0, 15 cm) is introduced through the trocar and, using the tool, suture is placed through the marked spots on either side of the drain. Subsequently, a knot that has at least three throws must be tied with one double and two single throws. Between each throw, the needle must be transferred to the other hand. Time and accuracy are assessed.

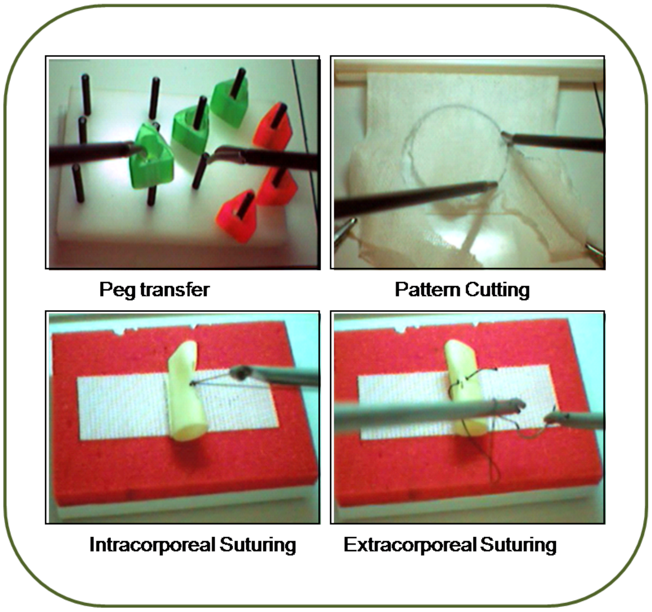

Figure 3: FLS box trainer tasks (without endoloop task); figures courtesy of flsprogram.org

FLS exercises have been extensively studied for differentiating skill levels for laparoscopic surgery and for predicting performance in the operating room. In a landmark study reported by Fried and coworkers, these two aspects were studied for over 200 surgeons after they completed training with the FLS systems [99]. Results showed that the assessment metrics could be used to differentiate between skills levels of novice and experienced laparoscopic surgeons. The metrics could also be used to determine improvements in skill as training of the novices progressed. Further, novices that were trained on the FLS tasks were compared to those that had no training on a live laparoscopic operation. Results showed that those with training performed significantly better than those without training [99]. These results are among the many studies that have showed a positive outcome when residents are trained on the simple box trainer with FLS tasks and metrics. As a whole, the overwhelming consensus in literature is that there is benefit to training with the FLS system. Accordingly, the FLS program has been adopted by SAGES, the premier organization for laparoscopic surgeons in the United States. The FLS exam is now administered in about 30 regional test centers in the United States. Recognizing the growing need for laparoscopic skills education and testing, the American College of Surgeons (ACS) has mandated that all general surgery residents demonstrate competency in laparoscopic skills by passing the FLS examination.

Although the FLS metrics and system have gained wide acceptance within the surgical community, many have questioned its value beyond *basic* laparoscopic skills. The FLS program only teaches the *basics* of laparoscopic surgery and is not a measure of competence in laparoscopic performance [99]. The laparoscopic operating room has many more sensory factors, such as complex haptics and real anatomy contrasted with the few, basic surgical materials presented during FLS, as well as collaborative performance in surgical teams.

As technology continues to improve, so should the quality of the simulators. Residents and surgeons should reap the benefits of more realistic and efficient trainers. To this end, virtual reality (VR) trainers have been proposed as an improved alternative. Using computer graphics software, realistic anatomy can be presented. Tracking of laparoscopic tools using 3D tracking technology can record and analyze motion of the trainee, obviating the most undesirable aspects of the box trainer - the need for an expert supervisor. Expert surgeons are required to train and to assess box trainer performance, and they suffer from lack of objectivity in assessment. With VR trainers, objective assessment is possible based on time, motion and force metrics. The performance of a trainee can also be recorded and tracked over a period of time. VR technology offers the promise of realistic, efficient and objective trainers. Recognizing the potential of simulators, the American College of Surgeons (ACS) has mandated that all residencies establish skills labs with “bench models, simulations, simulators, and virtual reality” [66,67]. Some commercial and research simulators are able to differentiate between skill levels, but very few studies have shown transfer of skills to the operating room. Thus, better simulators that are more realistic, more efficient in discerning skill, and that show strong transfer of skill to the operating room must be designed.

Laparoscopic Skills	**Physical Trainers**	**Virtual Reality Trainers**
Visual Skills – 3D to 2D – Depth perception – Visual-spatial processing – Hand-eye coordination – Tissue identification Haptic Skills – Fine motor control – Force application – Overcome interfering forces – Fulcrum effect for forces	Visual Skills – 3D to 2D – Depth perception – Visual-spatial processing – Hand-eye coordination – Tissue identification Haptic Skills – Fine motor control – Force application – Overcome interfering forces – Fulcrum effect for forces Realism – Laparoscopic tools – Tissues (Visual) – Friction & Fulcrum effect – Tissue behavior (Haptic) Assessment – Automatic	Visual Skills – 3D to 2D – Depth perception – Visual-spatial processing – Hand-eye coordination – Tissue identification Haptic Skills – Fine motor control – Force application – Overcome interfering forces – Fulcrum effect for forces Realism – Laparoscopic tools – Tissues (Visual) – Friction & Fulcrum effect – Tissue behavior (Haptic) Assessment – Automatic

Table 1: Comparison of Box and VR trainers for laparoscopic skills training.

2.5 Operator Perception of Haptics

Forces-based Description of Surgical Environment

Laparoscopic surgeons interact with tissues *indirectly* using tools. Laparoscopic surgery is characterized by loss and distortion of sensory information. Therefore, it is necessary for surgeons to learn a new way of sensing, interpreting and manipulating tissue with tools based on limited haptic and visual stimuli [101]. Haptic stimuli from tool-tissue interactions contain important cues and can aid the surgeon in skilled surgical maneuvers. An important part of laparoscopic training should thus involve teaching novices to perceive and interpret the forces they feel with the tool.

In order to deign efficient training systems, accurate knowledge of the types and range of haptic feedback is essential. When laparoscopic tools are inserted into the abdomen, they encounter organs and tissues, and the tool-tissue interactions produce forces and torques. Additionally, the abdominal wall, where the laparoscopic instrument is pivoted, produces a reaction torque due to the elasticity of skin. The tool also encounters friction from the trocar. These are some of the subtle haptic components that are present during laparoscopy. An understanding of the array of haptic stimuli felt by the surgeon is the basis for devising efficient training schemes.

Tissue Forces Quantification

The laparoscopic surgeon is primarily interested in feeling and handling tissue with tools. If tissue forces can be felt reliably, the forces can give clues about tissue health and properties. The surgeon can use the haptic cues to manipulate the tissue. Studies have sought to measure the interaction forces of laparoscopic tools with tissues during surgical procedures. These forces arise from gestures to manipulate and move tissue as well as from dissecting or peeling. Typically, high-precision tasks generate low forces at the extremity, while low-precision tasks generate higher forces. Tissue properties like mass, stiffness, consistency, shape, and texture can be haptically discerned using these felt forces. Several studies have shown that shape, texture, and consistency of tissues can be felt using haptic feedback alone. [103-105]. The forces applied at the tips of the instruments range from 0.1 to 10.5 Newton according to various studies [44],[85],[106]. The torque due to instrument-organ interaction can range between 0-0.1Nm [85].

Lever Effect

A lever is a physical mechanism where force is magnified around a fulcrum point. Simple levers are commonly used to move heavy objects by placing them on a beam and choosing a suitable pivot point that magnifies applied force. The location of the mass, fulcrum and applied force determine factor of force magnification. The physical setup of laparoscopic surgery creates a lever effect for the laparoscopic tool. For example, if the surgeon applies a force of 1N at the tool handle, and $1/4^{th}$ of the tool is outside the patient's body, force at the tip is 1/3N. Force magnification can be calculated using the torque balance equation, $F_1 l_1 = F_2 l_2$. The forces felt from tissue handling range from 0.5 – 12 N [44],[85],[106]. Based on typical values of instrument insertion lengths and forces applied by the surgeon, the force magnification factor due to the lever effect can range from 0.2 – 4.5 [85]. Recall that force at the handle is greater than force at the tip due to the lever effect.

Another physical effect of the abdominal wall is its reaction force to instrument motion. Reaction force is the response of elastic objects to tensile or compressive forces. Due to the elasticity of the abdominal wall, as the tool pushes against the borders of the incision, a reaction force is generated. Considering the physical set-up of the tool, this force acts at the pivot point. Perceptually, reaction torque on the tool resulting from force applied is more salient. For example, as the instrument is tilted during surgery, making an angle with the vertical axis, reaction torque proportional to the tilting angle is generated. Picod and coworkers measured reaction torques experimentally during OR laparoscopy and, from recorded data, proposed a mathematical model. The equation,

$$T = b\beta + c,$$

describes the relationship between torque (T in Nm) and tilt angle (β). The value b is an arbitrary coefficient of linear elasticity, assuming a linear elastic reaction force and c is an experimentally determined constant [85]. The study reported reaction torque in the range of 0-0.7 Nm.

Trocar Friction

One of the most significant sources of interfering forces is caused by friction between the instrument shaft and trocar. The trocar, a mechanical part placed in the abdominal wall, provides a sealing mechanism to prevent body fluids from escaping. Trocar sealing components are usually comprised of silicon and rubber flaps. Several trocar designs are available, covering a range of sizes, shapes and sealing mechanisms [96],[25].

Some researchers have speculated that trocar friction can reach magnitudes comparable to tissue forces, making haptic tissue perception nearly impossible [85].

Dobbelsteen and coworkers studied friction effects as it dynamically changed with instrument motion for six commonly used trocars [96]. They found frictional forces to be most dynamic at low velocities and stable at higher velocities. The magnitude of friction depended on trocar design and the direction and velocity of the tool. Two types of friction were noticed: kinetic friction, dependant on tool velocity, and "stick-slip" friction caused by trocar components. Kinetic friction caused due to motion of the tool shaft within the trocar ranged from 0.25 – 3 N. Picod and coworkers proposed a mathematical model for kinetic friction based on data gathered during live laparoscopy. Their model, derived from friction theory, used a *Coulomb-Viscous* equation of the form,

$$F_{friction} = -sign(v)A(1-e^{-kv}).$$

The model describes kinetic friction, where A is the maximum amplitude of friction (N), k is coefficient of nonlinear viscosity (sm^{-1}) and v is the absolute value of translational velocity

(ms^{-1}). The values of A and k can be determined empirically from trocar material and mechanical properties.

"Stick-slip" friction is caused from reversal of tool directions– for example quickly changing from pulling to pushing on tissue. During such motion, silicon and rubber parts of the trocar rub against the tool shaft causing friction. The magnitude of friction depends on the area of contact between trocar "flaps" and the instrument shaft. In a study by Dobbelsteen and coworkers, this "stick-slip" friction was found in five of the six trocars. Interestingly, when a few drops of water were added inside the trocars, kinetic friction was reduced by 15% - 45% [96]. Taking simple measures, e.g. regularly lubricating trocars, can significantly reduce friction and increasing haptic sensitivity for the surgeon [96].

Frictional forces are greatest at high instrument velocities and are comparable to tool-tissue forces [101],[44],[85],[96], but tissues are not handled at high tool velocities. Friction can mask more subtle tool-tissue forces, when the magnitudes of both forces are comparable [85]. Generally surgeons are able to use haptics from tool-tissue interactions to discern tissue properties. For example, Lamata and coworkers demonstrated that surgeons were able to distinguish between tissues of different consistencies based on feeling alone [107].

Force Transmission Ratio

When one grasps an object with bare hands, the body's haptic systems use both tactile information (texture, temperature) and kinesthetic information (mass, inertia) to exert appropriate grasping forces on the object. In open surgery, surgeons have the benefit of this rich haptic information. In laparoscopy, much of the tactile and kinesthetic information is lost. The ideal laparoscopic tool would transmit all haptic information at the tip to the handle. But current tools are very basic, transmitting only some kinesthetic and tactile cues to the handle.

To quantify the force reflecting capacity of laparoscopic tools, researchers have devised the term "force transmission ratio", defined as the ratio of grasp forces exerted at the tip to forces felt at the handle [68],[67]. Ideally, this ratio should be 1, but factors such as the mechanical gearing of the instrument, friction and damping in components cause energy losses. Studies by den Boer and coworkers considered more mechanically transparent devices. In their studies, haptic perception of a simulated pulse using several tools was quantified [108]. Sjoerdsma and coworkers tested commercially available graspers and found that some had approximately 50% force transmission loss [68]. This loss is discouraging because the quality of haptics for the operator depends on more perceptually transparent instruments.

In a recent study, van der Putten and coworkers studied the effect of haptic feedback from laparoscopic graspers, tweezers, and bare hands on grasping tissue-like objects with variable stiffness [109]. They reported grasping and lifting, using laparoscopic tools that required 10-14.5 times more practice trials. The number of slips during unsuccessful grasping was directly related to the force transmission ratio of the instrument and showed increase when object stiffness was increased [109]. Studies show that excessive grasping force applied to tissue can cause slippage and even tissue damage [101],[69]. Instruments with good force transmission ratios are crucial to safe grasping of tissue and attention to this detail improves surgeons' haptic sensation [109].

Modeling of Force Perception

Analysis of laparoscopic haptics from a perceptual standpoint may provide important insight from skills training. The first step towards perceptual analysis is listing *all* possible haptic components felt by surgeons. Some of these forces are too subtle for the surgeon to perceive. The set of all *perceivable* forces and torques has been called the *perceptual boundary* [110]. From this set of forces, the surgeons choose which ones give cues for the task at hand [101],[85]. The subset of useful forces for a specific skilled task has been called the utile *boundary* [110]. The grouping of these two sets of force cues are based on perceptual theories.

Lamata and coworkers sought insight into haptics from a perception standpoint [111],[110]. In their study, experienced surgeons were asked to identify tissues of varying stiffness by feeling them with tools, without any visual information. Later, these tissues were tested with standard laboratory equipment and ranked for stiffness. The researchers correlated the subjective opinion of surgeons with objective tissues stiffness values from the laboratory. Analysis revealed surgeons' perceive stiffness of tissues primarily from four parameters: tissue stiffness (K), grade of fixation of tissue in the abdominal wall (*gf*), the mass of tissue held within the graspers of the tool (BS), and the mass of the tissue manipulated. During pulling, the most prominent forces can be modeled based on the equation,

$$F_{pull} = (gf.K.BS)x + m.a + F_{trocar}.$$

Note that the mathematical model is perception based – new haptic quantities were defined by examining surgeons' haptic perception. In the model, tissue stiffness (K) is the Hooke's law-based characterization stress versus strain of tissues. K is highly non-linear for real tissues. Several studies have assumed linear behavior of the tissue for small displacements of the tool into the tissue. The grade of fixation (*gf*) quantitatively describes how firmly tissue is attached to the abdominal wall. Grade of fixation, *gf,* ranges between 0% and 100% [110]. An interesting perceptual parameter discovered in this study was "bite size" (BS), denoting the amount of tissue within the grasper's claws. When surgeons held bigger amounts of tissue they felt a more rigid tissue, altering real tissue stiffness. The combination of BS, K and *gf* produce *apparent* tissue stiffness to the surgeon, based on factors other than true tissue stiffness. In the model, mass of the tissue (*m*) was also speculated to affect tissue stiffness consistency. Trocar frictional forces were added to the perceptual model since these forces are of comparable magnitude to tool-tissue forces. The variables x and a denote position and acceleration of the tool respectively [110].

The value of such perceptual models can be significant for haptic training. This study showed that surgeons rely on *perceptual* information more than physical, objective values [112],[5]. Haptic perceptual training should include teaching residents to extract useful parameters from available haptic stimuli. Different surgical tasks can have different salient haptic parameters. Identification of task specific force cues (e.g. stiffness, mass) can be used in training, teaching attunement to salient parameters and ignoring interfering forces.

Effect of Experience upon Perception

Compared to open surgery, laparoscopic procedures have a higher rate of incidence for injuries [113],[114]. For example, of the approximately 500,000 cholecystectomies (mostly laparoscopic) performed in the early 1990's, as many as 2000 resulted in bile duct injuries. This statistic is not surprising considering the difficulty laparoscopic surgeons have with minimal sensory (haptic and visual) cues. Understanding the behavior of surgeons with laparoscopic tools and tissues can help devise better training and reduce injuries.

One of the leading causes of laparoscopic injuries is excessive application of force [115]. Since laparoscopic surgeons use tools instead of hands, they are prone to incorrectly estimate forces being applied on tissues. Cao and colleagues have conducted studies to analyze force application behavior using laparoscopic tools [112],[5],[116-118]. In one study, subjects used laparoscopic tools to probe tissue-like artificial materials [117]. Subjects were instructed to touch the material using as little force as possible. When they detected contact, the tool was to be withdrawn immediately. Users conducted the task with and without visual feedback and with and without trocars. To examine user behavior, two metrics were designed– the *force perception threshold* and *force application efficiency*. Force perception threshold was defined as the minimum force applied by the user to detect (perceive) contact. Force application efficiency was defined as the inverse of the amount of time elapsed between *actual* contact with the tissue and *perceived* contact with the tissue. The combination of both time- and force-based metrics is indicative of probing efficiency. Results showed when users detected contact with haptic feedback alone, they applied greater force, took longer to detect contact and made more surgical errors than in the haptics plus vision condition. If the tool was inserted through a trocar, all metrics showed increase; i.e., subjects performed worse. Friction from trocars caused subjects to apply greater forces to overcome its effects, raising the perceptual threshold to detect contact. This study isolated the effect of pure haptic feedback and trocar friction for force application [117].

In a later study, Zhou and colleagues assessed if experienced surgeons had different haptic behavior than novices. One can assume that expert laparoscopic surgeons have learned to apply optimal forces with the tool. The authors hypothesized that experienced surgeons would apply less force, with and without friction, and rely more on haptic feeling. The task was identical to the previous experiment as were the feedback conditions. Experienced surgeons consistently applied more force than novices to detect tissue contact. While novices applied an average force of 3.6N, experienced surgeons applied an average of 1.83N more than novices with no vision and 1.51N more than those with vision. On the other hand, experienced surgeons detected contact faster, averaging 0.45 seconds faster without vision and 0.1 seconds faster with vision. When the same task was conducted with trocar friction, experienced surgeons applied greater forces (63% more with vision and 41% more without vision). Novices also increased their applied forces but the increase was less pronounced. Rejecting the original hypothesis, experienced surgeons applied more force. When the experienced surgeons had visual feedback, they seemed to deliberately apply forces to visually *see* tissue deformation [5].

These studies give important insight into the perception-based haptic behavior of novices and experienced surgeons. When exerting forces on tissues, experienced surgeons apply greater force but not enough to damage tissues. They know by experience that perceiving contact forces from low applied force is subtle because of interfering components that can mask tip forces. Relying on these weak force cues is inefficient. So, to perceive tip forces with assurance, higher force needs to be applied to get higher reaction force on the handle, overcoming masking forces. However, expert surgeons are unlikely to exceed the limit of force that can cause tissue damage. The experienced surgeon has learned that clear perception is possible only at higher force levels, overcoming noise cues. They also know the force limit beyond which tissue injury occurs. The expert surgeon operates in this *perceptually optimal* force range [101],[85].

Perception-based analysis of haptic behavior can thus lead to specific criteria for training. Residents can be trained to operate tools in this optimal force range. The confusion caused by relying on subtle cues can be demonstrated. Perception-based criteria can enable faster, goal-oriented training, leading to efficient surgeons and safer patients [5],[116].

2.6 Utility of Haptic Feedback in Laparoscopic Surgery

Quantitative studies prove that haptic feedback *is* present during laparoscopy; however, some researchers have suggested that haptics is not useful for surgical tasks [85],[119-121]. Others have demonstrated that haptic feedback (primarily kinesthetic) can be *useful* for surgery [85]. Bholat and coworkers conducted one of the earliest studies on the qualitative aspect of haptic feedback [105]. Their study was designed to determine if experienced surgeons could use laparoscopic tools to determine properties like shape, texture, and consistency of objects. Subjects probed and manipulated various materials with tools and estimated the material properties by feel. Performance with laparoscopic tools was compared to conventional tools used during open surgery and direct touching with gloved hands (palpation). Subjects were given objects of different shapes, materials with different textures, and springs with varying spring constants. They determined shape, texture and consistency using three modes of touch. To identify material texture and spring consistency, reference materials were first felt; subjects reported these properties relative to the reference. Direct touching by hand was best for identifying object shape. Instruments were found to be better than hands in identifying finer textures. To determine object consistency, all there modes of haptic feedback were found to be comparable. This study found that laparoscopic instruments *do* provide haptic feedback useful for shape, texture and consistency identification. Other studies have shown that laparoscopic tools can be useful in determining specific object properties [105],[122].

Similarly, Lamata and colleagues performed several studies to determine if tissue consistency can be determined using haptics from laparoscopic instruments

[123],[111],[124],[107],[103],[110],[125]. Tissue consistency was defined as "resistance felt against the penetration (pushing) and withdrawal (pulling) of a grasper holding the tissue" [103]. In one of their studies (mentioned earlier in this work), surgeons reported tissue consistency using four primary modes: written questionnaire, visual feedback alone, haptic feedback alone, and combined visual and haptic feedback [103]. Subjects rated tissue consistency on a scale of 0 to 10– 0 being the tool felt with no mass grasped (0), 5 with a mass of 250g grasped, and 10 that of grasping a "fixed structure". In the written questionnaire, surgeons were given a list of ten common porcine tissues and were asked to rate them for consistency. In the visual session, 10-second recordings were played of four different tissues being pulled and pushed. Using this information, surgeons ranked the four tissues on visually perceived consistency. In the haptic session, subjects used four laparoscopic graspers that held the four tissues (used in visual session) and probed tissues. In the visual and haptic feedback session, subjects had both haptic and visual feedback to rank the four tissues for their consistency. An additional task presented after the haptic-only session was to identify the four tissues based on feel, from a list of 11 tissues and 4 tissues respectively. This task was expected to give insight into how well surgeons could identify particular tissue using haptic information alone [103].

Results from written questionnaires revealed low agreement with the ratings from the vision plus haptics stage. These results indicate that textual description of tissues alone was not sufficient for accurately rating tissue consistency. In the vision-only stage, consistency ratings were better that in the written stage but nevertheless, showed weak correlation to vision plus haptics results. This suggests that visual feedback alone cannot fully deliver consistency information. The correlation between the haptic session and haptics plus vision session was highest. Expert surgeons, however, performed equally well with or without visual feedback, probably because visual feedback adds little to an expert surgeon's knowledge on tissue consistency. From this result, the authors concluded that "tactile information seems to be the source used by users to feel tissues and rank their consistency" [103]. The ability of surgeons to identify specific tissues from a given list based on the haptic feedback alone was also assessed. Surgeons could not successfully equate feeling with tissue name based on haptic information alone. Primarily, the study demonstrated that in order to accurately render tissue consistency information to the surgeon, haptic feedback is necessary.

Another study demonstrating the significance of haptic feedback was conducted by Tholey and coworkers [104]. This study tested two research hypotheses: (1) haptic feedback alone leads to better characterization of tissues than visual feedback alone, and (2) combining visual and haptic feedback leads to better characterization than haptic feedback alone or visual feedback alone. Tissue-like artificial materials were handled using a custom-built laparoscopic tool connected to a robot. The robot controlled movement of the tool in 3D as well as grasping with the jaws of the tool. The study used three artificial, tissue-like materials whose softness varied considerably. In each trial, subjects were asked to rank the three materials from softest to hardest based on visual, haptic, or both visual and haptic feedback. For visual feedback, video from a CCD camera was presented to the user as the automated tool grasped the material sample. For haptic feedback, the jaws held the material and grasped it until the two jaws were at a pre-determined angle. The grasping force, a function of motor current of the tool jaws, was haptically presented to the user using a PHANToM haptic device. Data from the study showed that subjects were able to perform significantly better when both haptic and visual feedback was presented than when either haptic feedback alone or visual feedback alone was presented. When investigating the first hypothesis, the authors found that, though performance was better with haptics alone than with vision alone, this result did not achieve statistical significance. Though haptic feedback in this experiment was not the same kind as haptics present in laparoscopy, the sensory mode of touch can be more suitable for communicating certain object properties.

Another approach to validate the use of haptic information is by building better force reflecting tools and assessing performance with them. Bicchi and coworkers [126] and MacFarlane and coworkers [127] devised custom instruments that rendered tip forces at the handle using mechanical components. Bicchi and coworkers modified a commercially available laparoscopic tool by adding force and position sensors. Force information was presented to the user graphically. Preliminary results showed that the users were able to perform better using force information from the sensors [126]. In a similar study, MacFarlane and coworkers tested users' ability to differentiate compliance of different specimens based in three modes: using a gloved hand, a standard Babcock grasper and their custom "force-feedback" grasper. As can be expected, the gloved hand was the most effective in ranking compliance. The custom built device was better than the standard Babcock tool when ranking compliance. [127].

These studies point to the use of haptic feedback in reflecting properties of objects and how this can affect perception and performance for the better. These studies are examples showing the use of haptic feedback during laparoscopy. Certain specific tissue properties like consistency (stiffness) and texture can be most readily determined by tool-tissue haptics. These studies demonstrate that surgeons must give attention to the cues contained in haptic feedback. Laparoscopy trainees must be taught reliance on specific haptic cues.

2.7 Haptic Feedback in Training Involving the Application of Forces

Laparoscopic surgeons spend a substantial amount of operating time applying forces on tissues and organs for specific purposes. For example, by feeling the surface or gently tapping tissues with laparoscopic tools, abnormal tissues can be diagnosed [128]. This task is called *palpation*. Several studies, primarily at the Bio-Robotics Lab at Harvard University, have focused on remote palpation technology and the haptic sensations associated with it [129-131]. In open surgery, surgeons have ample force and tactile cues from feeling and handling tissues with gloved hands. In laparoscopic surgery, however, surgeons find tissue palpation difficult because of decreased and distorted haptics. Tele-robotic sensors and systems have been developed to detect lumps and unhealthy tissue based on tactile information when probing tissue with a tool. McCreery and coworkers developed a force-sensing probe that located simulated tumors in tissue based on a force range of 0 – 10N and resolution of 0.01N [132]. Tissue *manipulation* means grasping and moving parts to expose areas to be worked on and to clear interfering organs. *Dissection* is the removal of damaged tissue and organs by cutting and tearing it from healthy tissues. As one would intuitively assume, skilled surgeons use their tools to not only sense tissue properties but also to apply controlled forces on the tissue. Force skill is thus an important aspect of laparoscopic training.

It has been estimated that surgeons spend as much as 35% of their time performing dissection tasks [133],[134]. Wagner and coworkers studied the effect of haptic feedback on the performance of a blunt dissection task. The experimental task involved cutting through soft tissue (synthetic and real) and exposing an embedded, harder artery using a laparoscopic dissection tool. The physical setup consisted of a tele-robotic system with two standard PHANToM devices for haptic feedback. One device (the “follower”) was connected to the tip of the instrument and the other device (the “leader”) was used by the operator to perform the task. The follower device mimicked the motion of the leader device. The leader device, however, rendered force feedback so that the user felt forces depending upon his motion. Subjects received force feedback with different force gain amplifications, 37% haptic feedback and 75% haptic feedback, based on hardware capabilities. Participating subjects were novices from non-medical fields, surgical residents, and practicing surgeons. Analysis of subjects’ performance on the dissections tasks revealed that in the absence of force feedback, the average magnitude of applied forces increased by about 50%. Average peak force applied also increased by about 100% as it did without haptic feedback. The number of errors (forces exceeding threshold) increased by a factor of three when no force feedback was present. Conversely, the presence of force feedback significantly reduced the magnitude of forces applied at the tip of the instrument and also led to a reduction in the number of errors. Interestingly, users applied similar forces in both low fidelity (37% haptic feedback) and high fidelity (75% haptic feedback) conditions. This suggests that as long as forces are perceivable, even lower magnitudes of force feedback can be useful for force application tasks. The authors of the study speculated that increase in performance with haptic feedback was because subjects felt forces as physical constraints on the tissue. In an earlier study, the authors reported that rendering a virtual wall mechanism for a similar task reduced force errors by 80% [135]. For example, the stiffness of the artery and relative softness of tissue translated as physical contours and were cues for dissection. Surgeons in the subject pool had consistently applied higher forces and made more errors than novices. Their “errors”, however, did not adversely affect tissues and were below tissue damage forces. This confirms earlier findings that surgeons use a higher force range than novices when dissecting tissues [133].

The salient result of this study was that, with haptic feedback, subjects applied *lesser* forces to tissues. Tissue trauma occurs when forces beyond a certain range are applied. Other studies confirm findings by Wagner and coworkers and the effect of haptic feedback on human performance. Braun and coworkers tested if haptic feedback improved suturing performance on a cardiac surgery robot [136-138]. Results showed that, with haptic feedback, surgeons applied significantly less force and broke less suture material. When asked if haptic feedback has any psychological and sensory benefits, surgeons reported a greater sense of immersion in the surgical setting and reduced fatigue. Similarly, Deml and coworkers built a custom force feedback system for robot-assisted minimally invasive surgery. With force feedback enabled on the master device, unintentional injuries on tissues were reduced. Their study showed an increase in task completion time with haptic feedback [139],[140]. Dankelman and coworkers trained users for a force application task using force feedback presented graphically in the form of error bars. Subjects that received feedback performed better when tested on applied forces [141],[142]. These studies collectively ascertain that haptic feedback *affects* the magnitude of forces users apply with their tools. Since skilled force application is important for laparoscopic surgery, training must include haptic feedback. Simulators for force applications task must have haptic feedback for efficient instruction.

In a recent study performed by Chmarra and coworkers, the role of haptic feedback in force application tasks was studied. In this study, residents performed three tasks that required different levels of force application with the tool. Two trainers were used, a conventional box trainer and a VR trainer with no haptic feedback. Residents were asked to train using both trainers in a specific order: Box-VR and VR-Box. The Box-VR group trained on the box trainer first, followed by a VR trainer, while the VR-Box group trained on the VR trainer first. After training, residents performed all three tasks in a box trainer. Performance was assessed using three metrics: time to completion, path length, and depth perception. Results of the study showed that, for tasks that required minimal force application skill, no difference in performance was observed between the two groups. However, in the task where force application was essential, the Box-VR group performed significantly better then the VR-Box group. The advantage of the box trainer was the real haptics sensation felt by trainees as their tools interacted with materials. The VR trainer had visual feedback but no haptic feedback. The Box-VR group outperforming the VR-box group seems to indicate that the box trainer provided the necessary haptic training for controlled force application. When haptic feedback is absent, vital force cues are lost and users rely heavily on visual cues. Though some force cues (deformation, for example) can be discerned from visual display, it cannot completely compensate for haptics. The authors suggest that simulators that do not render haptic feedback cannot train users to correctly process the forces they feel during surgery.

Another interesting observation from the Chmarra study is the effect of simulator training *order*. Subjects that trained on the box trainer first had the advantage, learning to use haptic sensations from the tools and materials. Subjects that first trained on the VR trainer had poorer performance even though they were later exposed to the box trainer. Apparently, users that first trained without haptics could not learn to use haptic sensations from the box trainer later on. Haptic feedback, necessary for skilled force application, should be included in advanced laparoscopic simulators. Through VR simulators that do not have force feedback can teach basic hand-eye co-ordination and visual processing skills, force sensing and application skills need haptic feedback.

Haptic Feedback in Commercial Laparoscopic Trainers

With the development of commercial haptic technology in the last decade, researchers are seeking to include it in laparoscopic trainers. Currently, a few VR trainers have haptic feedback capability. Though addition of haptic feedback is expensive, it promises realistic "feeling" and immersion. An example of "first-generation" haptic laparoscopic trainers was provided by McColl and coworkers. They built custom hardware for simulating force sensations and measured user perception on the simulator. The Just-Noticeable-Difference (JND) metric was used to measure various haptics-based parameters like mass, friction, stiction, elasticity, roughness and viscosity. The JND for most haptic parameters was found be approximately 12 %. User performance was measured for a simple tissue holding task [62]. Though haptic simulators like McColl's have been physically designed, having them render realistic sensations has been arduous. Realistic haptic feedback is hard to simulate because less attention is given to perceptual and psychophysical aspects of device design. Consequently, only few commercial simulators have ventured to include haptic feedback.

Generally speaking, commercial haptic VR simulators have not been very successful in teaching force skills to residents. For example, Salkini and coworkers studied the effect of haptic feedback in the LapMentor II (Simbionix Inc.) surgical simulator. Residents performed three tasks requiring skilled application of force with and without haptic feedback. Residents were assessed based on simulator built-in metrics of speed, accuracy of movement and economy of movement. Results showed no major differences between the two groups. A surprising finding was that members from the haptic group had significantly slower movements of their dominant hand. The authors suggest that the haptics did not improve performance, perhaps due to poor haptic feedback of the simulator. Rendering unrealistic haptics, not based on physical principles can have little benefit [143].

Panait and coworkers studied the benefit of haptic feedback on Immersion Medical Inc.'s Laparoscopy VR simulator [144]. Ten residents performed two common laparoscopic training tasks with and without haptic feedback. The first task was *peg transfer* and the second task, *pattern cutting*, was more complex and involved precise force application. Residents performed both tasks at three difficulty levels chosen from the simulator's software options. Residents were assessed using the metrics of time to completion, instrument path length traced, errors, and grasping tension. Results from the study showed no significant differences in performance for the peg transfer task with or without haptics. For the pattern cutting task, however, there was a significant decrease in the time to complete the task for the haptics group. The other metrics, though they did not achieve statistical significance, showed a positive trend for the haptic feedback group. The authors concluded, akin to the study by Chmarra and coworkers, that haptic feedback allowed better performance and completion of more complex tasks. This haptic simulator showed a moderate benefit to using haptics, in contrast to the significant benefit showed by the box trainer [145]. One reason suggested for the poorer performance is that haptic feedback on the simulator needs further tuning. The authors point to the significant expense of adding haptics to current simulators and suggest using haptic simulators for training more complex haptic skills [144].

Kanumuri and coworkers performed an interesting study comparing two different types of laparoscopic trainers: VR (MIST-VR) and AR (ProMIS). The VR trainer did not have any haptic feedback; the AR trainers had haptic feedback from real instruments interacting with synthetic materials. The aim of their study was to see if two different types of trainers could produce similar training. Residents trained in intercorporeal suturing and knot tying tasks. After training, residents performed both tasks on an animal model, and performance was assessed by recording task completion rate and completion time. Both groups had comparable results after training. Note that the only two metrics were used to measure performance in this study and both were time-based. Using more metrics (accuracy, movement, and force) could give more insight into differences between the simulators [146]. When residents were asked if haptic cues were important in simulators, 88% responded in the affirmative. Residents also rated the AR simulators as ones that represented the real surgical setting more accurately. The authors conclude that haptics does play a role at least in the perception of surgeons and trainees; presence of realistic haptic cues can lead to a greater confidence in the relevance of the skill being learned.

The reason some studies show no benefit with haptics is because some specific skills do not necessarily need haptic feedback for training. Laparoscopic suturing is one example. Botden and coworkers conducted a study comparing box and VR trainers for teaching suturing skills [147]. Results showed better performance for box-trained subjects, though they did not reach significance. When residents were asked their preference between the two trainers, the box trainer was preferred over the VR trainer [147]. The authors speculate that haptic feedback may not be necessary for suturing training. A similar study by Tse and coworkers found that haptic feedback may not be significantly useful in laparoscopic suturing training. The authors hypothesized that the learning curve would be lees steep and quicker in the presence of haptics than without. However, after 5 hours of training with and without haptics, no significant difference was found in performance of the task. The authors reported that though the addition of haptics showed some value in enhancing performance, it is not significant enough to warrant use for suturing training [148].

Suturing primarily involves skillful, precise *movement* of the tool, especially knot tying. Haptic feedback in this case, primarily based on the tool's dynamics, is not pronounced. On the other hand, *accurate* haptic feedback is critical for tasks requiring skilled force application. Since force application is not the primary concern in suturing and knot-tying, haptic feedback may not have significant value.

Haptic Feedback in Novices and Experienced Surgeons

Strom and coworkers studied the effect of haptic feedback when introduced early in laparoscopic training. Thirty-eight surgical residents were randomly divided into two groups: early haptic training and late haptic training [149]. The early haptic training group trained with haptics for 1 hour then without haptics for 1 hour, whereas the late haptic group started training without haptics (1 hour) then with haptics (1 hour). The training tasks were two diathermy tasks on a VR simulator with and without haptics. The effect of haptics in this study could be isolated because, apart from haptic feedback, the graphical and hardware contexts were identical. The metrics used to assess performance were a combination of time, economy of movement, collision errors between instruments, and other task-specific movement errors. The evaluation scheme was validated from previous studies on the simulator. After two hours of training, results showed that the group that started with haptic feedback performed significantly better than the late haptic group. Also, the early haptic group saw a significant performance increase in the second 1-hour session that involved training without haptics. Thus, introduction of haptic feedback early in training could make the learning curve less steep. The benefit of haptics for novices may stem from having an additional sensory channel. Sensory cues can be distributed between visual and haptic sensory channels. Some studies suggest that perception is best when it is gathered from different channels (visual, haptic, auditory, etc.) and integrated [150],[151]. The novice trainee must learn to optimally process these different sensory stimuli and correlate them appropriately for performing specific task functions [149].

In the same vein, Cao and coworkers studied the effect of haptic feedback on cognitive loading and experience [112]. Cognitive loading is the level to which the brain is engaged while processing and performing tasks. The brain receives stimuli from different sensory channels, interprets them, and determines appropriate courses of action. The effect of cognitive loading while performing a primary task can be studied while presenting a less demanding secondary task to be performed. In their study, Cao and coworkers studied the effect of haptic feedback on cognitive loading while performing a simple transfer of material task in a laparoscopic simulator. Two simulators were used for this purpose: the MIST-VR, without haptic feedback and the ProMIS, with haptic feedback. Thirty-eight surgical residents and attending surgeons performed the TransferPlace task on both simulators, with and without haptics and with and without cognitive loading. Cognitive loading was imposed by presenting a simple arithmetic multiplication task (e.g. 21×11=?). Results from the study showed that subjects performed 36% faster and 97% more accurately with haptic feedback than without, even under cognitive loading. When not cognitively loaded, subjects performed 37% faster and 97% more accurately with haptics. This demonstrates two effects of haptic feedback. First, haptic feedback improves performance of the task. Second, haptic feedback reduces the effect of cognitive loading. Another interesting result of the study was the effect of haptic feedback on users with different levels of laparoscopic experience. When haptic feedback was present, performance improvement was much greater for experienced surgeons than inexperienced (when not cognitively loaded). Experienced surgeons may use haptic feedback more than novices because they have learned how to use force cues.

This result may importantly show that haptic cues are indeed *used* by experienced surgeons during surgery. While results showed some benefit for novices from haptics, it was the experienced surgeons that benefited most [112].

The use of haptic feedback by experienced laparoscopic surgeons suggests that novices must be trained to use haptics. Novices that are exposed to haptic feedback early learn how to process and use force cues. The presence of haptic feedback has important cognitive benefits, e.g. preventing mental overloading. When visual feedback is the sole source of sensory information, surgeons risk saturation of the visual sensory channel. When haptic cues are also present, distribution of information among the two channels and integration of sensory information results in optimal cognitive processing.

Haptic Simulation Fidelity for Training

A simulator replicates a real task with a degree of realism. When designing a simulator one may ask: what level of fidelity does the simulator need to have in order to achieve meaningful training and skills transfer? In many cases, it is not possible to render the simulator task as an exact copy of the real world task because of hardware and software limitations as well as cost considerations; however, rendering the *salient* features of the real environment in the virtual trainer may still be possible and efficient. Users train on the simulator using these salient features and transfer learned skills to the real task [152]. For this approach to be successful, however, knowledge of the salient features of the task must be known. Also, the features must be scaled appropriately, based on hardware requirements. In the context of reduced sensory information, the trainee learns to perceive cues needed for the task. *Simulation fidelity* is thus an important issue for laparoscopic trainers, especially for haptic feedback. Adding haptic feedback to current simulators can be expensive. For haptics in laparoscopic trainers to be beneficial, some important research questions pertaining to the scaling of haptic forces, the degrees of freedom required for efficient rendering and the role of hardware must be answered.

Kim and coworkers designed a virtual laparoscopic trainer that modeled laparoscopic pushing and cutting tasks. Haptic feedback was given to the users at different levels by approximated linear as well as non-linear tissue models. When force feedback was presented, subjects were able to more readily transfer skills learned in the trainer. Also, results showed comparable outcome in training between the linear (approximated) and non-linear models. Despite the highly complex, non-linear behavior of real tissue, an approximated linear model can be used to teach basic skills. This approach of using simpler, approximate models can overcome limitations in current haptic technology [153].

Research effort is also needed to understand how forces rendered by devices are perceived by humans. In a study by Bell and coworkers, real forces from a tissue probing task were simulated using a virtual device [154]. These virtual forces were scaled at four different levels, some proportional and some disproportional, to real forces. It was found that, during virtual probing, greater forces were applied, the time to detect tissue using the probe was longer, and movement errors were larger. The authors suggest that humans process virtual haptics differently than real haptics. The transfer of information between the virtual device and human is different from the real tool and human. Perceptual "tuning" of virtual devices seems needful of proper training and skills transfer [154].

Haptic Feedback in Laparoscopic Skills Evaluation

Conventional laparoscopic training involves expert surgeons training residents in an apprenticeship model [97]. The resident learns laparoscopic skills as applied to animals and humans. Sometimes, novice residents perform laparoscopic surgery on humans in the operating room under supervision. This training model not only poses ethical questions but has significant effects on operating time and costs. Though OR training cannot be completely eliminated, residents can come to the OR better prepared. Conventionally, box trainers were used to teach basic laparoscopic skills to the resident with some success. A major drawback, however, of the box trainer is the inability to assess performance. Expert surgeons are needed to rate and give feedback *as* the resident trains. This requires the expert surgeon's time, drawing him/her away from the operating room. The expert also needs to "start from scratch" when teaching skills. Eliminating, at least minimizing the need for an expert surgeon, until the trainee reaches basic skill proficiency is a better training model. Experts can be used to teach more advanced skills.

One of the most promising aspects of Virtual Reality trainers is automatic performance evaluation. Sensors in VR trainers read position and force data from laparoscopic instruments, recording and using that information for evaluation. Algorithms then use metrics to analyze and score trainee performance. Several commercially available VR and AR trainers feature automatic performance evaluation [155]. Considerable research in the past decade has been devoted to devise and validate metrics for performance assessment. Commonly used metrics are time, economy of movement, and movement errors. Intuitively, one can infer that as skill level improves, time to complete surgical task should decrease. Economy of movement can be measured to determine skill level because experts make goal-oriented movements, requiring optimal 3D paths. Movement errors quantify excessive motion, large movement errors possibly damaging tissue. Time and movement metrics are used in FLS skills assessment [156]. Other task-specific metrics have also been useful for differentiating skill level. For example, in suturing, distances between suture points, length of suture and suture quality can rate performance [157].

Researchers have used several metrics like path length, depth perception (based on linear motion), rotational orientation and area, volume swept during motion, and smoothness of motion to assess skill [221]. Cotin and coworkers, for example, proposed a composite of five kinematic parameters as a metric for assessment. The individual weighting of each parameter was not discussed in their report [158]. A survey of metrics used for laparoscopic skill assessment is described elsewhere [156]. Of the above cited metrics, most are time- or movement-based. While movement metrics show efficient tool handling, another key aspect of laparoscopic surgery is the application of optimal forces. Studies investigating force behavior report significant differences between novices and experienced surgeons [133],[157],[95]. Though force application seems a viable assessor of laparoscopic skill, few studies use force metrics for evaluation. Some studies have assessed depth perception as a function of movement along the axis of the tool. Force, F, on the other hand, is non-linearly related to linear motion coupled with mass (*$F = ma$, where m is mass and a is acceleration*). To evaluate performance based on force information, this relationship can be used. One reason force metrics may not have been used prolifically so far is because extensive information on laparoscopic force behavior was not available. With its documentation and the current availability of force sensors, using force metrics can aid the laparoscopic skills evaluation.

Most simulators assess performance after the task has been performed. From a perceptual perspective, real-time metrics *while* performing the task can be extremely useful to the trainee. The former have been called "outcome measures" and the latter "process measures" [157]. More recently, researchers have sought to develop real-time performance measures laparoscopic skills.

Earlier cited work by Wagner and coworkers showed that surgeons applied more forces than novices in a tissue dissection task [133]. Zhou and coworkers showed that expert surgeons consistently applied more forces than novices both in the presence of trocar friction and without friction [5]. Both studies were not conducted during laparoscopic surgery; they used simulated tissue-like materials in standard box trainers. The most comprehensive study of force behavior among laparoscopic surgeons was conducted by Dr. Jacob Rosen and colleagues at the Bionics Lab at the University of California, Santa Clara. In 2000, this group published results from a study where the objective was "...to measure and compare forces and torques (F/T) applied at the tool-hand interface generated during laparoscopic surgery by novice (NS) and experienced (ES) surgeons using an instrumented laparoscopic grasper…" [95]. A standard, commercial grasper was modified to hold two sensors, including:

1.A force/torque sensor to measure Cartesian forces and torques in all three axes

2.A second sensor to measure the grasping force between the claws of the gripper

A seven component force/torque vector was output from the sensors. Please note that forces and torques were not measured at the tip of the instrument, but at the handle. Ten surgeons, five experienced in laparoscopy and five novices, were recruited for the study. Each surgeon performed two standard laparoscopic procedures, cholecystectomy and Nissen fundoplication, on a porcine model. Common laparoscopic tasks like positioning organs, exposing and dividing specific ducts, dissection and suturing were classified based on expected force behavior from surgeons. Apart from measuring force data, the other goal of the study was to create a database of force "signatures" for specific tasks. A force/torque signature was defined as "a typical set of force and torque components associated with different tool-tissue interactions" that defined and characterized that surgical gesture. This data of force/torque signatures could then be used for evaluating performance. [95].

For the purpose of defining sub-tasks, five basic classes of laparoscopic operations were listed, called Type I actions. These are (1) idle state, where the instrument is not in contact with tissue but in motion, (2) grasping, where the surgeon's primary focus is grasping tissue, (3) spreading, where tissues are being manipulated, (4) pushing, for manipulating tissue as well as dissection and (5) sweeping, where retracting movements of the tool are dominant. Type II and Type III actions are defined as combinations of these five basic gestures with increasing complexity. While surgeons performed laparoscopic procedures, video and force data was recorded. Video data was correlated with force data during analysis to associate pertinent force data with sub-tasks [95].

Analysis of the data showed five areas where differences between experienced and novice surgeons were observed. First, the type of gestures performed by novices and experts were different. Though both groups had clearly defined goals, the surgical gestures used to accomplish the goals were different. Some gestures used by novices were not used by experts. This may point to efficient dexterity and tool handling by experts. Second, there was a significant difference between the mean completion times between the two groups. Novice surgeons took 1.5 to 4.8 times longer than experts. Another interesting fact is that novices spent a significant amount of time in "idle" (no tissue contact) state than experts, possibly because novices are more tentative when handling tissues. We earlier cited Zhou and coworker observations that expert surgeons possess a working knowledge of how tissues "feel" and apply more forces confidently [5]. Another probable reason for greater time spent in the idle state could be because novices have lower dexterity and tool-handling skills [95].

Perhaps the most interesting result of the study pertains to the force/torque magnitudes during gestures and the differences between experts and novices. From the seven component force/torque data for each participant, three components showed statistically significant differences: (1) force in the direction of the axis of the tool, (2) grasping force, and (3) sweeping torque. The means of applied force/torque magnitudes between the two groups were also significantly different. In 8% of analyzed tool-tissue interactions, no significant difference was observed. In 92% of tool-tissue interactions, however, significant differences between novices and experts were observed. In 23% of these cases, novices applied higher forces than experts and, in 69%, experts applied higher forces than novices. The tool-tissue interactions associated with these significant force differences were classified into two broad tasks: tissue dissection and tissue manipulation. Tissue dissection is where force is being exerted by the surgeon on the tissue along the axis of the tool. Tissue manipulation is when force is being applied to move tissue, ducts, etc. Analysis revealed that experts applied more forces when *dissecting* tissues and lower forces when *manipulating* tissues. The opposite is true of novices. Novices seemed to use excessive caution when dissecting tissue but greater force during tissue manipulation. These results validate the intuitive assumption that experienced surgeon not only have greater hand-eye coordination but also are trained to apply optimal forces on tissue that are task-specific. Surgeons and novices do differ in force application skill level. Results from the study can provide the foundation for force-based metrics in evaluating laparoscopic skill [95].

Rosen and coworkers later used this force/torque signature data to construct a statistical model, based on Hidden Markov Modeling, for evaluating skill [159]. [225]This model requires that laparoscopic tasks be divided based on defined classes of gestures and the availability of force/torque magnitude information. Using this model, data from experts and novices were analyzed. Significant differences were reported in force/torque magnitudes, type of gestures and time for completion. The advantage of such a model is that skill level can be objectively assessed. If more data is used in the construction of the model, it can potentially differentiate between various levels of skill (junior, mid-level, senior residents). The statistical model can also potentially assess performance in real-time [225]. [225]Rosen and coworkers are also involved in the development of a robot, the Blue-DRAGON, that analyzes the kinematics and dynamics of laparoscopic tools [160], 226].

Dubrowski and coworkers sought to investigate if time, motion and force variables were indicators, not merely of performance, but of performance improvement. In their study, six junior resident and seven expert surgeons performed 20 simulated sutures on an artificial artery model. No feedback was given during performance. Residents were given oral instruction as well as demonstration of the suture task by an expert surgeon. During performance, hand movements were measured using electromagnetic markers, and force was measured using a six-dimensional force/torque sensor. The authors hypothesized that the following variables would be indicators of improvements in skill level: suturing time, amount of wrist rotation, hand velocity, applied forces and time lags between rotation of wrist and application force. Both surgeons and residents performed 20 simulated sutures, data being recorded for each trial. Analysis of data revealed that expert surgeons showed greater wrist rotation, applied higher average forces, showed shorter time lag between wrist rotation and force initiation, and completed sutures in shorter times. When skill increase between trials was analyzed, juniors showed improvement in the amount of wrist rotation and elapsed time between rotation of the wrist and force application. The authors suggest that during early stages of learning suturing, these variables may suggest improvement in learning. The variables wrist rotation and elapsed time between rotation of the wrist and force application can be assessed and feedback in real-time. The authors hypothesize that learning a skill may consist of several stages, progressing through learning of dexterity skills, followed by force application skills, followed by temporal skills. The authors suggest that force application may be a skill that is learned in later stages of training. The study also confirms that higher average force was applied by expert surgeons. However, to extract information on force process variables, skill learning further investigation is needed [157]. This paradigm of training based on specific key or salient variables has been validated by Singapogu and coworkers [64].

An experiment by Moody and coworkers on force metrics is worth consideration [3]. In their first experiment, performance on a suturing task was assessed by four metrics: mean stitch completion time, inter-stitch time, force applied, and bimanual co-ordination. Nine people with varying levels of experience performed suturing on a simulated aorta using instrumented forceps and needle holders. Results from this study showed that force data was the clearest indicator of skill distinguishing the two groups. Experienced surgeons consistently applied more forces than novices. Quality and symmetry of the suture assessed by experts also differentiated between novices and experts. In the second study, a commercial haptic feedback device was used to render forces on a virtual suture platform. Participants performed the virtual suture task for ten trials, with or without haptic feedback. Results showed that as the number of trials increased, time to complete the stitch and length of stitch improved. The effect of haptic feedback, found to be statistically significantly, resulted in lower stitch completion times [3].

A successful skills evaluation metric should differentiate between skilled and unskilled performance. Based on presented studies, laparoscopic experts' force behavior is different than novices. This information is the basis for force metrics in evaluating laparoscopic skill. Thus far, few studies have reported the use of force metrics. Force measures also can potentially differentiate between *levels* of skill. More research is needed examining the use, effectiveness and validity of force-based metrics for assessing laparoscopic skills.

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CHAPTER THREE

PERCEPTUAL SALIENCE-BASED HAPTIC RENDERING

3.1 Introduction

The traditional interaction paradigm for the display of displaying haptic information in virtual environments is point based, with the user feeling vibrations or forces at one or more points of intersection between a haptic device *avatar* and a simulated object. While point based interaction is common in the real world, there is another pervasive form of touch that involves muscular effort via kinesthetic and proprioceptive mechanisms during the manipulation of hand-held objects. Consider, for example, the wielding of a stick or the lifting of a coffee cup by its handle; without visual feedback humans can perceive certain properties of hand held objects, including their length, orientation, and heaviness. This kind of touch, which involves the perception of object properties via motions of the object, is called "dynamic" or "kinesthetic" touch [1-5]. Currently, very few virtual environments incorporate kinesthetic haptic feedback. However, as haptic interfaces evolve in their rendering capabilities, the inclusion of this type of haptic feedback seems plausible and desirable. We examined the effectiveness of a haptic device in rendering properties for kinesthetic touch using a skills training paradigm. Human users interacted with virtual "sticks" using the haptic interface (virtual environment) and were trained to report the felt lengths of the virtual sticks.

It has been hypothesized that kinesthetic information about held objects is related to the dynamics of the object. Several candidate mechanical quantities, sometimes called "invariants" and which are tied to the objects' dynamics, have been suggested to be the basis upon which humans perceive object properties [1], [6]. These quantities include the mass (m) of an object and its first moment. A mechanical quantity of particular interest is the second moment of the object's mass distribution, its *inertia*[1] [6-11].

During the last two decades, nearly one hundred publications have reported studies on haptic perception using the kinesthetic or "dynamic touch" paradigm [8-19]. In a vast majority of these studies the role of the inertia tensor was found to be central to the haptic perception of occluded objects that are held and manipulated. Inertia has been found to be related to perceived length [8-11], width [12], height [13], shape [19] and weight [14], [15]. Thus, in addition to the mass of an object, the perception of geometric properties, such as length, height, width and shape, are apprehended on the basis of mass-based properties. Specifically, the perception of these properties seem to be based on the object's inertial eigenvalues rather than on its actual geometric dimensions [16-19]. In addition, these studies have demonstrated that the perception of object properties via dynamic touch is a function of mechanical "invariants", rather than the continuously changing forces and torques during object manipulation [8]. While the haptic system is sensitive to time-varying forces and torques, it seems to use them to register mechanical quantities that remain invariant, like inertia [1]. In fact, evidence suggests that dynamic touch functions by producing muscle forces and torques that set an object in motion in order to produce reactive forces and torques corresponding to the object's mass

[1] Inertia is defined as the resistance of the object to angular acceleration. The inertia tensor, $\boldsymbol{I}$, describes the spatial distribution of the object's mass and its resistance to rotational accelerations in three dimensions. For a rigid object rotating about a fixed point of rotation, $\boldsymbol{I}$, is a constant and as a time-independent quantity, $\boldsymbol{I}$ is an "invariant" mechanical quantity describing the mass distribution of the rotated object. The eigenvalues of $\boldsymbol{I}$ (or principal moments of inertia, I_1, I_2, and I_3, where $I_1 \geq I_2 \geq I_3$) describe the resistances to rotations about the respective directions of the eigenvectors (or principal axes of inertia, e_1, e_2, and e_3, where e_1 is the axis of maximum resistance and e_3 is the axis of minimal resistance) [6-11].

distribution. As “invariants” must be defined with respect to quantities that change, mechanical invariants such as ***I*** only manifest themselves when an object’s disposition is changed (e.g., when forces produce changes in position, velocity or acceleration). It follows that the time-varying forces and torques produced by the muscles serve to reveal the time invariant mechanical quantities to which the haptic system is sensitive [1], [2], [6], [8-19] . Even when the point of rotation is not fixed, an invariant form of ***I*** can be quantified which is employed during dynamic touch to perceive properties of hand-held objects [10].

Despite a large body of work demonstrating the perceptual capabilities of kinesthetic touch, few virtual environments have been designed to convey haptic information through this mode of interaction [20]. As virtual haptic environments increasingly focus on more realistic and perceptually “smart” interaction methods, we believe that kinesthetic feedback explicitly modeled after dynamic touch may provide for richer, truly multimodal, interactions. Including this mode of haptic feedback may enable users to more easily perceive properties of objects encountered virtually and use this information for skilled action. Virtual environments designed with kinesthetic interaction can be employed in a variety of applications useful for haptic skills training, skills transfer, virtual prototyping, etc. (applications will be more fully discussed in the Conclusions section).

The primary objective of this study is to examine how effectively a haptic device can be used to render kinesthetic feedback in the context of haptic skills training. The paradigm used to assess this is to train users to perceive the lengths of virtual sticks from felt haptic feedback displayed by the device, and determine experimentally mechanical quantity underlies their perception. In other words, we seek to test whether or not a haptic device can be used to train users to become sensitive to mechanical quantities of rendered objects, increasing their reliance on these quantities.

We employ the perceptual framework of *attunement* and *calibration* to study this research question. *Attunement* is the process by which users learn to identify an object property by basing their perceptual judgments on specific mechanical quantities (or "variables") that are both available to the perceptual system and which correspond with the property in question. For example, since the amount of liquid remaining in an opaque beverage can corresponds directly to the weight being hefted, a user can simply lift the can and sense the amount of liquid by becoming attuned to weight (though the perception of weight is itself based upon an attunement to a specific set of invariant mechanical parameters [2], [15], [21]). During the process of attunement the user converges on the perceptual variable(s) that is correlated with the perceived property and makes judgments based on it. This process occurs only in the presence of feedback, since without feedback one or more uncorrelated variables may be employed [22], [23]. The user senses multiple mechanical variables during haptic interaction with objects; variables that are correlated with the property, called *specifying* variables, and variables that are ambiguously related to the property, called *non-specifying* variables. Before feedback, the user perceptually estimates an object property based on a combination of variables, both specifying and non-specifying. However, as feedback about the object property becomes available, the user will converge on the variable(s) that is most correlated with the object property and accurately predicts it. This feedback process has been termed the "education of attention," or simply "attunement" [1], [22]. In this study, we will employ a haptic device to render virtual objects that can be interacted with kinesthetically and measure its efficacy by testing if users show improved attunement (sensitivity) to mechanical quantities after training.

Attunement to the correlated variables alone does not necessarily produce accurate perceptual judgments. For a perceptual judgment to be accurate, the user must not only *attune* to the specifying variable and but also learn the magnitude of that variable. The variable must be metrically scaled to the property for accurate estimation to occur. This perceptual process, referred to as *calibration*, involves the learning of the correct scaling factor for specifying variables through feedback. Both attunement and calibration can occur simultaneously during the same feedback process, where the user not only learns to weed out non-specifying variables but also learns to scale the specifying variables appropriately for accurate judgments [22], [23]. For example, a person may not only learn to attune to weight as a variable that is correlated with the amount of liquid remaining in a beverage can, but via calibration they also learn to scale their judgments to be metrically accurate with regards to the specific amount of liquid remaining. At the conclusion of this process, the perceiver is conscious of a specific amount of liquid remaining in the can, rather than the mechanical parameters underlying the perceptual system's apprehension of weight.

The effect of attunement and calibration on kinesthetic perception has been previously studied by having subjects wield physical objects (e.g. cylindrical wooden sticks) and estimating their physical properties (e.g. length) [22-24]. Results from the studies confirm that feedback can indeed guide attunement and calibration to one or more mechanical variables. For example, studies by Withagen *et al.* have shown that the accuracy of perceptual judgments can be improved by training subjects to become attuned to one mechanical variable over another through a feedback process [22]. In their work, the length of unseen, wielded rods with different lengths, diameters and densities were to be estimated by users. During a pre-test stage, before any feedback was given, subjects wielded a set of rods (the test set) and made perceptual judgments of their lengths. Results showed that during the pre-test the subjects were basing their judgments on some mechanical variables that were not highly correlated with the actual length. However, during the feedback stage, training was given using a different set of rods (the feedback set) and the actual length of each rod was shown to the user after each judgment was made. In a subsequent post-training phase, once again with the original set of test rods, it was found that the feedback training did induce both attunement and recalibration; after feedback, subjects made perceptual judgments that were more correlated with inertia and which were scaled appropriately to the feedback that had been given. In such experiments it is convenient to have subjects report the lengths of the unseen rods, rather than inertia [8-11], because length is a variable that is well understood and the subjects find this intuitive. The important point is that through feedback their perceptions of length become attuned to and scaled to inertia, and this is hypothesized to be a powerful mechanism for training perception.

The results from the literature on kinesthetic perception suggest that attunement and calibration within the dynamic touch paradigm holds great promise for the user-centered design of haptic virtual environments. Rendering mechanical properties of objects accurately could add to the user's sense of realism in the virtual environment as well as make perception of object properties more accessible and accurate.

3. 2 Materials and Methods

Experimental Design

In the present work, following the procedure employed by Withagen *et al.* using real rods [22], we designed *virtual* rods with different mechanical properties that can be rendered and felt using a haptic device. Users were asked to estimate the length of these virtual rods based on the felt forces and torques alone (no visual feedback). This task has been employed in hundreds of experiments involving haptic perception of real rods, and is easily understood by subjects [2], [6-11], [21]. The experiment is divided into three phases: *pre-test*, *feedback* and *post-test* (see Figure 4). In all three phases, subjects are asked to wield virtual rods using a haptic device that is completely occluded by a black screen (to remove visual feedback). After wielding, subjects report the length estimate of the virtual rod on a reporting scale apparatus. Two sets of rods, one for testing and another for training with feedback, were simulated to have the mechanical properties listed in Table 1.

In the *pre-test*, subjects simply wielded the simulated rods from the test set and then estimated the length of each rod. No feedback was given during this stage. It was expected that in the pre-test the subjects would base their length judgments on some individualized function of mass moments [21], [22], the subject estimation process is represented as $l_e = f_i(I_1, m, M, l, ..)$ in the pre-test assessment process in Figure 4 to represent that prior to attunement each subject may base their judgment on a different variable or on a different set of variables. This data serves as a reference to compare any improvements after training.

During the *feedback session*, subjects wielded simulated rods from the feedback set. After feeling each simulated rod with the haptic device, subjects estimated the length of the felt rod and displayed their estimate on the report apparatus. After this was done, their estimate was "corrected" by the experimenter pointing to the *inertial length* of the rod (derived from I_1 of the rod, see Section 2.E) on the report apparatus. The inertial lengths were based on a pre-formulated function of inertia, denoted as $f(I_1)$ in Figure 4, and not their actual length. The purpose of using an inertia-based feedback function was to discern if the users can be trained to attune to this mechanical quantity and calibrate their length judgments based on it. Subjects were trained using this feedback method for multiple rods. As training progressed, we hypothesized that subjects would become attuned to the inertia of felt rods by establishing the correlation between the inertial length (given as feedback) and felt inertia through torque. We also hypothesized that over time, subjects would learn to accurately scale their length judgments. Since the inertial length function, $l_f = f(I_1) = 3.0\sqrt[3]{I_1}$, was used during training, we expected that following the feedback session, users would produce length judgments based on this model. It is expected that during the training stage the subject should begin to learn the training function such that $l_e \approx l_f = f(I_1)$.

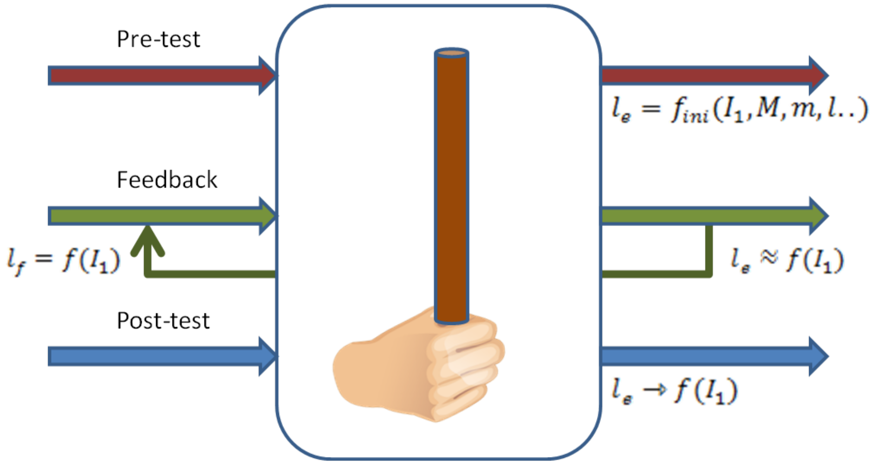

Figure 4: Experiment Design: baseline—training—post-test model

In the *post-test* session, subjects were once again given the simulated rods from the test set in random order and asked to estimate their lengths. No feedback was given in this phase. It was hypothesized that in the post-test session the subjects would base their estimations of length more heavily on inertia. This would demonstrate successful attunement and calibration as governed by the feedback [21], [22]. That is, it is expected that after the training stage the subject's estimate of length should approach the training function as $l_e \rightarrow l_f = f_f(I_1)$.

Using this process, we seek to test the ability of the haptic device to render mechanical properties of virtual objects and its ability to support user training through attunement and calibration.

Haptic System: Hardware and Software

The experimental setup is depicted in Figure 5. The haptic interface is used to render simulated rods via output forces and torques. The haptic device used in this experiment was a Quanser five degree-of-freedom (5-DOF) Haptic Wand (Quanser Incorporated, Ontario, Canada). It consists of a pen shaped end effector connected to two pantographs (top and bottom) and is capable of five DOF position and orientation sensing and force/torque rendering in each of these same five directions. The device produces forces in the x, y, and z directions and torque in the roll and pitch directions. The yaw torque about the longitudinal axis of the end effector is not measured and is passive. The maximum continuous exertable force is 2.5 N and the maximum continuous exertable torque is 450 N-mm. The haptic wand was placed on an adjustable table to enable comfortable interaction. The software control platform for this device was WinCon (Version 5.0) used in conjunction with MATLAB®/Simulink® (Version 7.1/6.3). The WinCon toolbox used with Simulink contains software modules for the haptic wand which can be used in conjunction with other toolboxes within the MATLAB® environment. The haptic device was occluded from the subject's view by a black, opaque screen.

During each experimental trial the subject wielded a rod that was simulated as though held at one end and then indicated their estimate of the rod's length on a visible reporting apparatus. The reporting apparatus was a 1.2-m rail with an adjustable pointer. The pointer could be positioned using a string and pulley system that ran along the length of the rail. Subjects wielded the simulated rod by manipulating the haptic device with their right hand and positioned the pointer with the left hand to produce an estimated length value. The subjects' estimate was based on the visible scale of the report apparatus that they produced with the pointer, but it was not based on an extrinsic scale, such as inches or centimeters, as no such gradations were provided on the visible portion of the report apparatus [6-13]. Subjects alternated between indicating length from the top and bottom of the report rail to avoid using reference points on the reporting apparatus as a bases for their judgments. This also eliminated over- and under- estimations by the subjects that may be caused by any bias on the part of the subject to place the pointer towards the top or bottom of the rail. After the subject finished adjusting the pointer, the interviewer recorded the judged length using a ruler affixed to the rail (seen only on the interviewer's side) and then returned the pointer to its starting position for the next trial.

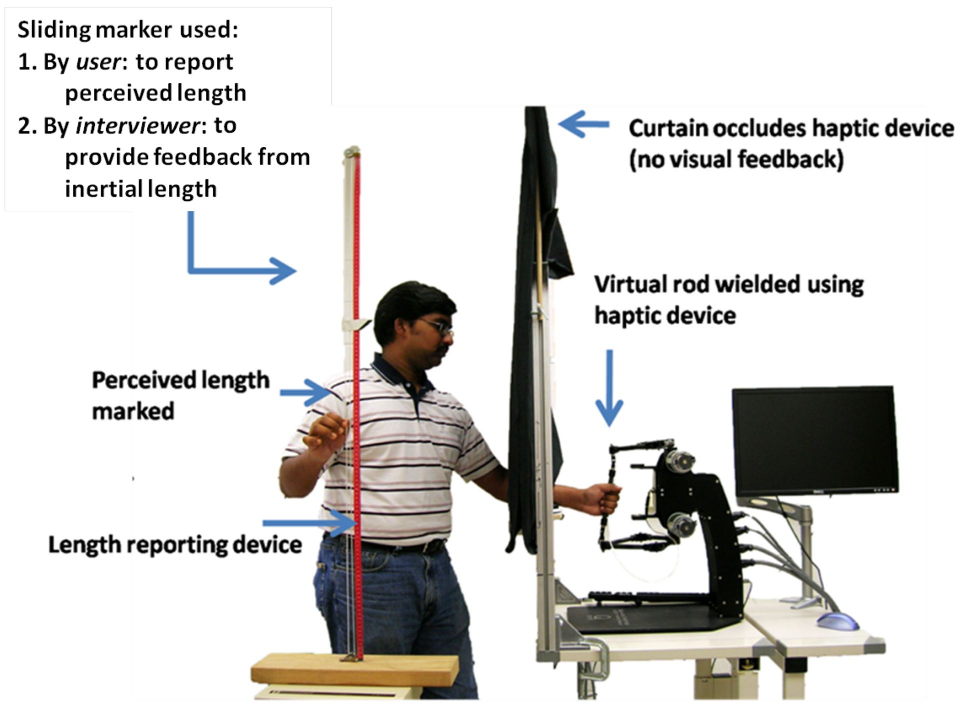

Figure 5: Experimental setup

Modeling and Force Rendering of Virtual Rods

In order to simulate rods wielded with the haptic device, a dynamic model was derived with position and orientation of the haptic device-end effector as the input. The forces and torques exerted by the virtual rod are the output of the model, rendered using the haptic device. In the dynamic model, the wrist, which exerts and feels forces and torques, is treated as one joint. Also, motion of the rod within the hand is not considered in this model; it is assumed that the rod is held firmly within an enclosed fist. There has been some discussion regarding the proper frame of reference (origin at the center of wrist or endpoint of the rod) to use in modeling the dynamics of hand-held rods. Most researchers have assumed a rigidly coupled link between the wrist and the end of the wielded rod and have modeled the mechanical properties of the rod using a point of rotation located in the wrist [8], [17], [19]. More recently it has been shown that a more accurate assumption for understanding perception is to have a reference frame at the endpoint of the rod instead of the wrist. Calculating forces and torques with respect to the end-point of the rod leads to accurate predictions of subjects' judgments [7], [21]. We derived the dynamics of a wielded rod with the reference frame attached to the endpoint of the rod as shown in Figure 6. A step-by-step derivation of the virtual rod dynamic model is presented in Appendix A. To the best of our knowledge, such a detailed model is not available in current dynamic touch literature and may aid future research.

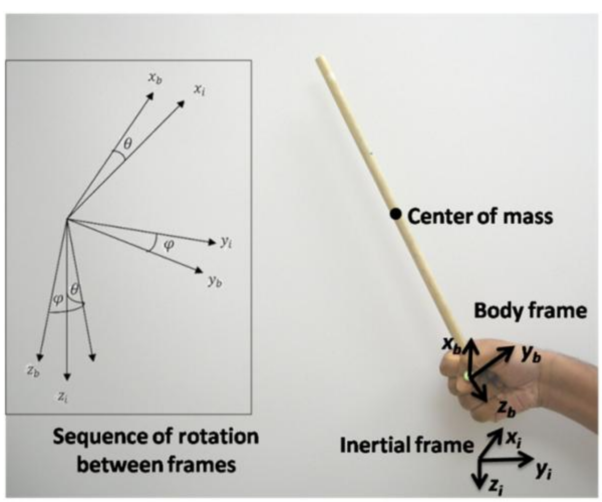

Figure 6: Inertial and body reference frames

The dynamic model was implemented using control software; specifically the dynamics were built as a block diagram in Simulink and compiled into real-time executable code. The rods were simulated using the mechanical parameters shown in Table 1.

Rod Number	Rod length (m)	Density (kg/m)	Inertia, I_1 (kg-m^2)	Mass (kg)	Moment (kg-m)	Feedback length (m)
Feedback Rods						
1	0.9	0.05	0.012	0.045	0.020	0.690
2	0.8	0.05	0.009	0.040	0.016	0.613
3	0.8	0.13	0.022	0.104	0.042	0.843
4	0.7	0.13	0.015	0.091	0.032	0.738
5	0.7	0.20	0.023	0.140	0.049	0.852
6	0.6	0.20	0.014	0.120	0.036	0.730
Test Rods						
1	1.0	0.05	0.017	0.050	0.025	0.766
2	0.9	0.05	0.012	0.045	0.020	0.690
3	0.9	0.10	0.024	0.090	0.041	0.869
4	0.8	0.10	0.017	0.080	0.032	0.772
5	0.8	0.15	0.026	0.120	0.048	0.884
6	0.7	0.15	0.017	0.105	0.037	0.774
7	0.7	0.20	0.023	0.140	0.049	0.852
8	0.6	0.20	0.014	0.120	0.036	0.730

Table 2: Properties of the simulated rods used in the experiment and the artificial, inertia-based feedback training function

Attunement Feedback Function

During the training phase, after users wield the virtual rods and estimate their length, their "real" length is indicated on the report apparatus. Using this mechanism for multiple rods, it is hypothesized that users learn to interpret length based on felt torque. The fedback length, however, is not the actual length of the rod; "inertial length" of the virtual rod, based on inertia of the rod alone, is given as feedback to the user. The feedback function relating length of the rod as a function of inertia alone is mathematically expressed as $l_f = f(I_1)$. To specify an appropriate function, $f(I_1)$, first consider the expression for inertia of a rod, $I_1 = m\mathrm{l}^2/3$. Substituting the weight per length, ρ, of any rod into the inertia formula yields $I_1 = \frac{\rho l^3}{3}$.

This can be rearranged as $l \propto \sqrt[3]{I_1}$. A constant of proportionality of 3 (for carbon material) yields the mapping: $l_f = f(I_1) = 3\sqrt[3]{I_1}$. Note that this equation defines a new (false) length, the *inertial length*, that is a function of the rod's inertia. The scale factor is chosen to make the inertial length range close to its real length. The constant of proportionality assumes a constant density. Since users are trained using a metric based on inertia alone (inertial length), it is expected that they will become sensitive to I_1, felt inertia, after training. Since the feedback length is directly based on inertia, we hypothesized that after training the results will show a greater reliance on inertia. Column in Table 2 shows the inertial lengths for each of the training and test rods. The effect of the attunement process is studied during the post-test phase.

Participants

Ten subjects (six male, four female) aged 22-29 years participated in the experiment after providing informed consent in accordance with the Clemson University Institutional Research Board (IRB). Participants were recruited primarily by email and were offered ten dollars in compensation for their time. All subjects were right handed as determined by a written questionnaire. None of the participants had any previous experience with the haptic device.

Experiment Protocol

After completing informed consent forms, subjects were given a standard three minute explanation of the experiment, stating the primary goal as estimating length of simulated rods before and after feedback (training). It was never disclosed to the participants that inertia was the specifying variable to which they were being perceptually trained. Two physical wooden rods were shown to demonstrate the concept of dynamic touch and subjects were encouraged to wield the rods and estimate their lengths with eyes closed. Once the subjects understood the idea of length perception by dynamic touch, they were instructed on the layout of the sessions; pre-test, feedback and post-test. In all three sessions subjects stood in front of a black curtain which occluded the haptic device. The height of the haptic wand was adjusted to suit the height of the standing subject.

During the pre-test session, subjects were given eight different test rods in random order, two times each (eight rods in random order, followed by eight rods again in random order). To wield a simulated rod, subjects reached under the curtain, placing their arm on an armrest and held the end-effector of the haptic device at its center. After making sure they were within the workspace of the device, they were instructed to wield the rod. Subjects were encouraged to wield about one axis (pitch or yaw) for a smooth, continuous feel. At the beginning of the pretest session and during the introduction, it was mentioned that subjects were holding one end (bottom) of the simulated rod. Due to design considerations in modeling the rod, subjects were instructed to minimize motion of the end of the rod within the hand but were encouraged to wield freely. Since the haptic device has force and torque limitations, if these output values exceeded a threshold, a "beep" sound was produced to warn the subject. If more than four beeps were produced in a trial, it was terminated and restarted again after instruction.

In the feedback session six feedback rods were given three times each in random order. After the subject wielded and reported their length estimate (l_e) of a rod on the report device, the inertial length $\left(l_f\right)$ of that rod was then indicated on the reporting rail by the interviewer. For example, if the feedback length is 0.5m then the experimenter moved the indicator to a position that is 0.5 meters from the bottom of the report rail. In this way the interviewer used the reporting device to give length feedback to the subject that was based upon the feedback function, $f(I_1)$. The experimenter alternated using the top and bottom of the indicator as the zero reference (i.e., alternated feedback measurements presented as a distance between the top of the report rail and the indicator with a distance between the bottom of the report rail and the indicator). Thus subjects received immediate feedback about the length of the rod while still wielding the rod and could learn from the feedback. This was repeated for all the 18 trials, each trial with the appropriate inertia length value.

In the post-test session the eight test rods were given, two times each in random order. In this session no feedback was given and subjects marked the estimated length of the rods on the reporting device (as in the pre-test session).

Subjects were offered a break half way through each session. The time needed for each subject to complete the experiment was approximately ninety minutes. Subject 1 completed 24 trials in the pre- and post-tests, but it was decided that since this resulted in a prolonged experimental session the protocol was adjusted to the one described above.

3.3 Results and Discussion

Data analysis was performed to answer two primary research questions: First, can the haptic device render mechanical variables that have been shown to underlie and aid kinesthetic perception? Second, can this haptic device be used to train users to become attuned and calibrated to a mechanical variable during kinesthetic interaction in a virtual environment? Two software packages were used for data analysis: Minitab (v. 15.1) for statistical analysis and MATLAB (v. 2007a) for graphing. To enable data analysis using correlations and regression models, the relationship between the mechanical variables had to be linearized since the relationship between length and inertia of the rods is non-linear. Thus, following standard practice in the dynamic touch literature, all data was computed using logarithms of the recorded data [6], [7], [22].

Overall Analysis

The primary objective of the study was to test the attunement to mechanical variables after feedback. To test for this, a regression model was computed with the logarithm of perceived length (l_e) as the independent variable and logarithm of principal major inertia (I_1) as dependent variable. The regression model from pre-test data of all ten subjects was calculated to be

$$\log(\textit{reported length}) = 2.75^{*} + 0.552^{*}\log(\textit{inertia}).$$

The *R-squared* statistic showing “goodness of fit” was .216 (p-value < 0.001). This indicates that about 22% of the variance in the length estimations was accounted for by inertia.

For post test data, the regression model was similarly calculated as

$$\log(\textit{reported length}) = 2.57^{*} + 0.398^{*}\log(\textit{inertia}).$$

The *R-squared* value, however, nearly doubled to 42.2% (p-value < 0.001). The post-test data shows that reported length after training was more heavily based on inertia than in the pre-test. These results indicate that the device rendered inertia in a way that could be apprehended by the participants and the haptic training with the inertia-based feedback function increased the reliance on this mechanical quantity. That is, after training, subjects were more attuned to inertia. The haptic device was thus able to render inertia of wielded virtual rods in a way that enabled haptic perception and training based on it.

Subject	R^2	Intercept	Log(Inertia)
Pre-test			
1	15.9	2.21†	.219
2	10.6	*2.49*†	.455
3	37.0†	2.51†	.385†
4	54.5†	2.87†	.633†
5	46.7†	2.39†	.294†
6	24.8†	2.42†	.389†
7	13.8	2.53†	.433
8	73.3†	3.49†	.937†
9	32.6†	3.01†	.667†
10	48.9†	3.60†	1.07†
Post-Test			
1	62.5†	2.39†	.322†
2	52.2†	3.11†	.710†
3	55.0†	2.64†	.433†
4	60.2†	2.27†	.211†
5	47.2†	2.24†	.325†
6	43.1†	2.51†	.357†
7	70.1†	2.46†	.341†
8	54.2†	2.63†	.416†
9	49.3†	2.83†	.562†
10	54.1†	2.38†	.292†

Table 3: Regression Models for Individual Subjects († denotes p-value ≤ 0.05)

Individual Subject Analysis

In post-test, all ten subjects showed a significant relationship between perceived length and inertia, while in pre-test only seven of the ten showed a significant relationship (see Table 2). Overall, eight of the ten subjects showed a greater reliance on inertia after training, as indicated by an increase in the *R-squared* statistic. The two exceptions were Subject 5 and Subject 8. Subject 8 showed a significant dependence on inertia during pre-test with an *R-squared* value of 73.3%. After feedback, the reliance on inertia dropped to an *R-squared* value of 54.2%, which remained significant. Subject 5 showed almost no improvement in *R-squared* value although in both pre-test and post-test their dependence on inertia was significant.

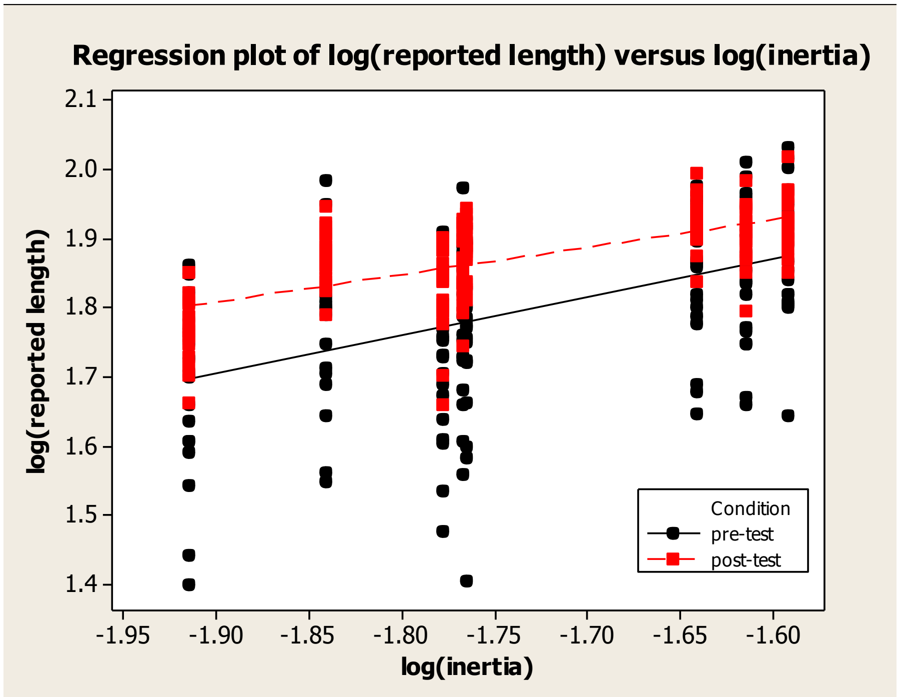

Figure 7: Regression plot for user attunement to inertia in Pre-test and Post-test

(Dots show individual user data and lines denote regression models)

Scaling Analysis

Previous studies investigating haptic attunement to specific mechanical variables have also found evidence of the complimentary process of calibration [22-23]. In attunement, the correlation between perceptual judgment and variable(s) specifying perception is tested. However, to correctly identify an object property, users not only need to base their judgments on the specifying variable(s) but also must do so with an accurate scaling. Analysis of our data showed a significant improvement in calibration after feedback. A measure used to test scaling or calibration is the mean difference between inertial length corresponding to the feedback function, $l_f = f(I_1)$, and the subjects' perceived length (l_e) values. For the pretest data this mean difference had a mean value of -14.56 cm while in the post test it was reduced to -3.82. A paired t-test between the data confirmed that this difference was statistically significant (t = -7.56, p < 0.001). This result indicates that not only were users able to attune to inertia as depicted by the haptic device, but they were also able to use feedback to calibrate the scale of their perceptual judgments to that which was provided during training (see Figure 8).

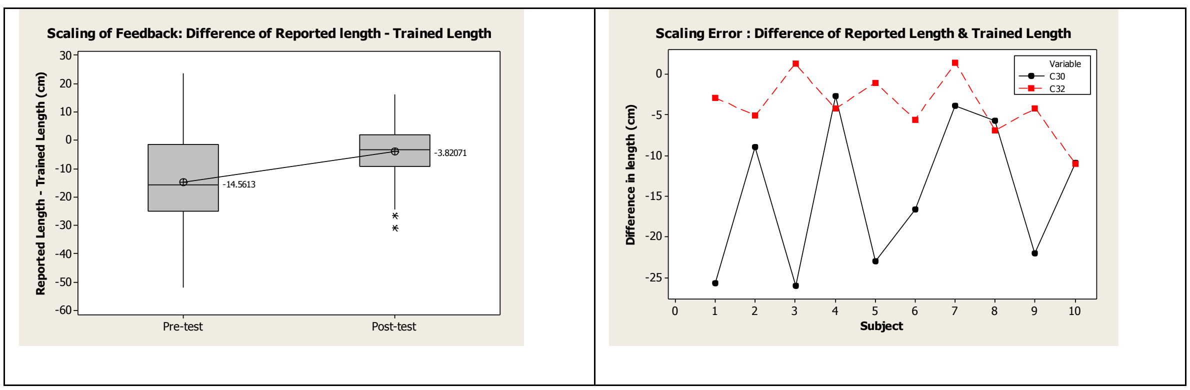

Figure 8: Scaling Information during Pre-test and Post-test

3.4 Conclusions

This study demonstrates that virtual environments can be designed to incorporate kinesthetic interaction using intentional haptic feedback via force-based interface devices. Using the framework of attuning users to specific rendered variables (in this case, inertia), subjects can learn to interpret properties of virtual objects (like length, weight, etc.) based on haptic sensitivity. Specifically, we found that users can attune to the inertia of virtual objects after training with inertia-based feedback and their judgments can become appropriately scaled.

Rendering the dynamics of objects enables perceptual learning. As a result, users will be more adept at skillful haptic manipulations. In surgical simulators, for example, rendering the moment and inertia of surgical tools may allow for quicker perception and more intuitive learning of tool functionality. The transfer of training from virtual simulations to performance in the real world has also been an area of recent interest [25]. Depicting mechanical properties of manipulated objects may enable smoother transfer of training to the real world as these variables are used for haptic perception.

Another interesting area of application involves simulator fidelity. High fidelity systems strive to render the virtual (training) environment as close as possible to the real world. In many cases, given current technological limitations, this is impossible. In medium and low fidelity simulators a subset of parameters available in the real world that are needed for training are simulated. For example, in a simulator training pilots in manipulating the controls of a plane, the graphic rendering of the scenery has been shown to be not critical [25]. Analogously, for haptic surgical training for laparoscopy, it is important to determine which parameters are critical for training specific skills. With tool use and object manipulation, the apprehension of mechanical properties by kinesthetic touch may be critically important as they have been shown to underlie real-world object perception. In some cases (or for low fidelity simulators), rendering the inertia or first moment alone could suffice in training the users in the skilled use of the virtual tools or objects. In short, training for attunement and calibration can serve as an important methodological tool during the development and testing of haptic devices.

Additional work may lie in the efficient rendering of stiffness or other properties of non-rigid materials. The effectiveness of many virtual skills training environments, particularly in the area of medical and surgical simulation, is a function of perceptually optimal rendering. Further work needs to investigate the attunement–based haptic rendering framework for non-rigid objects, like tissues, which can be deformed, torn, cut, or otherwise altered by the user. It is important to note that such properties may still be appropriately quantified by mechanical invariants, such as the stiffness constant (K), which users may potentially become attuned to..

We have also shown here that the dynamic touch paradigm provides a simple psychophysical measure that can be used to compare the ability of haptic devices and simulations to render mechanical properties. In the present experiment the resulting *R-squared* values predicting subject judgments from simulated mass moments were found to be much lower than what has been observed in past experiments involving real objects [8-11]. While this reveals limitations in the ability of our device to render mass moments, the protocol presented can be successfully employed to benchmark haptic rendering platforms in skills simulators by comparing them with real objects. Future work should investigate the range of mechanical properties that various haptic devices can render based on their specifications. These studies should lead to recommendations concerning which devices are best for rendering specific object properties, specific skill learning or during specific classes of manipulations.

Our finding that a haptic device can be employed for the attunement and calibration of kinesthetic perception (i.e. unsupported holding or dynamic touch) points out a potential limitation inherent in many virtual environments and skills training simulators currently in use. Hidden or inappropriate training may result from unintended attunement that occurs when feedback is not controlled or is administered in an inconsistent manner. As a result, haptic training may not transfer to the real training environment, as can be noted from several virtual surgical simulator studies [26].

For the further study of attunement with haptic devices, hardware accommodations during device design should be made such that the motions, forces and torques of rendered virtual objects are as close to possible to real objects. In the haptic device used in this experiment, some “backlash” (energy losses among mechanical parts) was observed in the haptic device for heavier rods. This can result in poor haptic rendering and user perception, and may have contributed to the moderate-to-high results evidenced. Despite these limitations, we demonstrated that the haptic device can render mechanical variables and that this can be used for training users to become more perceptually sensitized to mechanical quantities, increasing their kinesthetic perception.

In the future, we plan to test the transfer of training from the virtual world to real world trainers [27]. We also plan to further modify rendered dynamics taking the concept of mechanical salience into consideration while designing the feedback mechanism for virtual skills training environments [7].

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CHAPTER 4

FEASIBILITY STUDIES FOR THE ROLE OF HAPTIC FEEDBACK IN LAPAROSCOPIC SKILLS TRAINING

4.1 Role of Haptic Feedback in a Basic Laparoscopic Task Requiring Hand-eye Coordination

Introduction and Background

The role and utility of haptic feedback in laparoscopic surgery is a topic of much debate in the current literature [1]. Recently, quantitative haptic information recorded during *in vivo* laparoscopy has been documented and demonstrates the presence of haptic (kinesthetic) feedback [2]. Further, these force values lie within a range that are perceivable by human operators [3]. The presence of haptics during surgery raises important questions for laparoscopic training. For example, what type of training will lead resident trainees to efficiently perceive and process haptic information during surgery? Also, what specific tissue properties are more readily perceived by haptic feedback?

The Fundamentals of Laparoscopic Skills curriculum is used as the standard for laparoscopic skills training in U.S. medical schools [4]. The technical component of this program consists of five tasks ranging for basic hand-eye coordination to advanced force application and suturing. Previous studies have shown that haptic feedback is useful during force application tasks as well as in determining properties like tissue stiffness [5],[6]. However, the role of haptic feedback for learning hand-eye coordination laparoscopic skills is not well understood. This study investigated the role of haptic feedback in a FLS-based peg transfer-like task.

Materials and Methods

For this study, virtual "blocks" of three colors were created with identical physical properties. The virtual environment was created using the Chai 3D library (www.chai3D.org). The physics of the environment was handled by Open Dynamics Engine (ODE) which contains collision detection and collision response algorithms. The virtual blocks were manipulated via a standard haptic interface, the Novint Falcon®. The low-level device control was done using the Chai 3D haptic library.

The users' goal was to stack the virtual blocks into sets of three according to their color. Users performed this stacking task with haptic feedback from the device and without haptic feedback. The task of stacking was chosen because it was used in previous studies for basic laparoscopic skill learning [7]. After users completed the virtual tasks, they performed a similar stacking task in the real world.

A custom laparoscopic box trainer was built for this purpose using published specifications [8]. One standard laparoscope, inserted through the incision, was used to stack metal nuts of 1.7 cm diameter (Figure 9). Akin to the virtual task, the real task comprised of stacking nine nuts into groups of three according to their color. Participants of the experiment were first briefed about experiment's objectives and randomly assigned to receive either the haptics or non-haptics virtual task first. The metric for assessing performance was time to completion measured in seconds. After completing both virtual tasks, subjects performed the real task of stacking metal nuts in the physical trainer. Time to complete the task was also used for performance assessment of the real task.

Ten subjects participated in this experiment after providing informed consent. The participants were students between 18-25 years of age. Recorded time data from all three sessions is shown in Table 1.

Results and Discussion

The hypotheses of the experiment are: (1) time to completion with haptics will be significantly shorter than without haptics and, (2) time scores from the haptic session will be more correlated to real task time scores than the non-haptic session scores. Statistical analysis was performed using Minitab (v 15.1).

To investigate the first hypothesis a Mann-Whitney U-test was performed to compare the haptic and non-haptic scores. Results showed that scores were significantly different at a p-value of < 0.01. The median completion times were 110 and 165 seconds for the haptics and non haptics sessions, respectively.

To investigate the second hypothesis, a correlation analysis was performed between the real scores and the haptics scores as well as real scores and the non-haptics scores. Results showed that non-haptic session scores were significantly correlated with real task scores ($r=.747$, p-value < 0.05) whereas haptic scores were not significantly correlated with real task scores ($r=.432$, p-value$=.21$). This result, contrary to the hypothesis, shows no correlation between haptic scores and real task scores.

Table 4: Time to complete stacking task in all three sessions

Subject	No Haptics (seconds)	Haptics (seconds)	Real (seconds)
1	165	95	195
2	141	65	150
3	194	117	145
4	119	116	170
5	148	54	99
6	166	143	111
7	99	51	94
8	272	140	300
9	246	104	218
10	182	122	102

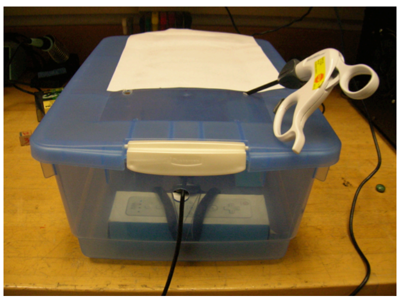
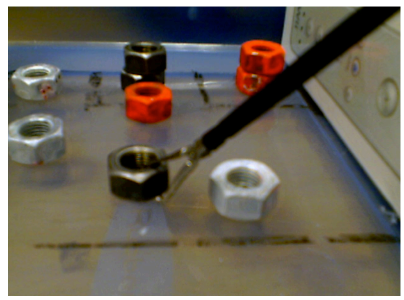

Figure 9: Physical laparoscopic trainer setup used for task

Conclusions and Future Work

The results of this study suggest that haptic feedback does not significantly affect task performance for basic hand-eye coordination tasks in laparoscopic training. This observation confirms earlier results from Chmarra and coworkers who suggested that haptic feedback was not necessary for basic laparoscopic tasks primarily involving hand-eye coordination skills. Consequently, when teaching these skills to residents, visual feedback is the primary sensory mode of learning and should be focused on accordingly.

4.2 Haptic Tasks for Physical Laparoscopic ("Box") Trainers to Differentiate Surgeon Skill

Introduction

Physical or "Box" trainers are extensively used in medical skills training labs worldwide to impart basic laparoscopic skills [1]. These trainers typically consist of a hollow box fitted with a camera looking down on the workspace. The top of the box has ports through which laparoscopic tools are inserted and images from the camera show tool-material interactions to the user on a monitor. Medical students perform a host of standardized exercises on the trainer. The Fundamentals of Laparoscopic Surgery (FLS) trainer, for example, includes skills like transferring of small plastic pegs with tools, cutting a circular pattern on a gauze sheet, an "endo-loop" task and suturing [2]. Residents are primarily scored on time taken to complete tasks and some accuracy measures.

Many studies have demonstrated the efficacy of this low-cost, "low-tech" method of training in enabling novice surgeons to gain a certain level of proficiency in basic laparoscopic skills. The FLS trainer is one of the few laparoscopic simulators with demonstrated predictive validity—the transfer of skills from simulator to operating room [3]. A weakness of box trainers, however, is that they address only *basic* laparoscopic skills, primarily in the domains of tool use and hand-eye coordination. While this is a necessary focus, expanding it to include other domains, like haptics can enable training a more comprehensive skill-set [4].

In this work, we design four tasks in which skilled use of force stimuli is necessary for optimal task performance. Laparoscopic surgeons and novices are timed on haptic tasks with the following hypothesis:

> *Surgeons' time-to-completion of haptic tasks are significantly shorter than novices' time-to-completion.*

Materials and Methods

A physical trainer was constructed based on the specifications provided by Beatty and coworkers [5]. It consisted of typical components of a box trainer discussed above. Four haptic tasks were simulated in the trainer with commonly available materials; the first two were simulated with rubber bands and the second two with latex exercise sheets. For the rubber band tasks, a small wooden base with four nails arranged from left to right was used as the base. The nails were numbered 1, 2, 3 and 4, from left to right. Participants were instructed to stretch the rubber band from nails 1—2, 2—3, 3—4 and in the reverse order, 4—3, 3—2 and 2—1. Timing was initiated after the 1—2 segment started and ended after the 2—1 segment was completed. The two rubber bands used—thin (#33, Staples, Framingham, MA) and thick (#64, Alliance rubber Company, Hot Springs, AR)—differed in dimensions and strength.

The cutting tasks, though based on the FLS pattern cut task, used flexible materials that provide greater haptic feedback to the user. For the first cutting task, small latex exercise sheets were marked with a circle, 2 inches in diameter. Participants were instructed to cut along the circle with standard laparoscopic tools as accurately as possible (staying close to the marked perimeter). The second cutting task comprised of cutting the fingers of a glove (Ansell medi-Touch, Dothan, AL), each finger marked by a horizontal line at the top. For both tasks, timing commenced when the first cut was made and ended when the cut was completed.

Seven surgeons and eight novices were recruited to participate in the experiment approved by Clemson University's Institutional Research Board.

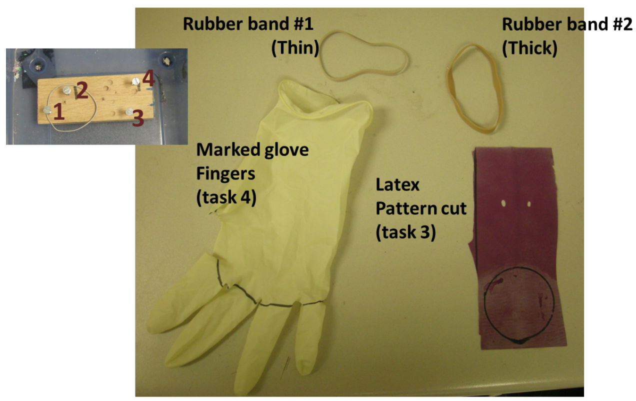

Figure 10: (left) Sequence of rubber band stretch, (right) Marked materials for the four haptic tasks

Results and Discussion

All results were analyzed based on times to completion of surgeons and novices. As shown in Figure 11, data demonstrate that all four of the haptic tasks differentiated surgeons from novices (p-values for Tasks 1, 2 and 3 < 0.01; Task 4: 0.037). The high p-values for a small sample size suggests that haptic tasks may be more efficient in distinguishing surgeons from novices than basic laparoscopic tasks, especially since basic skills can be correlated with factors like video game experience. Chmarra and coworkers also used a rubber band task in a box trainer to test laparoscopic skill learning with similar results [6].

In conclusion, we believe that physical laparoscopic simulators should include tasks testing and training for haptic skills. This could enable accelerated training, not only of basic hand-eye coordination skills but also of more advanced, haptic skills. This work suggests some tasks that could be readily incorporated in conventional box trainers for that purpose.

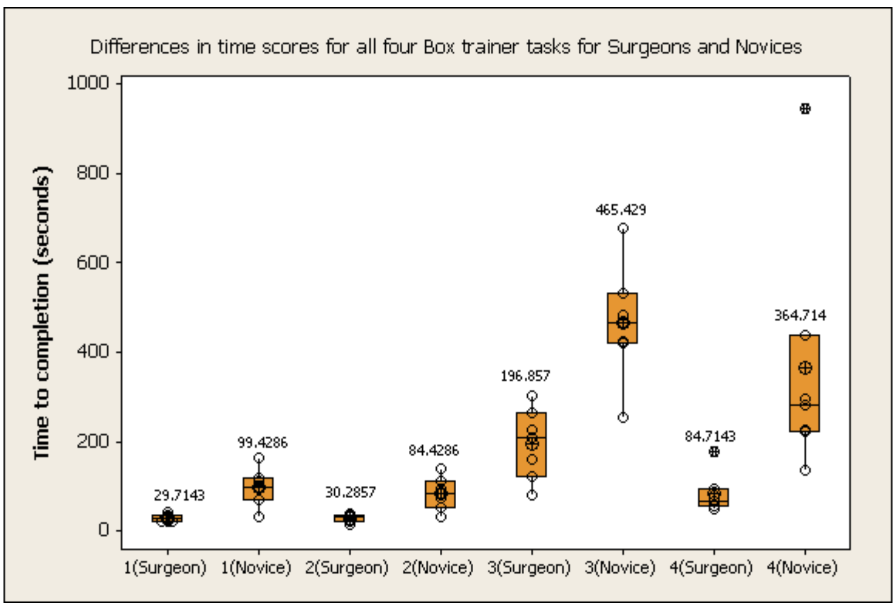

Figure 11: Surgeon and Novice completion times (in seconds) for four haptic tasks; 1 =thin rubber band 2 = thick rubber band, 3= latex pattern cutting, 4= glove finger cutting

4.3 Assessing Surgeon and Novice Force Skill on a Haptic Stiffness Simulator for Laparoscopic Surgery

Introduction

The last two decades have been marked by significant technological advances in the field of minimally invasive surgery [1]. Driven by patient demand and other factors, laparoscopic surgery is now considered a “mainstream” surgical technique. Medical schools increasingly require that residents demonstrate proficiency in basic laparoscopic skills for certification [2]. However, acquiring these skills is particularly challenging for surgeons because of the feeling of “remoteness” from the surgical site, caused by the use of long tools and camera images and greatly diminishing sensory stimuli during surgery [3].

Popular training simulators and curricula (e.g., Fundamentals of Laparoscopy) were designed to teach basic laparoscopic skills to residents. Students perform a variety of tasks with laparoscopic tools, such as transferring small pegs, cutting a circular pattern on gauze material, and suturing; performance is measured using metrics like time and accuracy [4]. Several studies have documented the efficacy of such training programs, particularly the FLS program, in imparting basic laparoscopic skills [5]. The FLS simulator, however, emphasizes training a core set of basic skills that are *necessary* for proficient laparoscopy; more advanced skills also need to be addressed by surgical simulators [4]. It can be argued that the FLS program addresses the eye-hand skills required for precise surgical maneuvers but does not specifically address force-based skills. Hence, there is a need for training methods to augment the FLS skills and include advanced skills based on force or touch stimuli.

This work is motivated by the general hypothesis that proficient laparoscopy involves a haptic skill component. As a first step in demonstrating this we examine the force behavior of laparoscopic surgeons and novices on a computer-based haptic simulator. It is hypothesized that, due to their regular interaction with tissues, expert laparoscopic surgeons possess haptic skills that are distinguishable from those of novices. The three hypotheses of the study are:

H1: *Exploratory forces exerted by surgeons on virtual materials are significantly different than novices.*

H2: *Surgeons are significantly better than novices at using touch to identify an unknown material from a set of materials.*

H3: *Video game experience is a predictor of haptic stiffness-based skill on the simulator for both surgeons and novices.*

Materials and Methods

The goal of this study was to examine the differences in ability of surgeons and novices to apply forces on virtual materials; to this end, a haptic interface and virtual materials were used to conduct experiments with both groups.

In the experiment two stiffness values were rendered, one varying linearly and the other varying non-linearly over a range of possible haptic device displacements. Participants were asked to penetrate one of the two virtual materials while a score ranging from 0 to 150 was visually presented. The scores represent the force required by the subject to hold the device at the current penetration depth. Thus the score changed as they moved the device through the material, increasing as they penetrated into the material and decreasing as they withdrew. Participants were instructed to learn to create penetration depths resulting in scores of 10, 25, 50, 75 and 100. Training time was three minutes, within which the subject was allowed to freely move the device back and forth through the material at any chosen pace. After the training period, the participant was asked to reproduce the five scores (10, 25, 50, 75 and 100) in a random order. No visual feedback was provided during this testing stage and scores were recorded for each trial. This procedure was repeated for both stiffness values.

As part of the initial questionnaire, participants were asked to indicate their video gaming history. This information included: number of hours per week spent in video game playing and types of games played (console-based, first person shooter, etc.).

Figure 13 depicts the stiffness profiles and corresponding scores on both linear and nonlinear materials. The score was calculated as a function of the user's penetration distance into the material:

$$score = x_p \bullet c \, ,$$

where x denotes penetration distance and c is a constant. While the user penetrates the material, a corresponding force is felt based on the stiffness profile of the material. Thus, for the two materials in this study, scores can be written as a function of felt force as:

$$score = (f / k) \bullet 5000 \text{ ; } \textit{linear material}$$

$$score = (f / k)^{1/3} \bullet 5000 \text{ ; } \textit{nonlinear material}$$

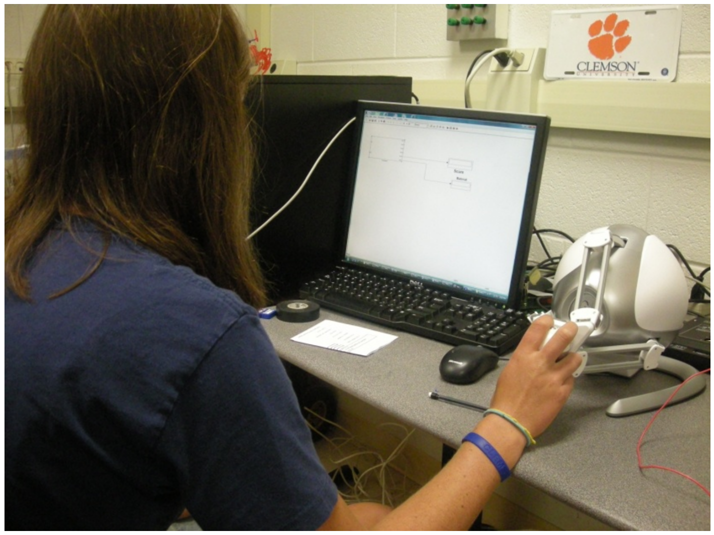

Figure 12: Experimental setup with Falcon® haptic device and visual feedback on the screen during training. During the testing phase, the monitor was turned off (no visual feedback to user).

The experimental setup is shown in Figure 12. The haptic device used for the experiment was the Falcon® (Novint Inc., Arizona, USA). The workspace for the Falcon is 10cm ×10cm × 10cm and maximum force rendered is about 8 N in each of the three Cartesian directions. MATLAB/Simulink (Mathworks, Natick, MA) software was used to render the virtual materials, control the haptic device, and build the user interface. QuaRC (Quanser Inc., Ontario, Canada) is used in conjunction with Simulink to provide real-time rendering at 1 kHz update rate.

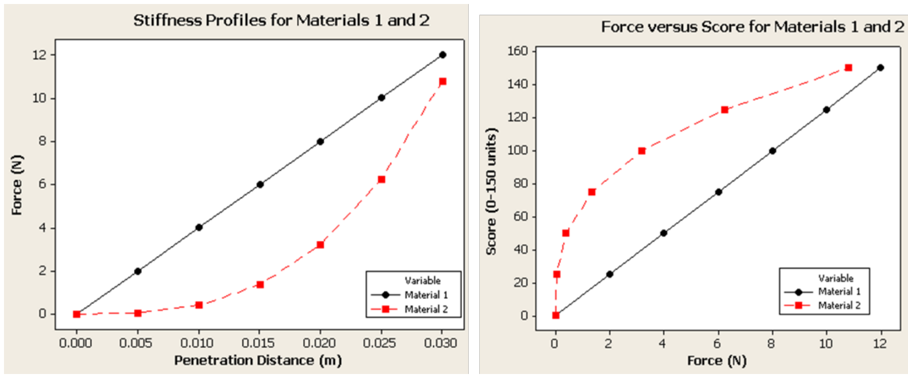

Figure 13: Force (left) and Score (right) profiles for rendered linear and nonlinear materials; as users penetrate into the virtual material with the haptic device, force rendered increases (linearly or nonlinearly) and feedback score is a function of penetration distance.

Results

Trials 2, 3, and 26 of the 4th novice were removed as outliers (standardized residuals = -3.65, -3.03, and -3.4, respectively). The slopes and intercepts of the functions predicting produced forces from target forces for the individual subjects in each condition are presented in Table 1. Perfect performance would result in an r^2 = 1, slope = 1, and intercept = 0. To test the three hypotheses, multiple regression techniques were used to determine differences between the two groups (surgeon vs. novice).

	Surgeons			***Novices***		
Subject	r^2	**Slope**	**Intercept**	r^2	**Slope**	**Intercept**
1	.692	.64	31.7	.658	.72	19.8
2	.528	.65	28.8	.526	.47	46.4
3	.795	.95	-5.0	.781	.61	37.1
4	.830	.78	6.4	.501	.61	30.1
5	.677	.84	9.5			
Overall	**.704**	**.72**	**14.3**	**.617**	**.60**	**33.4**

Table 5: Regressions of produced force versus actual force for Surgeons and Novices

Figure 14 depicts the relation between target force and produced force for novices and surgeons. Each point represents the judgments made by an individual subject to a given target force. A multiple regression confirmed that the forces produced by surgeons were different from those produced by novices. The multiple regression was performed with a target force × group interaction term, yielding an $r^2 = .633$ (n = 284), $p < .0001$. A statistically significant main effect was found for intended target force (*partial-F* = 440.71, P <.0001), as well as for the two groups (*partial-F* = 12.43, P <.0001) and the interaction (*partial-F* = 7.22, P =.008). Therefore, both the slopes and intercepts of the functions predicting produced force from target force were different for the two groups. This result validates our first hypothesis H1 that surgeon and novice force-based performance is different. Overall, the forces exerted by novices were higher than those of surgeons by an average of 19.1 score units. Also, the overall slope for surgeons was .72 and for novices was .60, suggesting greater accuracy for surgeons. These results confirm earlier studies reporting superior haptic skills for surgeons compared to novices [6–8].

After learning the force behavior of both materials before test trials began, participants were asked to verbally identify which material was being presented (1 or 2). A multiple regression model was used to analyze the ability of surgeons and novices to accurately reproduce the linear or non-linear nature of the materials presented. The model was formulated with the actual as presented model and condition as predicted (reported) model; the model yielded an $r^2 = .315$ (n = 284), $p < .0001$. The model was first performed with a target force × group interaction term, yielding an $r^2 = .316$ (n = 284), $p < .0001$. This result confirms that surgeons indeed differed from novices when asked to recognizing which material was presented by touch alone. Surprisingly, contrary to initial hypothesis H2, novices were overall better than surgeons at identifying which material was presented, with accuracy rates of 86% compared to 70% for surgeons. A simple regression predicting the reported material from actual material resulted in an r^2 = .297 (n = 284), indicating that the difference between surgeons and novices accounted for only 1.9% of the variances in reported material.

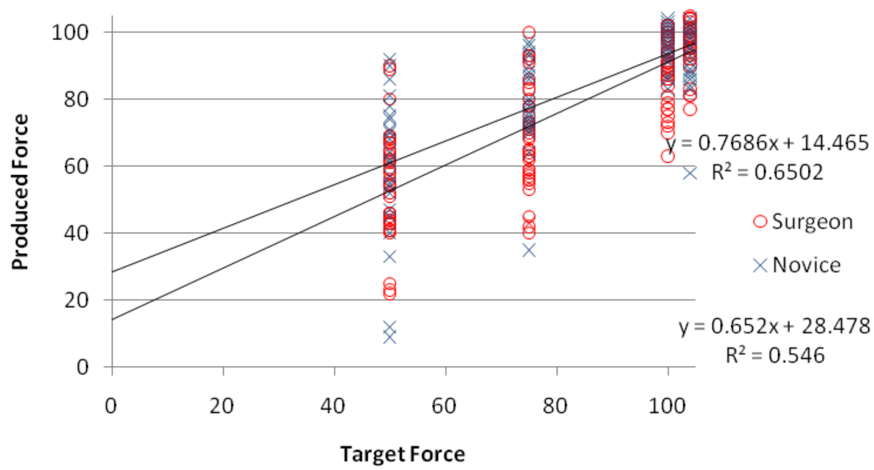

Figure 14: Graphical regression models for Produced force versus Target force for Surgeon and Novice groups

Hypothesis H3 was based on previous research demonstrating that aspects of laparoscopic skill are correlated with video games experience [9]. We postulated that haptic laparoscopic skills may also be correlated with video game experience.

The multiple regression model to investigate gaming experience with haptic skill showed no statistically significant difference in produced forces based on hours per week of video gaming experience (regardless of surgical experience). Also, no statistically significant difference in reported materials based on hours per week of video gaming experience and surgery experience was evidenced.

Discussion

In this study, we used a haptic simulator (haptic device and software rendering) to investigate the ability of surgeons and novices to learn and reproduce the stiffness of virtual materials; stiffness varied linearly or non-linearly with penetration distance based on the material. Based on our analysis, surgeons were more accurate than novices at reproducing penetration distances that corresponded to target stiffness values. This result suggests that a haptic simulator may be used to distinguish surgeons from novices. Further work should be directed at the possibility that haptic simulators can be used to improve novices' force-based skills. Simulator-based training of this nature is relatively inexpensive and is ethically more desirable than using animal models or training in the operating room. Further work is needed to refine the testing and haptic simulation to quantify levels of surgeon haptic skill.

An interesting statistic indicates that novices can better identify which material is presented to them than surgeons. One possible explanation for this is that surgeons are not required to identify which tissue is being touched for proficient laparoscopy; however, they need to apply controlled forces based on the combination of visual and haptic cues. In a similar study performed by Lamata and coworkers, surgeons were asked to feel certain tissues and pick which one was being felt from a list of tissues. They reported very low correlation for predicting tissue based on textual description alone [10].

Based on these data, laparoscopic surgeons may pay little attention to exactly what tissue is being handled.

Regarding the correlation of video game experience with haptic skills, our preliminary data show no indication that these skill sets are correlated. This question should be a topic of future study. It is possible that video game experience only predicts performance in novices or it may predict speed of training.

Overall, it is hoped that the data and results presented here will spawn new research in the area of haptic skills for laparoscopic surgery. It is the authors' observation that while past research has investigated the acquisition of basic laparoscopic skills, better simulators and curricula should address the training of advanced haptic skills required for proficient laparoscopy.

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CHAPTER 5

SIMULATORS FOR OBJECTIVE DIFFERENTIATION OF FORCE-BASED LAPAROSCOPIC SKILLS: TOWARDS A SALIENT HAPTIC SKILLS TRAINER

5.1 Introduction

Proficiency in laparoscopic surgery requires mastery of a complex skill set that is fundamentally different from open surgery [1]. For example, surgeons need to master moving long laparoscopic instruments in response to video images relayed from the camera (*hand-eye coordination*) [2], and translating the two-dimensional camera images to the 3D anatomical context (*visual perception*) [3], [4]. Further, the forces experienced through the laparoscopic instrument are fundamentally different from those experienced in open surgery wherein surgeons can directly touch tissues with gloved hands; in laparoscopy, forces on the instruments used are altered by friction in the trocar as well as the pivoting of the tools causing a fulcrum effect [5–8]. Surgical residents today must learn this unique skill set in addition to the skills of conventional surgery, despite the added burden of a growing and changing mass of "medical knowledge" and the constraints of limits on duty hours [9], [10]. There is considerable need, therefore, to identify the skills required for proficient laparoscopy and teach them efficiently to residents.

Laparoscopy skills acquisition methods are depicted in Figure 15, including both simulators and operating room-based training. The current standard for basic laparoscopic skills training is the Fundamental of Laparoscopic Surgery (FLS) curriculum and trainer which includes five basic tasks simulated in a hollow, “low-tech” box [11]. Several studies have demonstrated the efficacy of this curriculum for developing basic, hand-eye coordination and suturing skills [12–15]. However, the FLS curriculum does not currently include training for the precise force-based skills required for laparoscopic surgery. As a result, though residents acquire some foundational laparoscopic skills on the FLS trainer, they do not hone their force-based skills. Most force-based training currently seems to occur in the operating room. This approach is not only expensive but also raises important ethical questions. Consequently, there is a need for the design and validation of haptic (force-based) skills simulators that will better prepare residents for the operating room.

What is remarkable about the success of the FLS skills training curriculum is that the program does not seek to recreate the surgical environment realistically; rather, the five training tasks recreate the *salient* hand-eye coordination skills that are basic to perform laparoscopic surgery. Similarly, it is hypothesized that there is also a set of salient *haptic* skills needed for skilled laparoscopy. It should be noted by salient we mean the core skill set, the combination of elements of which lead to the sequence of motions and force-based maneuvers during surgery. This set of salient haptic skills may then serve as the basis for a haptic skills training program, similar to the FLS training method.

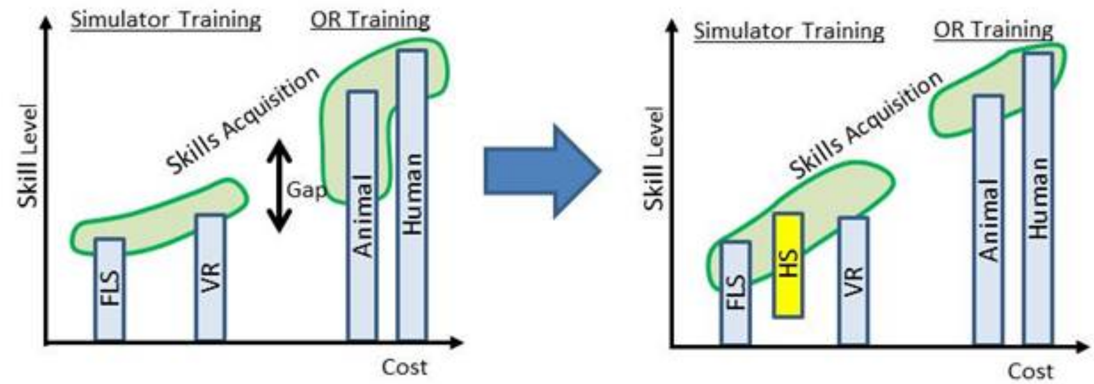

Figure 15: A new haptic skills training component is proposed, labeled "HS", that would help narrow the gap between simulator and operating room training by equipping trainees with basic surgery specific haptic skills before entering the operating room.

Several investigators have sought to analyze the motions and forces needed for proficient laparoscopy [5], [16], [17]. Richards and coworkers' detailed study, for example, documented force data from expert laparoscopic surgeons and novices as they performed two common laparoscopic procedures on an animal model. Surgical maneuvers were decomposed into simpler skills. Analysis of *in vivo* force data revealed that surgeons and novices differed in their force application with laparoscopic tools for three core skills shown in Figure 16: grasping, probing and sweeping. All three of these skills require precise and controlled application of forces and surgeons exhibited superior haptic skill on these tasks [16], [18], [19]. *Grasping* is defined as applying pinch forces on the laparoscopes handles to grasp and handle tissues. *Probing* is defined as using the laparoscopic tool to prod the tissue and perform dissection, a large part of laparoscopic procedures. *Sweeping* is defined as the lateral motion of the tool as tissues and organs are being moved or cleared in order to reach the surgical site of interest.

Based on this study, we propose that these three surgical maneuvers—grasping, probing and sweeping—that require skilled application of forces are *salient haptic laparoscopic skills*. Learned and skilled application of force seems to be essential for successful outcomes of these tasks. It should be noted that there might be other potential force-based salient skills. For instance, when a person wields an occluded object, such as the laparoscopic tool, they perceive certain mechanical properties of the object (e.g. moment of inertia and center of gravity); studies have shown a correlation between perception of these mechanical properties and estimation of physical features of objects like length [20], [21]. Although the authors have previously shown [22] that surgeons and novices perform significantly differ in their ability to estimate the length of wielded sticks, it is expected that because of the small inertia of the laparoscopic tools and other factors (small movements, relatively slow motion, and confounding trocar forces) that this is a not a significant force skill in surgery.

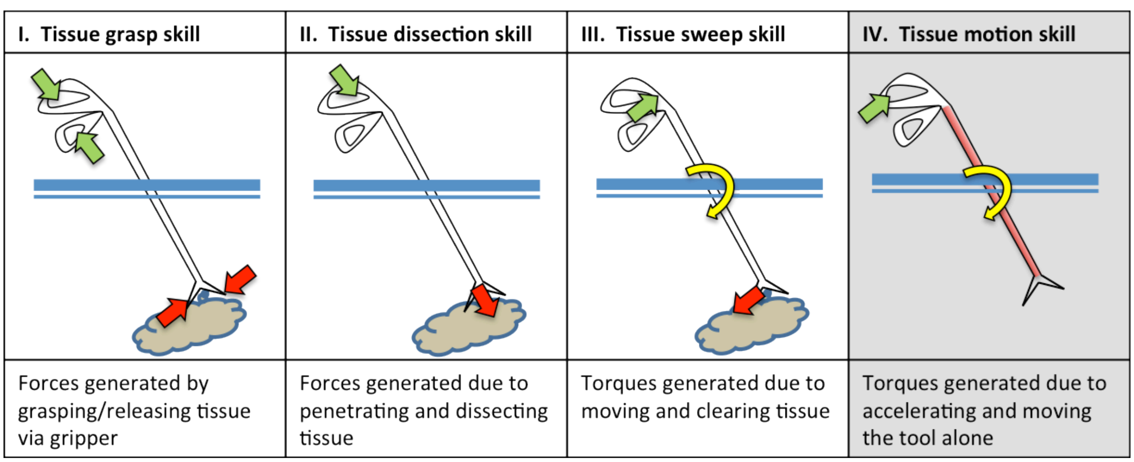

Figure 16: The three salient skills proposed as the basis for decomposing any laparoscopic forced-based procedures.

No validated simulator or training method currently exists for specifically measuring and distinguishing levels of haptic skill proficiency. Building a haptic skills training program that is objective and cost-effective involves the construction and validation of simulators for salient skills. In this study, we implemented haptic simulators for grasping, probing and sweeping, the three salient skills. As a first step in validating these simulators and the salient skills approach, the performance of experienced surgeons and novices was assessed.

The goal of this study, therefore, is to use custom designed simulators for specific haptic laparoscopic skills to objectively measure the performance of the expert surgeons compared to novices.

5.2 Materials and Methods

Simulators for Salient Skills

Three custom haptic simulators were designed and developed for rendering the three salient skills— grasping, probing and sweeping. Each simulator had the same primary components: a modified laparoscopic tool (Autosuture® Endo™) that was connected to a direct-drive DC motor (Tohoku Ricoh®), with enclosed encoder for measuring displacement of the laparoscopic tool. As the user moves the tool, displacement is sensed by encoder readings, which is used to compute reaction torque applied by the motor. Applied torque, in turn, results in force feedback to the user, giving the illusion of an artificial "virtual" material being encountered using the setup.

The hardware associated with the simulators included a Quanser® Q4 board used for data acquisition connected to a computer with MATLAB® software for control algorithms. The input to the force feedback algorithms was position sensed by the encoder while the output was force applied on the laparoscopic tool.

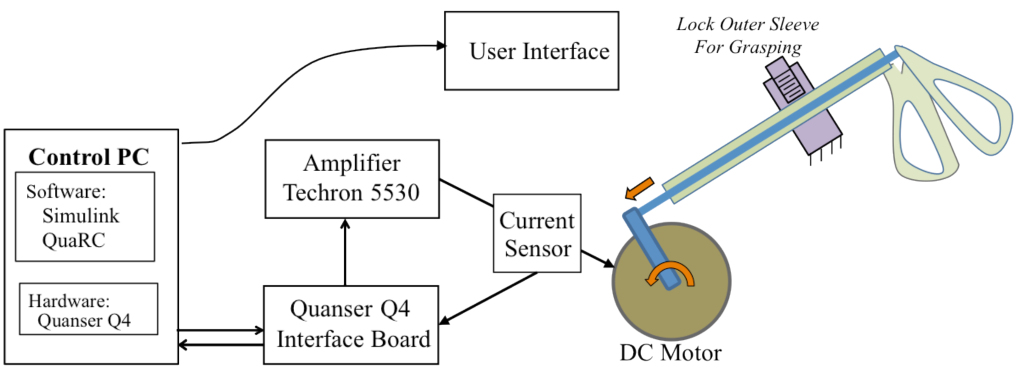

Figure 17: High-level system diagram of the proposed simulator architecture

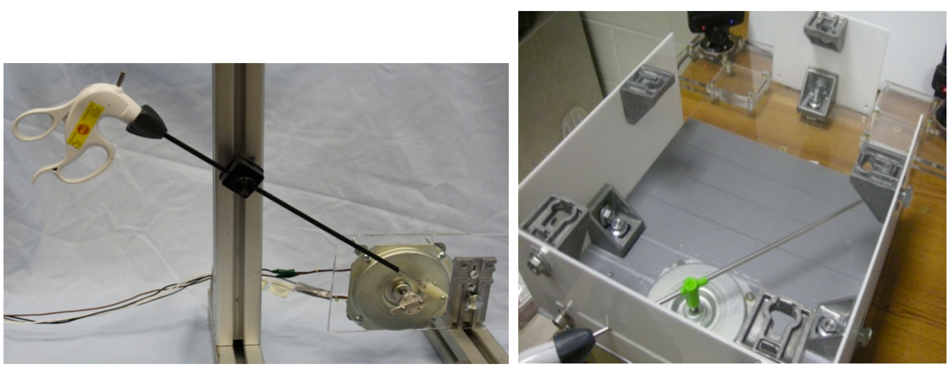

Figure 18: Probing and grasping simulator (left), sweeping simulator (right); the probing simulator was slightly modified for grasping.

Users held the probing simulator laparoscopic tool and pushed along the axis of the tool, resulting in reaction force applied on the hand. Similarly, for the grasping simulator, users applied pinch forces on the handle of the tool and felt resulting reaction force on the handles. To engage the sweeping simulator, users laterally rotated the tool about a pivot point to replicate motions used during surgery to clear and rearrange tissues and enable ample access to the surgical site.

Study Participants

A total of 34 participants enrolled in the study and were divided into two groups: *novices,* with no prior surgical experience and *surgeons,* with some level of surgical experience (including residents and attendings). All participants provided informed consent. The study was approved by the Clemson University institutional review board. Before participating in the experiment, participants completed a brief questionnaire containing demographic information as well as their video gaming history since previous studies have shown a correlation between laparoscopic skills and video gaming experience [23].

Experimental Task

All three simulators had the same force-based task rendered with their respective tool motions. The goal of the task was to record the application of precise forces by novices and surgeons with laparoscopic tools. When using each simulator, all participants were presented with a graphic (as shown in Figure 19) with distinct markers numbered I, II, III, etc., when using each simulator. The red marker in the graphic moved from left to right in response to the users' tool motion, the range of motion spanning past the last marker on the graphic. Between the first and the last markers, users felt force feedback as they manipulated the laparoscopic tool. Before beginning the experiment, participants were informed that the purpose of their task was to learn and reproduce precise forces at each of the markers.

During probing and grasping, two additional tasks called perceived minimum force ("min") and perceived maximum force ("max") were incorporated. For the "min" task, participants were instructed to produce the least amount of force necessary for feeling contact with the material. For the "max" task, participants were instructed to produce the maximum force they could apply to the simulated tissue before breaking it (tissue beaks were recorded as errors). The material was simulated such that a little beyond the maximum marker 4, force rendered was would abruptly change to zero, simulating tissue puncture.

Two sessions were designed for the experiment; in the first *pre-test* session, participants were given three trials to familiarize themselves with the precise forces required at each marker. This was facilitated by instructing them to make three complete "runs" from extreme left of the graphic to the right, and learning the force at each marker in the process. After three complete sweeps, the first session was completed.

In the *testing* session, visual feedback was turned off and users were asked to reproduce the force at each of the markers in random order. That is, using the laparoscopic tool, users applied precise motion to the tool until a suitable reaction force was perceived as corresponding to the marker.

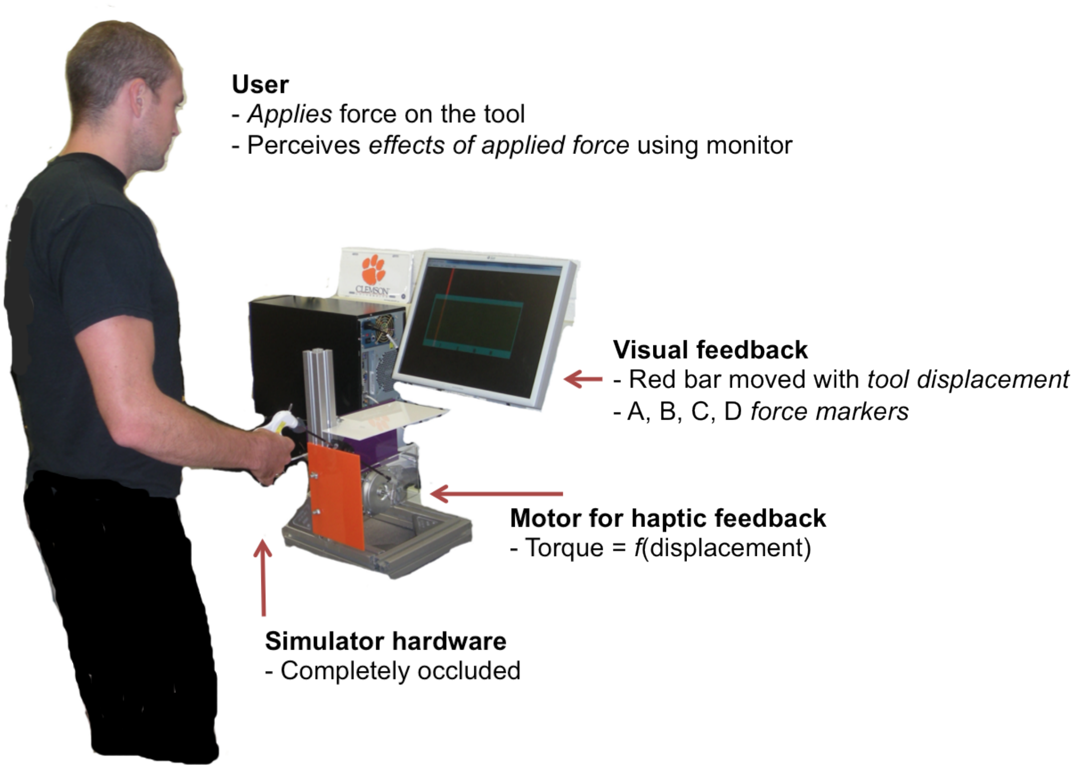

Figure 19: Simulator setup with main components: tool interface, visual display, and occluded haptic rendering hardware

Metrics for data analysis

Forces vary linearly with tool movement from left to right on the graphic. In rendering terminology, a linear spring ($f = K \cdot x$) was rendered for force feedback resulting in a linear force pattern for a linear displacement pattern.

To record performance on the simulators, a scoring system was devised to measure force. This was accomplished by normalizing sensor readings for displacement for a range of 0–130. The score varied in real time as users applied forces to the tool. During the experiment, scores were not visible to the user but were used by experimenters to record performance. The black markers on the graphic corresponded to scores of 25, 50, 75 and 100 for grasping and probing simulators and 25, 50, 75, 100 and 125 for sweeping simulator. Force scores were not recorded in the pre-test session. In the testing session, force scores were marked for each marker after participants confirmed their estimates.

To measure performance, regression models were computed, individually and for both groups collectively. Analysis of variance (ANOVA) analysis was used to compare scored performance of surgeons versus novices.

5.3 Results

Overall mean r^2 values, slopes and intercepts are presented in Table 1 and were obtained by averaging the coefficients produced by individual linear regressions performed for each participant. While the overall mean r^2 values are higher for surgeons than novices in each task, the mean differences amongst these averages in individual r^2 coefficients did not reach statistical significance. For probing and grasping tasks, novices produced significantly more overall force than novices on the force task, as evidenced by the differences in intercepts.

	Probing			Grasping			Sweeping		
	N	***S***		***N***	***S***		***N***	***S***	
r^2	.68	.72	$t(9)=-1.1$, $p=0.34$	.59	.79	$t(9)=-0.83$, $p=.44$	.89	.93	$t(10)=-0.52$, $p=.62$
Slope	0.69	0.84	$t(9)=-1.3$, $p=0.26$	0.66	0.85	$t(9)=-1.24$, $p=0.26$	0.90	0.81	$t(10)=1.85$, $p=0.09$
Inter-cept	30.47**	7.92**	$t(9)=2.16$, $p=0.06$	23.45*	5.92*	$t(9)=2.28$, $p=0.05$	11.11	13.77	$t(10)=-0.5$, $p=0.64$

Note: *$p<0.05$; **$p<0.01$; N=novices, S=surgeons

Table 6: Overall r^2 values, slopes and intercepts averaged over participants.

For each salient skill, multiple regression analyses were conducted to assess interactive effects of force magnitude between surgeons and novices, where reproduced forces were plotted as functions of the actual force required (10,25,50,75,100, and/or 125) and experience level (novice and surgeon). These results are displayed in Table 2. In addition, differences between novices and surgeons were assessed for each of the force levels for each laparoscopic task using between-subjects t-tests, presented in Table 8.

Probing

Both novices and surgeons produced more forces as probing force levels increased, though novices produced significantly more force than surgeons across the four force levels ($p < 0.05$, see Table 2 and Figure 20).

While novices produced significantly more forces at most levels of the simulated task, the largest differences between the two groups occurred at the lower force levels. Novices produced significantly more forces at level 25, level 50, and level 75 ($p < 0.05$). There was no statistically significant difference between the two groups at level 100 (See Table 3).

Grasping

Both groups produced more forces as grasping force levels increased. At lower levels of the simulated task, novices produced significantly more forces than surgeons. However, as the force levels increased, the difference in exerted force between novices and surgeons decreased ($p < 0.05$, see Table 2 and Figure 20).

At the lowest force level, 25, novices produced significantly more force than surgeons ($p < 0.05$), However, there was no statistically significant difference between the two groups at level 50, level 75, or level 100 (See Table 3).

Sweep

For the sweep task, both novices and surgeons produced more forces as force levels increased; at lower levels both groups produced similar amounts of force. However, as force level increased, novices produced significantly more forces than surgeons ($p < 0.05$, see Table 2 and Figure 20).

There were no statistically significant differences in produced force when comparing novices and surgeons at the lower levels of the material, namely 25 and 50. However, as force levels of the simulated material increased, the differences between the groups increased. Novices produced significantly more forces at level 75, level 100, and level 125 ($p < 0.05$, see Table 3).

	Probing		Grasping		Sweeping	
Effect	**df**	**Partial F**	**df**	**Partial F**	**df**	**Partial F**
Force Required (10,25,50,75,100 and/or 125)	123	88.36**	125	88.92**	179	975.94**
Experience (novice & surgeon)	123	13.54**	125	8.76**	179	0.61
Interaction	123	2.47	125	4.71*	179	5.38*

Note: **p*<0.05; ***p*<0.01

Table 7: Results of multiple regression analyses comparing novices and surgeons across the different required force levels, by laparoscopic task.

	Probing		Grasping		Sweep	
	Novice	Surgeon	Novice	Surgeon	Novice	Surgeon
25	46.5** (12.8)	30.2** (15.1)	39.7* (16.2)	28.28* (9.11)	31.1 (8.9)	33.2 (8.5)
50	65.5** (14.4)	49.0 ** (18.3)	55.5 (14.3)	49.0 (12.7)	57.4 (14.0)	54.9 (7.4)
75	85.4** (12.6)	68.7** (14.9)	74.9 (15.5)	65.4 (16.1)	81.6* (13.1)	74.3* (7.6)
100	95.63 (6.25)	93.50 (9.73)	87.1 (11.8)	93.7 (10.9)	102.9* (10.8)	95.6* (8.4)
125					121.1** (7.8)	113.8** (7.9)
r^2	***.68***	***.72***	***.59***	***.79***	***.89***	***.93***
Slope	***0.69***	***0.84***	***0.66***	***0.85***	***0.90***	***0.81***
Intercept	***30.47*****	***7.92*****	***23.45****	***5.92****	***11.11***	***13.77***
Note: *p<0.05; **p<0.01						

	Probing		**Grasping**		**Sweeping**	
Force Level	**df**	**t**	**df**	**t**	**df**	**t**
25	30	3.34**	31	2.42*	34	-0.73
50	30	2.89**	31	1.36	34	0.65
75	30	3.43**	31	1.71	34	2.04*
100	30	0.67	31	-1.41	34	2.28*
125					34	2.79**

Table 8 (top) Comparisons of scores between surgeons and novices by force levels on each task; (bottom) Results of between-subjects t-tests assessing differences in produced forces between novices and surgeons for each required force level, for each laparoscopic task.

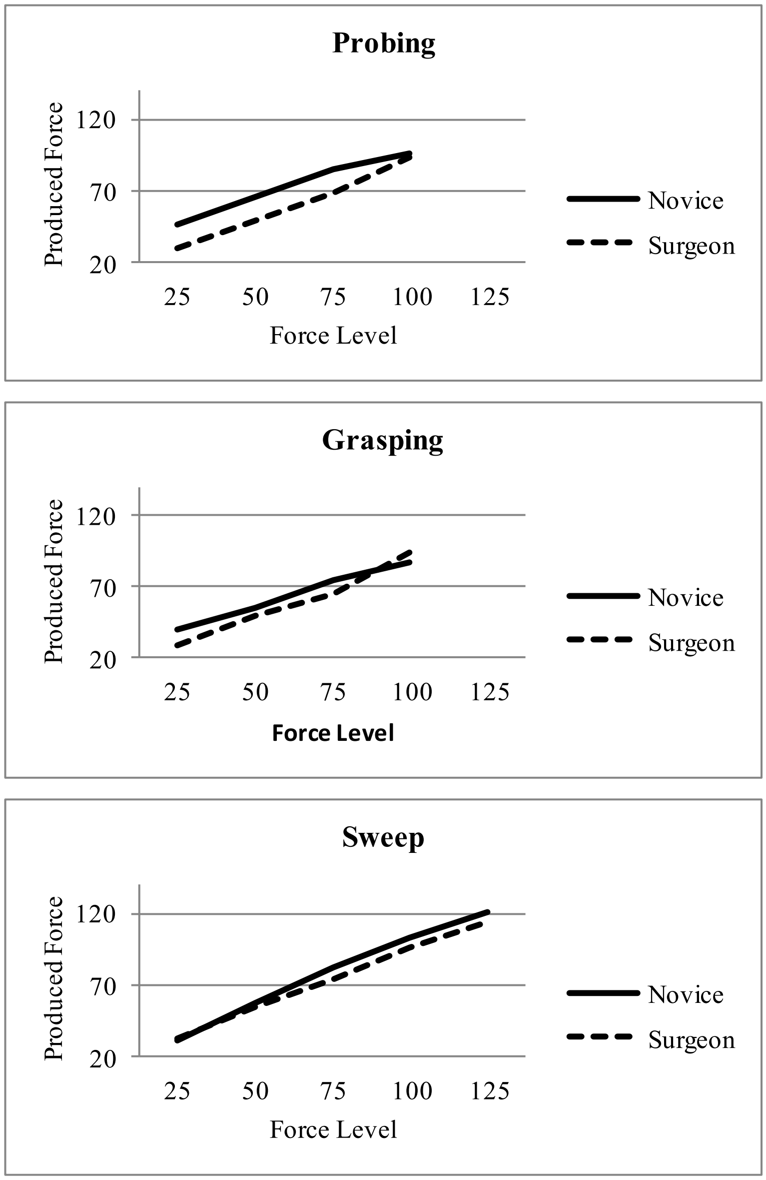

Figure 20: Interactive means plots for produced force by novices and surgeons across force levels, for each laparoscopic task.

Minimum and Maximum Penetration

Minimum ("Min") and maximum ("Max") penetrations distances were also examined between novices and surgeons for the probing and grasping tasks; the means of the Min and Max values are displayed in Table 9.

	Probing		Grasping	
	Novices	Surgeons	Novices	Surgeons
Min	40.1** (9.0)	20.9** (11.3)	31.7* (13.9)	23.5* (11.6)
Max	100* (8.2)	89.2* (17.6)	98.8 (7.9)	94.2 (13.7)
Overall	70.1 (31.6)	55.0 (37.5)	65.2 (35.7)	58.9 (37.8)

Note: N=42; *p<.05 and **p<.01.

Table 9: Mean forces produced for minimum and maximum penetration distance values for novices and surgeons, for probing and grasping tasks.

For the probing task, novices produced significantly greater forces when applying the minimum amount of penetration depth to perceive contact with the simulated material (t(42)=6.12, p<.001). Novices also produced greater amounts of force than surgeons when producing the maximum penetration force (t(42)=2.6, p=.01).

For grasping, novices again produced significantly more force than surgeons when producing minimum penetration force distances (t(42)=2.11, p=.04); the difference between the two groups was not significant when producing maximum penetration force (t(42)=1.31, p=.19).

Tissue "breaks" were also recorded for the probing and grasping tasks; the total sum of tissue punctures is displayed below in Table 6. Novices produced a significantly greater amount of mean tissue breaks than surgeons during the probing task (t(86)=3.4, p<.005), though there was no significant difference in mean tissue breaks during the grasping task (t(86)=1.23, p=0.22).

	Probing		Grasping	
	Novices	Surgeons	Novices	Surgeons
	11**	1**	8	5
Total	12		13	

Note: *p<.05 and **p<.01.

Table 10: Sum of tissue 'breaks' for novices and surgeons for probing and grasping tasks.

Accuracy

The absolute difference between required force and produced force was compared between novices and surgeons for each surgical task as a measure of overall variability, or error. Means and standard deviations for novices and surgeons by surgical task are displayed in Table 7.

Novices produced a significantly higher degree of absolute error than surgeons in the grasping task ($t(124)=2.12$, $p=.04$). However, while novices were more variable in their force production, there was no difference in overall error between the two groups for either the probing task, $t(122)=1.32$, $p=.19$, or the sweeping task, $t(178)=0.49$, $p=.62$.

	Novices	Surgeons
Probing	15.5 (11.9)	13.0 (-8.2)
Grasping	14.2* (10.1)	10.6* (8.5)
Sweeping	8.7 (8.6)	8.2 (6.3)

Note: * p<.05

Table 11: Means and standard deviations of absolute error (produced – required force) of novices and surgeons for each laparoscopic task.

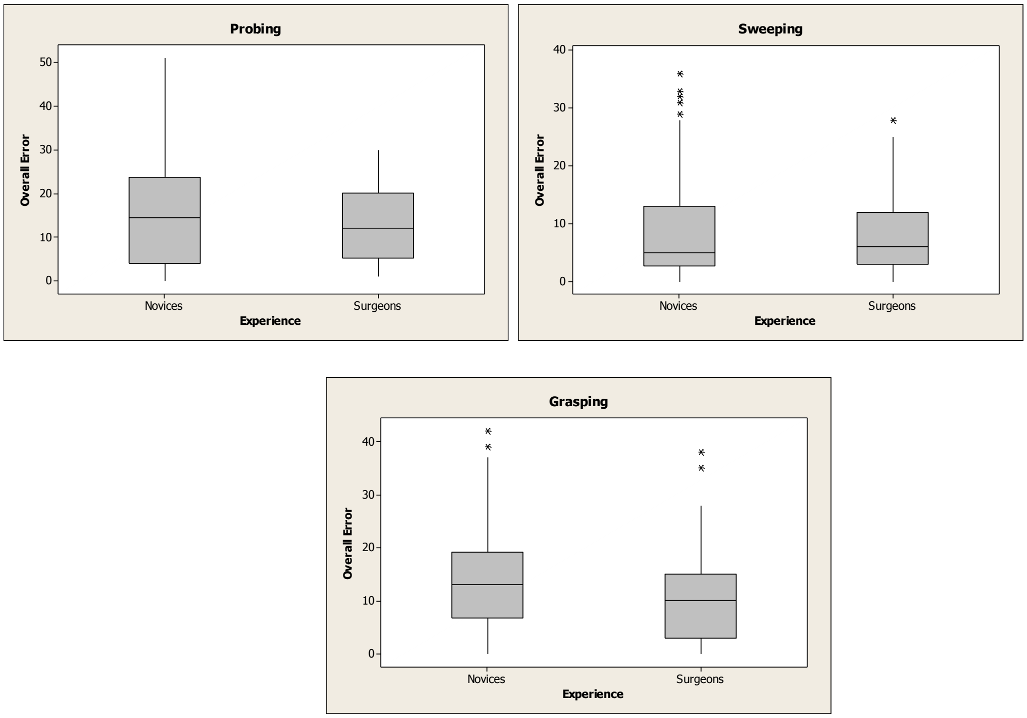

Figure 21: Box plots for overall error (absolute difference of produced force – required force) of novices and surgeons for each surgical task.

Discussion

The motivation of this study was to validate haptic surgical simulators for specific force-based laparoscopic skills. To this end, three custom haptic simulators were built and, force behavior of surgeons and novices was collected on a haptic task on the simulator. Results from the study can be summarized as follows:

1) *data demonstrate that surgeons possess a haptic skill set that is under-developed in novices.* This study directly addresses the contention in current literature as to whether or not haptic skills are required for proficient laparoscopy: surgeons *do* possess superior force-based laparoscopic skills than novices and the simulators

presented in this work can be used as objective means of establishing the presence of a haptic skill set in surgeons.

2) *computer-based haptic simulators can be used to objectively measure and differentiate haptic skill of surgeons and novices.* One of the most desirable aspects of a simulator is the ability to objectively measure the skill of its users, thereby eliminating the need for expert surgeons to "look over the shoulder" and subjectively grade the residents' performance. Force data collected on the task described in this paper was used to compare performance of the novice group versus the surgeon group. Thus, the difference in force skills of surgeons and novices was objectively demonstrated on the simulator.

It should be noted that results presented in this paper are in distinctly different with most studies using haptic laparoscopic simulators. Driven by the need for better laparoscopic simulators, several popular virtual reality (VR) simulators have included expensive haptic feedback. However, generally speaking, commercial haptic VR simulators have demonstrated only poor to moderate results thus far. For example, Salkini and coworkers studied the effect of haptic feedback in the LapMentor II (Simbionix Inc.) surgical simulator [24]. Residents performed three tasks requiring skilled application of force with and without haptic feedback and were assessed based on simulator built-in metrics of speed, accuracy of movement and economy of movement. Results showed no major differences between the haptic and non-haptic groups. A surprising finding was that members of the haptic group had significantly slower movements of their dominant hand. The authors suggest that haptic feedback rendered by the simulator was poor and possibly not relevant to the type of forces encountered in laparoscopic surgery.

Similarly, Panait and coworkers studied the benefit of haptic feedback on the Laparoscopy VR simulator (Immersion Medical Inc.) [9]. Ten residents performed two common laparoscopic training tasks (peg transfer and pattern cutting) with and without haptic feedback. Results from the study showed no significant differences in performance for the peg transfer task with or without haptics. However, there was a significant decrease in the time to complete the task for the haptics group for the pattern cutting task. The addition of haptic feedback in this study showed only a small benefit for training [25]. Other recent studies with commercial haptic simulators also conclude with similar results pointing to immature rendering mechanisms [26].

The reasons for poor results from commercial haptics-enabled simulators are hard to pin-point. The exact mechanisms for rendering haptic feedback in these simulators are mostly unknown, making it difficult to ascertain if physical rendering mechanisms could contribute to poor results. We suggest that the primary reason for low satisfaction with commercial simulators this is that haptic feedback is being rendered for basic tasks where force-feedback may be irrelevant. In an earlier study, we compared a VR peg transfer-like task with haptic and no haptics and compared performance with a haptic task in the box trainer. Performance (measured by time taken to complete task) on the box trainer showed higher correlation with the non-haptics group than with the haptics group [27]. Haptic feedback, thus, may not be essential for tasks where hand-eye coordination skills are primary (like peg transfer). Another reason for poor results on commercial simulators may be that, though haptic feedback is rendered, performance is assessed using conventional time and motion-based metrics. Validated force-based metrics on simulators may be needed to clearly distinguish haptic skills of surgeons and novices.

Framework for Haptic Skills Simulators

Based on this study and above the cited arguments, we suggest that the first step in the development of haptic simulators for laparoscopic surgery is to isolate *salient haptic skills*, i.e., skills where haptic feedback is critical for the successful outcome of the task. In this study, we simulated three salient haptic skills: probing, grasping and sweeping. These skills were chosen based on a pioneering study by Richards and coworkers where force data from novices and surgeons was collected during common surgical procedures. Results revealed that surgeons differed from novices in three skilled "maneuvers": sweeping forces comprising lateral movements of the tool, probing forces comprising dissection-like motions and grasping forces. This data is the basis for our three proposed salient force-based laparoscopic tasks: probing, grasping and sweeping. The focus in development and validation of simulators for haptic skills must begin with these *salient* force-based skills where precise application of forces is critical to successful task outcomes.

5. 4 Conclusions

In this work we have demonstrated that haptic simulators, built to focus on the force-based skills of grasping, probing, and sweeping, can objectively measure haptic skills levels, which can then be used to differentiate the haptic skill levels of surgeons from those of novices. This result suggests that there is a continuum of skills proficiency between these extremes, e.g. residents with some experience should have better haptic skills than novices. Future work will focus on measuring the actual shape of the learning curve from novice to expert in order to provide the means to evaluate absolute level of skill and progression of training and towards haptic skills mastery.

The difference in performance between surgeons and novices in the three force tasks suggests that specific force-based skills are required for proficient laparoscopy. Further, if a set of salient haptic skills is identified, then teaching these skills could accelerate resident training. Future efforts will focus on determining if the grasping, sweeping, and probing skills span the set of haptic skills used by experienced surgeons and the development of a single haptic device to implement the training. This initial step will involve the engineering maturation of the simulation device itself and also development of the curriculum that most efficiently uses the device to teach the skills. The next step will be to design and test training curriculum focused upon these specific haptic skills.

The knowledge that experienced surgeons do have a different set of haptic skills could help advise how to better incorporate relevant haptic feedback into surgical simulators or even surgical robots. Finally, and perhaps most immediately applicable, this study highlights the importance of encouraging the resident learner to hold the laparoscopic instrument and feel the characteristics of tissues and forces early in training.

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CHAPTER 6

A NOVEL HAPTIC SKILLS SIMULATOR FOR TRAINING SALIENT FORCE-BASED LAPAROSCOPIC SKILLS: A VALIDATION STUDY

6.1. Introduction

The ethos of surgical education is rapidly shifting from the traditional approach of "See one, do one, teach one", which emphasizes training in the operating room, to enabling better-prepared surgeons entering the operating room by practicing on surgical simulators [1]. This paradigm shift is propelled by factors such as work hour restrictions on residents and regulations mandating surgical skills simulators in the United States [1–3]. Operating room training also raises important ethical questions when undertrained residents are involved and costly animals labs are used for basic skills training [4]. The promise of surgical simulators is to optimize operating room training by accelerating the learning of basic surgical skills on low-cost and less-threatening simulators [5].

Novice surgeons experience a steep learning curve in attaining laparoscopic skills. Thus in recent years a variety of simulators have been proposed for teaching laparoscopic surgical skills. Further, the overlap between skills required for open surgery and those required for laparoscopic surgery is not significant [6]. The setup of laparoscopic surgery poses unique hurdles for the surgeon to overcome. Unlike open surgery, surgeons use long tools to access the surgical site through small incisions in the abdomen and camera images from the surgical site are relayed via an endoscopic camera onto a monitor [7]. Thus the surgeon needs to learn to translate the two-dimensional camera images into their 3D anatomical context (visual perception skills, [8]) while coordinating their hand movements with the resulting camera images (hand-eye coordination skills, [9], [10]). They also must learn to operate with decreased force perception because the indirect touching of tissues results in a reduced sense of touch (haptic skills, [11]). In light of these challenges it is imperative that effective simulators are designed to efficiently teach the surgical skills that are specific to laparoscopic surgery. Figure 22 shows a possible decomposition of a generic surgical procedure into first tasks and then elemental surgical maneuvers [12]. Based on this type of decomposition of surgical tasks from previous studies ([12], [13]), a set of core haptic skills was proposed. Note that this same decomposition supports the framework of the Fundamentals of Laparoscopic Skills simulator and curriculum [5].

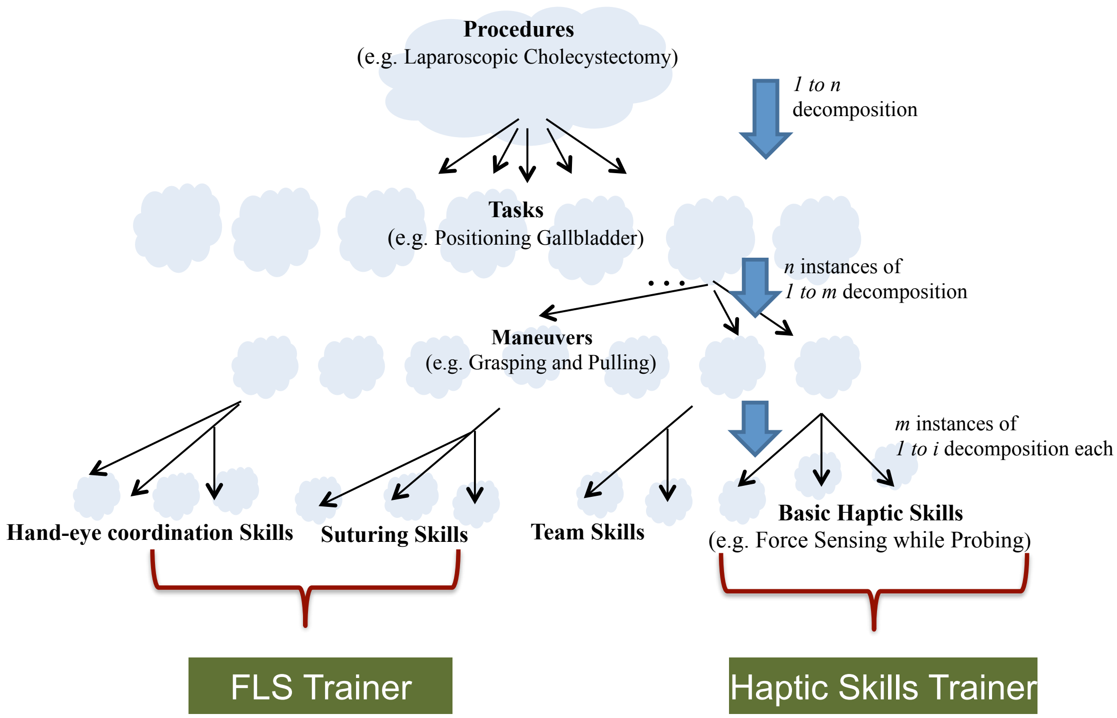


Figure 22: Decomposition of surgical procedures to distill core skill sets. While the popular FLS skills address basic hand-eye coordination and suturing skills, more advanced haptic skills have not yet been successfully distilled and validated. In this work, we proposed three salient or core haptic skills—grasping, probing and sweeping—for testing and training haptic surgical skills.

The most widely employed laparoscopic simulator is the Fundamentals of Laparoscopic Skills (FLS) trainer. Commonly called the FLS "Box" trainer, it features a "low-tech" hollow box with a webcam and five associated tasks simulating basic hand-eye coordination skills such as transferring small pegs and suturing using laparoscopic tools. Though this simulator compares poorly in realism to the anatomical surgical site, it has been demonstrated by several studies to effectively impart basic laparoscopic skills.

Fried and coworkers, for example, published a detailed study demonstrating the construct validity of the FLS curriculum [5], [14]. Recently, the FLS trainer was also demonstrated to have predictive validity, with the training on the simulator being shown to transfer to the operating room [15].

There are significant limitations to the FLS trainer and its associated curriculum. Probably the most serious limitation is the need for an expert surgeon to assess the performance of a novice trainee and give feedback for improvement [16]. Also, the FLS curriculum simulates only basic laparoscopic skills; more advanced force-based and anatomic skills are not part of the simulator. Virtual Reality (VR) simulators have been proposed to improve upon traditional Box trainers by adding a greater skill set for training and for objectively assessing the performance of trainees [17].

Training surgical residents towards laparoscopic skills proficiency involves progressing beyond learning skilled pointing and placement of instruments. This work addresses the specific aspect of adding force-based skills to laparoscopy training simulators. In previous studies, we identified force-based skills that are required for skilled and safe laparoscopic surgery. Based on literature review and pilot studies [3], [18], [19], three salient haptic laparoscopic skills were identified as tasks where the application of precise forces was critical to successful performance. These salient haptic laparoscopic skills were: probing, grasping and sweeping. Probing was defined as pushing on tissue to perceive object properties or for surgical tasks like cautery or dissection. Grasping was defined as using pinch motions at the tool handle to grasp tissue for various surgical operations or for simply clearing tissue. Sweeping was defined as applying leverage to tissue using the abdominal wall as the pivot point for this lateral motion of the tool. Richards and coworkers reported that surgeons significantly differed from novices in the magnitude of forces applied in these three tasks in in vivo surgical procedures [12].

Novel computer-based haptic simulators were designed and implemented for simulating grasping, probing and sweeping tasks. As a first step towards validating these simulators, the examined the force magnitudes applied by surgeons and novices on the simulators. Data analysis confirmed the original hypothesis that force magnitude applied by expert surgeons on the tool was significantly different from force magnitudes applied by novices on a virtual material [4]. All three tasks, novices generally applied significantly greater force than surgeons at specific force ranges.

While the earlier study demonstrated that haptic skills of surgeons and novices can be objectively differentiated using haptic simulators, the real value of a simulator lies its efficiency to train skills of users. In this work, we test the salient haptic skills simulator for training validity, i.e., does training on the haptic simulator improve performance as measured by objective force-based metrics?

6.2. Materials and Methods

Participants

Thirty undergraduate students participated in the study. Ages of the participants ranged from 17-26 years, with a mean age of 19.9 years (*SD*=2.2). The sample was primarily male (66.7%, with 20% female and 13.3% choosing not to respond). The study was approved by the Clemson University IRB (Institutional Review Board) and all participants provided informed consent. None of the participants had any previous experience with laparoscopic surgery.

Apparatus

The simulator used in this study was developed at Clemson University for the purpose of training force-based laparoscopic skills. The device was designed to simulate the grasping, probing, and sweeping actions proposed as salient haptic skills in laparoscopic surgery. Prototypes of three devices, separate devices for probing, grasping and sweeping, were described in an earlier publication where the validation of the haptic simulators for skills testing was shown [13]. In that work, the three haptic interfaces were used to differentiate the skill levels of surgeons from those of novices. For this study, the simulators were refined and the functionality of the previous prototypes was combined into a single simulator. A functional description of the Core Skills Haptic Trainer is shown in Figure 23 where in can be seen that the user selects a skill, i.e., grasping, probing, or sweeping, that is then implemented by the system. The user moves the input device and feels an applied force as a result of the movement (impedance control).

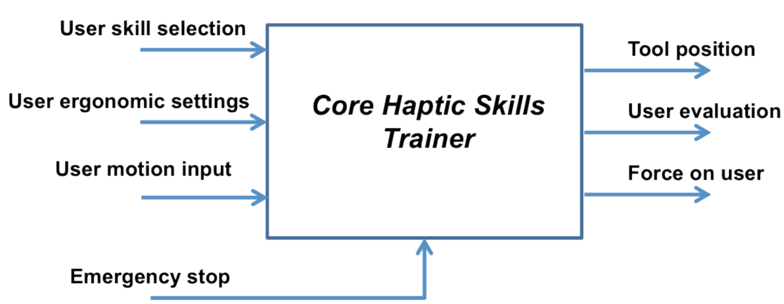
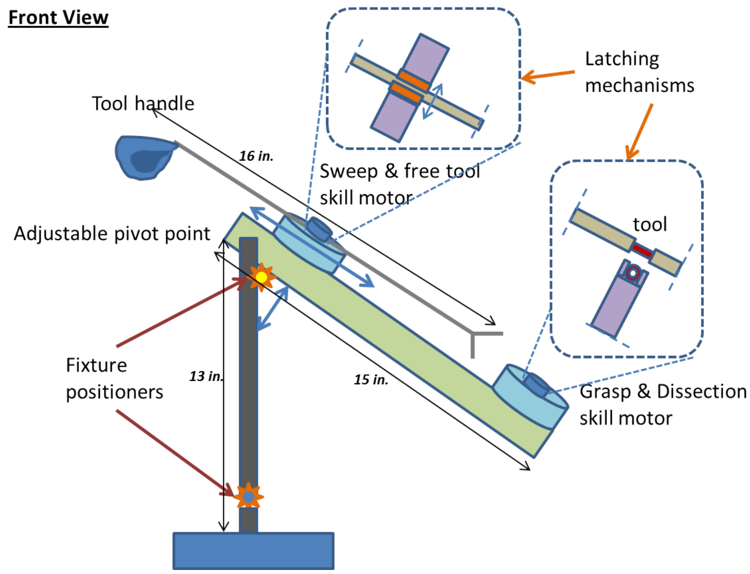
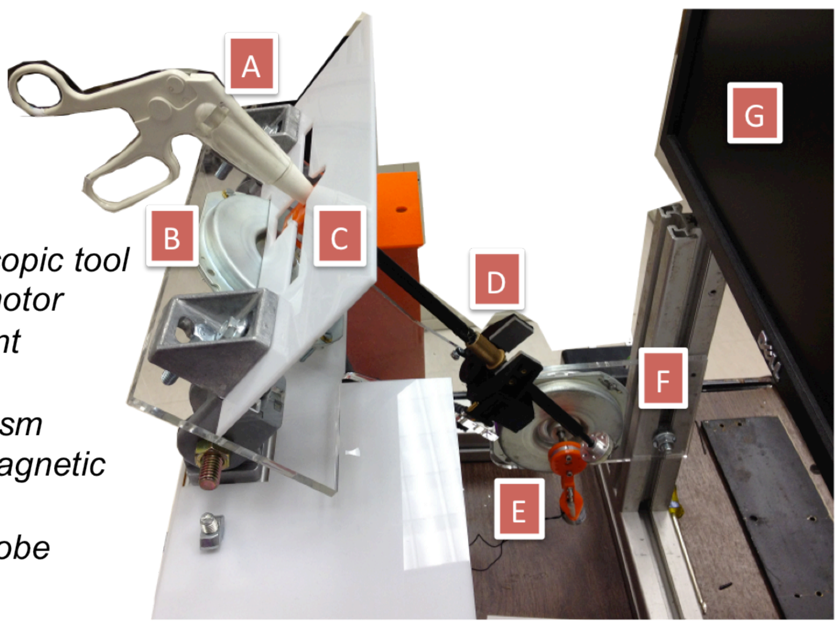


Figure 23: Functional description of the Core Skills Haptic Trainer.

The schematic in Figure 24 shows how the three individual tool motions are overlaid to produce a single simulator. The proposed sweeping task can be simulated by forcing the user held tool handle to pivot about a point, the system must apply a torque at the rotation point to simulate the feeling of pushing on a compliant mass, e.g. a tissue or organ, through a lever (the fulcrum effect). The probing task can be simulated by constraining the tool handle to move along the tool handle length and then producing a force on the tool handle to simulate that the user is pushing on a compliant mass. The grasping task can be simulated by making the user interface a scissor grip where forces can be applied to the two halves of the scissor mechanism to simulate the feel of grasping a compliant object through a laparoscopic gripper. With these tasks in mind, a modified laparoscopic tool (the gripper was removed from a standard Autosuture™ Endo® tool) was connected to a robotic device to produce the appropriate motions and forces on the tool.

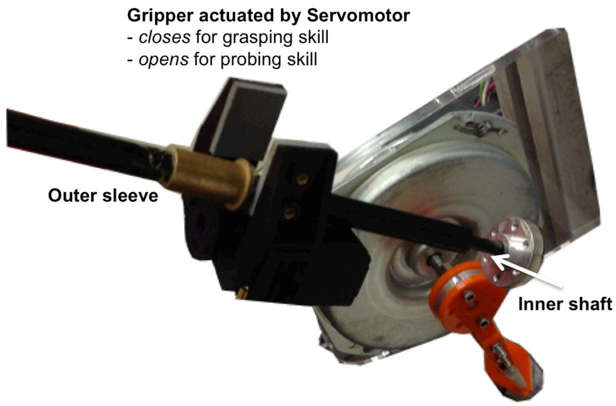


(A)



A. Laparoscopic tool
B. Sweep motor
C. Pivot point
D. Latching mechanism
E. Electromagnetic coupler
F. Grasp/probe motor
G. Monitor

(B)



(C)

*Figure 24: **(A)** Schematic of the tool motions and layout and dimensions of the Core Haptic Skills Training Simulator; **(B)** Photograph of the system used in the training experiments; **(C)** latching mechanism for grasping and probing skills.*

The robotic motion system shown in Figure 24 comprises two direct-drive DC motors (Tohoku Ricoh™), one at the center and one towards the bottom of the tool (see Figure 24), controlled by a computer. The system uses the motors to produce force-feedback by generating a torque in response to the motion applied by the user on the tool handle. Each motor has an embedded encoder that was used to optically sense motor position, and hence the user motion. The motor connected at the mid-section of the tool, labeled as "B" in Figure 24, was responsible for rendering sweep torque while the motor at the bottom, labeled as "F" in Figure 24, rendered forces that simulated probing and grasping actions. Though the same motor was used for both probing and grasping forces, the motions at the handle of the tool were different for these tasks. For grasping, the outer sleeve of the laparoscopic tool was held fixed so that only the inner shaft of the tool, connected to the motor, moved when motor torque was applied. For simulating dissection, the scissor grip was locked and the outer sleeve and the inner shaft of the tool moved in tandem because no grasping motion was allowed at the handle of the tool. The data acquisition and output was done with a Q4 Hardware-in-the-Loop (HIL) card (Quanser Inc.) connected to a standard computer. The motors were driver by a Techron (AE Techron, Elkhart, IN) 5530 linear amplifier. Software (haptic) algorithms were programmed in MATLAB/Simulink (v. 2008a) and executed in soft real-time using QUARC (Quanser Inc., v. 2.1). Additional details of the design and construction of the simulator are described in [13].

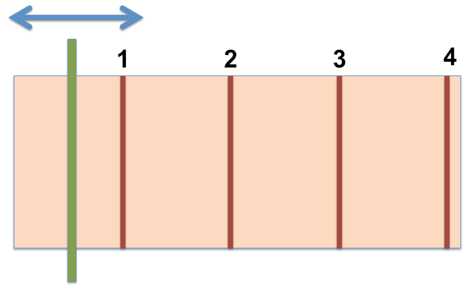
The haptic forces were generated using an impedance control. In the grasping and probing tasks, the position of the tool tip or angle of the scissor grip was measured by the grasp/probe motor encoder. A virtual material was programmed using software algorithms such that, proportional to the simulator tool's end-effector penetration into the virtual material, a force would be generated using a standard spring equation either $f = K \cdot x$ for probing or $\tau = K \cdot \theta$ for grasping. This force is converted into a torque that was rendered by the motor (depending on which skill is being practiced). Similar calculations generate the torques applied by the sweep motor.

Experimental Task and Protocol

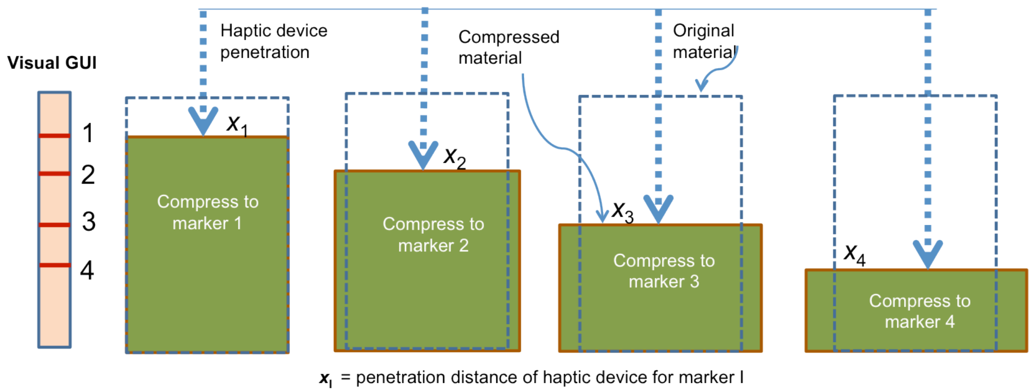
The experiment was designed to test the hypothesis that structured training on the haptic simulator on all three force-based surgical tasks would result in significantly lower absolute errors after training. The force learning task for all three skills—grasping, probing and sweeping—were almost identical. Participants were presented with a graphic on the simulator's monitor similar to Figure 25, which had numbered force markers (1-4 for grasping and probing; 1-5 for sweeping). Experimental setup is shown in Figure 26.

As the user applied skill-specific motions on the tool the green bar on the graphic moved proportional to applied displacement. A linear "virtual material" model was used in this study to compute reaction force based on applied displacement. For linear penetration into the virtual material (linear motion), the force experienced via the tool was also linear from left to right of the graphic.

At the outset of the experiment the participants were instructed that the goal of the task was to learn the precise forces at each of the markers. Additionally, for grasping and dissection tasks, two other data points were collected which were referred to as "min" and "max" to participants. "Min" was defined as the minimum force that users felt necessary to perceive definite contact with the material. This metric was patterned after Zhou and coworkers pioneering study on perceptual differences between expert surgeons and novices [20]. Also, participants were asked to estimate the greatest force they felt that they could apply without puncturing the material. Like soft tissues encountered during surgery, the virtual material model was programmed to "break" a little after the final marker (# 4) during the grasping and probing tasks. These metrics were included based on a previous study demonstrating that surgeons and novices can be differentiated based on their "min" and "max" force data [20].



(A)



(B)

Marker	Score
1	25
2	50
3	75
4	100
5 (Sweep only)	125

(C)

Figure 25: ***(A)*** *Graphical User Interface (GUI). As participants moved the tool the green marker moved across the range of the graphic. The markers 1, 2, 3 and 4, represented the four values (five for sweeping) at which the precise forces were to be learned;* ***(B)*** *Illustration that compression of a virtual material corresponds to different penetration lengths, represented by markers 1, 2 , 3 and 4 (this graphic is not shown to the users);* ***(C)*** *Score values at each marker on the GUI.*

After participants provided informed consent to participate in the study, a brief PowerPoint presentation was used to brief them on the purpose of the experiment as well as the particular skill (grasping, probing or sweeping) and task they were to perform. Each participant performed only one of the tasks in a single session lasting about forty minutes in duration. The experiment was structured in three phases as pre-training—training—post-training, commonly used in many skills training experiments [21], [22].

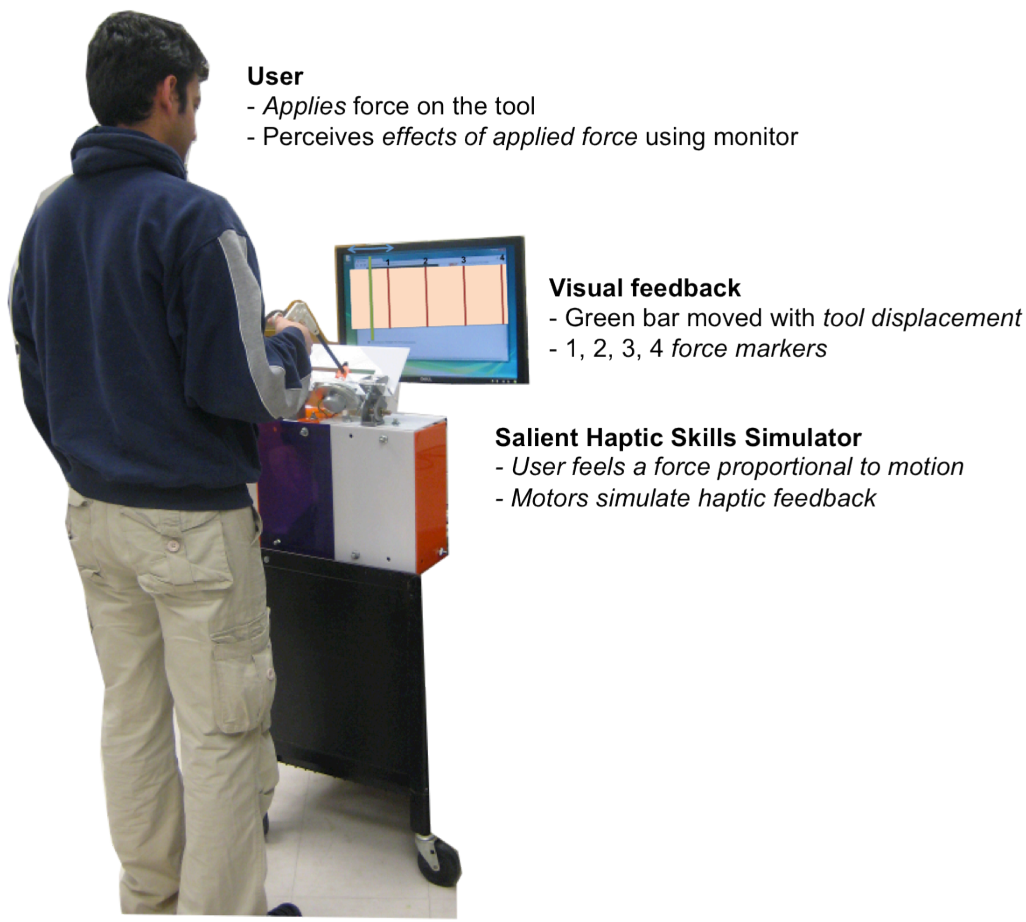


Figure 26: Experiment setup: participants performed one of three force-based surgical skills—probing, sweeping or grasping—on the simulator. The graphic with force markers was relayed via the monitor in specific phases of the experiment.

In the pre-training phase, participants were instructed to move from left to right of the graphic two times, paying attention to the forces felt at respective markers. After this, visual feedback (monitor with graphic) was turned off and participants were asked to produce forces felt at various markers by moving the tool handle. Four sets of readings for markers 1 through 4 (1-5 for sweep) were collected (in random order) in this phase. After this phase, participants were briefed about the training phase where the goal was to learn precise forces at each marker using the graphic. The protocol for each reading was as follows: the participant would be asked to make an estimate of force using the tool for a particular marker without visual feedback; once the force estimate is made, visual feedback was turned on enabling participants to see the error of their estimate. It was hypothesized that as the trials progressed in the feedback phase, the force error would converge towards zero. The feedback phase consisted of five sets of readings from 1-4 (1-5 for sweep) in a random order, with a 2- minute break after the second set. Post-training data was collected exactly as in the pre-training with no visual feedback and with four sets of readings conducted in random order. The purpose of the post-training readings was to test learning by comparing force scores with pre-training scores.

Metric for Data Analysis

The forces produced by the participants at each marker were recorded using a custom metric called score, devised based on the encoder measurements from tool position. Since the purpose of this study is to examine force behavior, encoder readings can be used to indirectly yield reaction force using a linear spring model, $f = K \cdot x$, where x measures the position of the tool relative to the surface of the virtual material and K is the stiffness constant. To further simplify force readings and make it “human readable”, the constant K was normalized such that score was in the range of 0-130 units for the span of the graphic. The force markers on the graphic corresponded to score units of 25, 50, 75 and 100 (125, for sweep). Participants were not made aware of this metric for the experiment.

6.3. Results

Ten participants were assigned to each condition. Multivariate outlier analysis revealed one participant in the Grasping condition produced extreme forces and was thus removed from further analyses.

Absolute Error

To determine accuracy of produced forces, absolute errors were calculated for each participant for each trial. Mean absolute error and standard deviations for the pre-training and post-training phases are given in Table 12 for each of the three tasks. Paired t-tests were conducted for each task comparing mean absolute error in the pre-training and post-training phases. Mean absolute errors were found to be significantly lower in the post-training phases for all three surgical tasks (Grasping, Probing, and Sweeping), indicating that participants were producing forces with improved precision.

	Grasping (n=9)		**Probing (n=10)**		**Sweeping (n=10)**	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*
Mean	15.94*	12.01*	17.26*	10.18*	17.15*	9.2*
SD	6.9	3.42	4.79	3.1	6.61	2.81

*Table 12: Absolute error means and standard deviations for pre-training and post-training phases by surgical task. Note: post-training significantly different from pre-training at *p<.05.*

Mean Differences in Produced Forces

Paired t-tests were used to analyze mean differences between pre-training produced forces and post-training produced forces by task and by force level. Mean produced forces and standard deviations for the pre-training and post-training are given in Table 13 for each of the force levels within each of the three tasks.

	Grasping (n=36)		**Probing (n=40)**		**Sweeping (n=40)**	
Force	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
25	42.2	34.6*	49.67	37.68**	38	30.55**
	(13.03)	(17.13)	(13.24)	(13.26)	(17.06)	(11.37)*
50	58	50.16	69.68	51.25**	57.72	52.78
	(22.8)	(12.75)*	(15.27)	(14.18)	(19.98)	(9.32)**
75	77.5	77.41	80.55	78.65	75.55	77.78
	(17.17)	(15.87)	(16.53)	(11.58)	(19.74)	(9.59)**
100	94.3	92.47	101.55	96.13	95.15	104.03*
	(19.97)	(15.51)	(15.44)	(9.56)	(20.66)	(11.58)**
125					122.75	126.32
					(23.29)	(14.44)**

*Table 13: Mean force produced, standard deviations (in parentheses), and significance values for pre-training and post-training phases by surgical task and actual force. Note: post-training significantly different from pre-training at *p<.05, **p<.001.*

Produced forces were compared between pre- and post-training phases for each task for lower score (25 and 50) values. Significant mean differences were found in all three surgical tasks between pre-training and post-training phases for the lowest force of 25. On average, all participants in all three task conditions performed significantly better in the post-training phase when asked to produce a force of 25. In the probing task, participants performed significantly better in the post-training phase when asked to produce a force of 50. In the grasping and sweeping tasks, participants also performed better, though the results were not significant (graphical representations of mean differences for these data are shown in Figure 27).

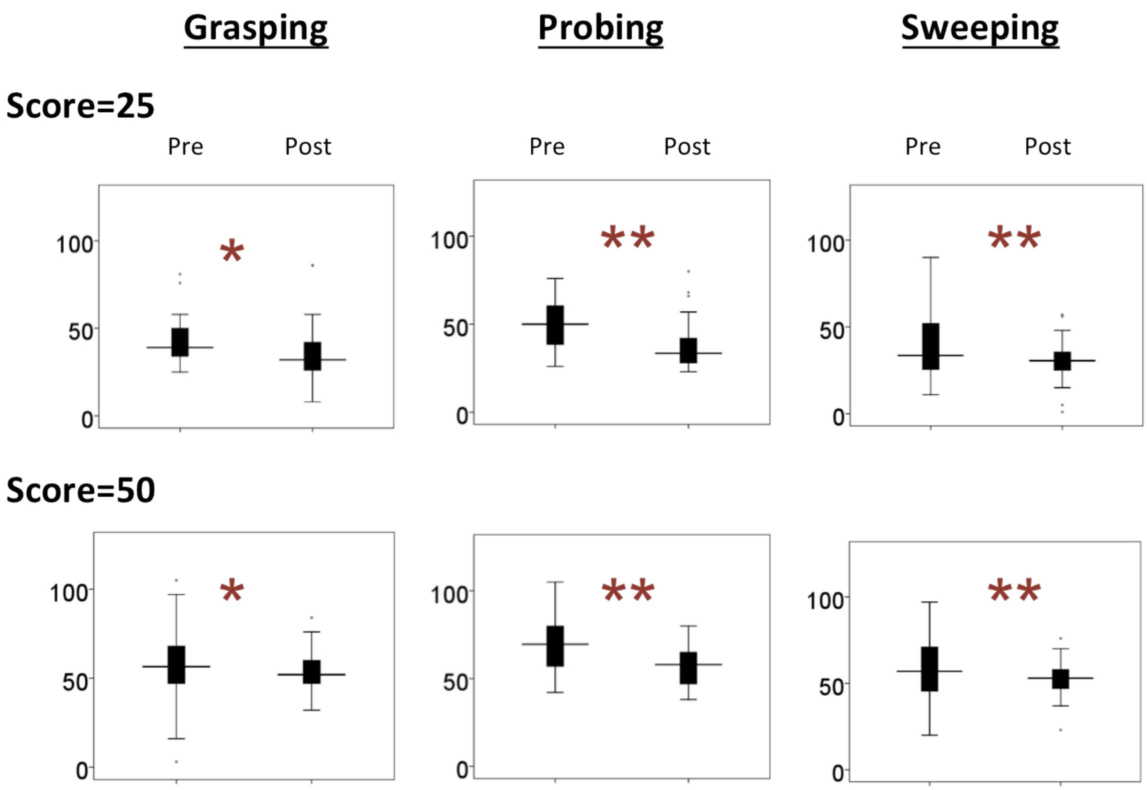


*Figure 27: Graphical summary of pre-training and post-training mean produced forces for each surgical task for lower target score values of 25 and 50. Y-axis of each graph represents score values used as a measure of force. Note: *=post-training significantly different from pre-training at p<.05; **p<.001.*

Mean differences between pre-training and post-training at higher force values (75, 100, and 125) were also assessed (see Figure 28). No significant differences were found in any of the three tasks between pre-training and post-training phases when participants were asked to produce a force of 75. In the sweeping task, participants produced significantly different forces in the post-training phase from the pre-training phase (though only slightly more accurately) when asked to produce a force of 100.

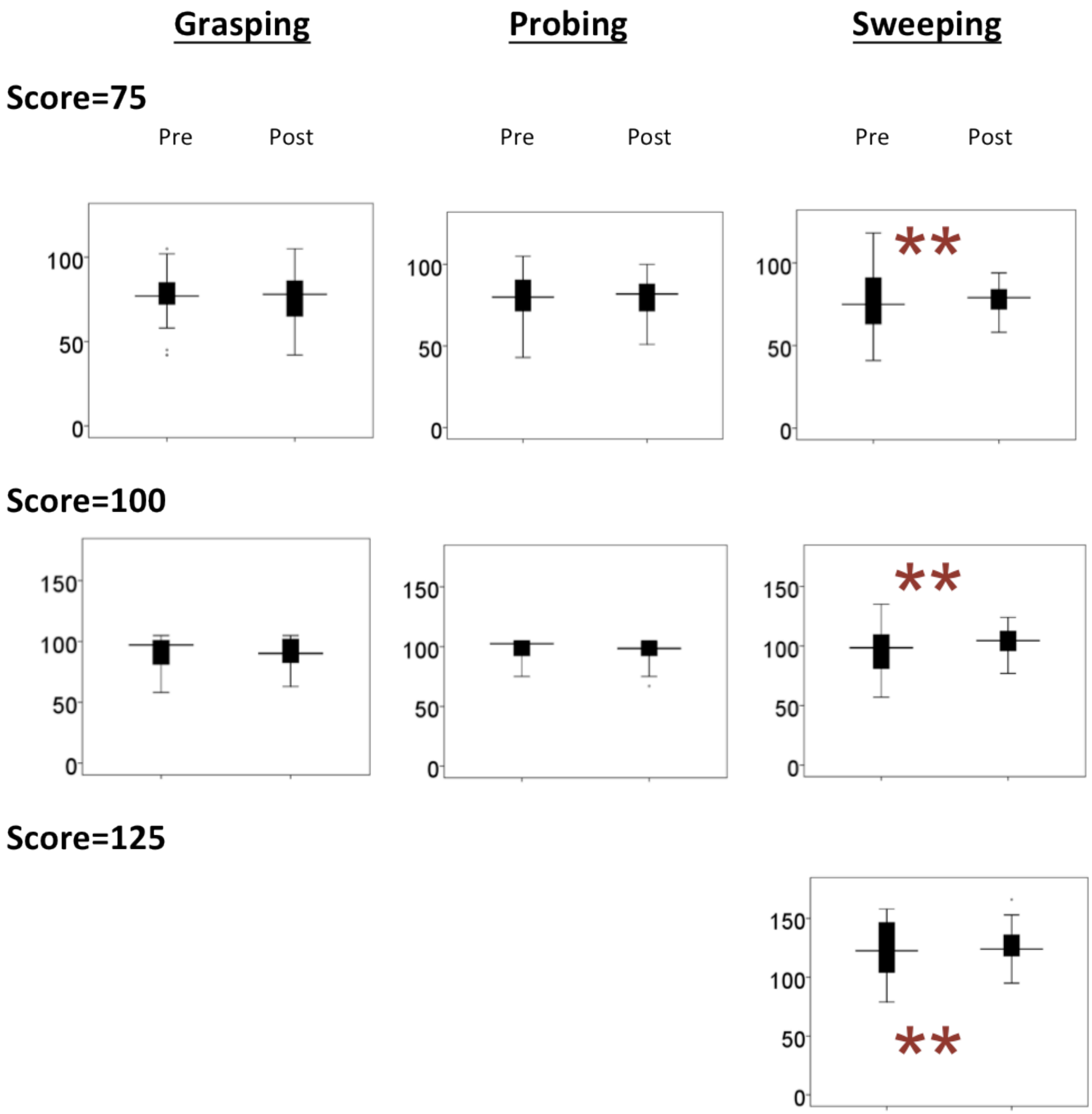


*Figure 28: Graphical summary of pre-training and post-training mean produced forces for each surgical task for higher target score values of 75, 100, and 125 (sweep only). Y-axis of each graph represents score values used as a measure of force. Note: *=post-training significantly different from pre-training at p<.05, **p<.001.*

Standard Deviations

In nearly all task and force combinations, standard deviations were less in the post-training phase, indicating that training lessened variability in force production among participants; participants produced more precise forces in the post-training phase (Table 13). Levene's test was used to test homogeneity of variance. For the Grasping task, standard deviations were significantly lower in the post-training phase for the actual force of 50. For the Probing task, differences in standard deviation approached significance (p <. 10) for the actual forces of 50, 75, and 100. In the sweeping task, standard deviations were significantly lower in the post-training phases for all actual forces (25, 50, 75, 100, and 125).

Over/Under Estimations

Interestingly, participants tended to overestimate forces for both pre and post-training phases, and to a greater extent at lower force values than higher force values. For actual forces of 25, 50, and to a lesser extent, 75, participants overestimated the amount of force required to produce said forces. This effect was not seen for the force level of 100, in which participants typically *under*estimated the amount of force required (see Figure 29).

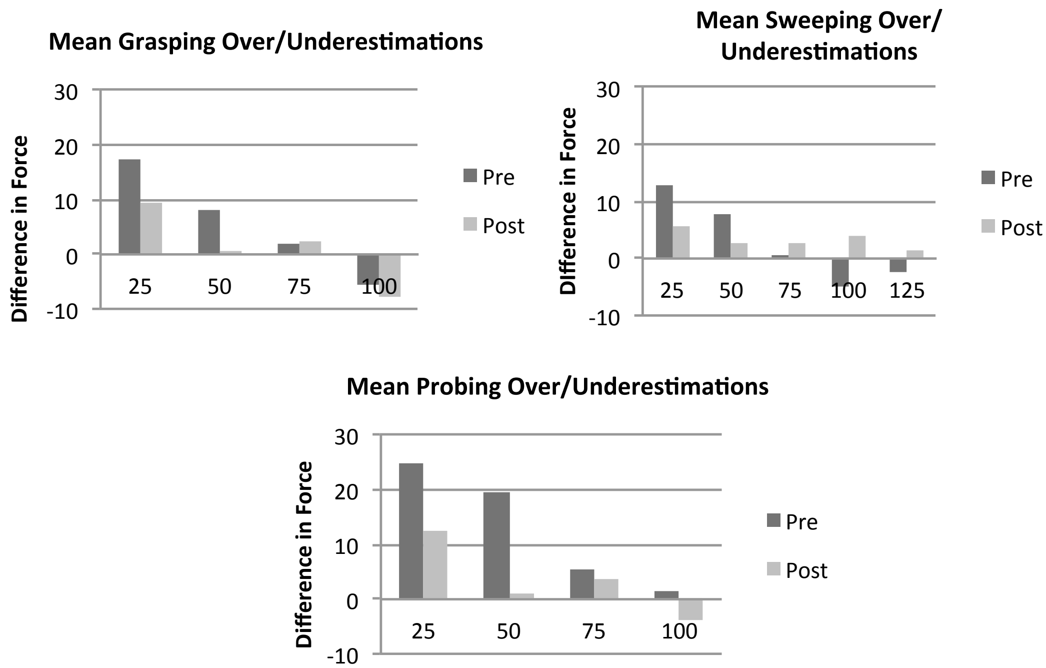


Figure 29: Under/over estimations of produced forces by force values for all participants for each surgical task.

Minimum and Maximum Forces

When asked to produce the minimum amount of force needed to feel contact with the "tissue," participants in both the Grasping and Probing tasks produced significantly less force in the post-training phase than the pre-training phase, indicating that they were more sensitive to the haptic force feedback given by the training device after training. This effect was not seen when participants were asked to produce the maximum force possible before "breaking." See Figure 30 and Table 14 for means, standard deviations, and significance values for the Grasping and Probing tasks.

	Grasping (n=36)		Probing (n=40)	
	Pre	*Post*	*Pre*	*Post*
Minimum	16.75	10.17*	44.13	29.9**
	(10.89)	(5.53)	(14.86)	(8.74)
Maximum	94.05	95.9	95.95	94.63
	(9.2)	(6.84)	(7.23)	(10.8)

*Table 14: Mean minimum and maximum amount of force produced, standard deviations (in parentheses) and significance values by surgical task. Note: post-training significantly different from pre-training at *p<.05, **p<.001.*

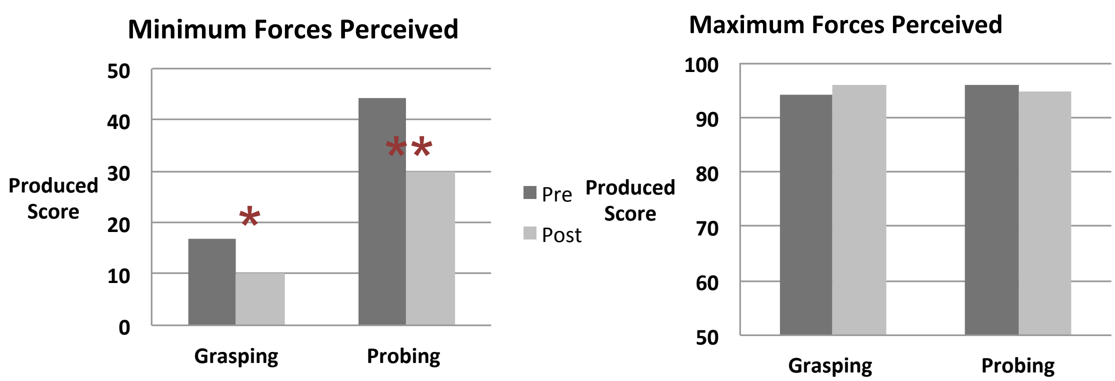


*Figure 30: Minimum and maximum perceived forces for grasping and probing. Note: post-training significantly different from pre-training at *p<.05, **p<.001.*

Breaks

In the current study, “breaks” were recorded as errors on the part of the participant. The virtual tissue would “break” if the participant exerted too much force for the tissue to withstand. Frequency of breaks during pre-training and post-training by surgical task and actual force can be seen in Table 15. Frequency of breaks pre-training and post-training for minimum and maximum forces can be seen in Table 16.

	Grasping (n=36)		Probing (n=40)		Sweeping (n=40)	
Force	*Pre*	*Post*	*Pre*	*Post*	*Pre*	*Post*
25	0	0	0	0	0	0
50	1	0	1	0	0	0
75	1	1	2	0	3	0
100	5	3	15	10	17	20
125					30	39
Totals	7	4	18	10	50	59

Table 15: Frequency of breaks by surgical task and actual force.

	Grasping (n=36)		Probing (n=40)	
	Pre	*Post*	*Pre*	*Post*
Minimum	0	0	1	0
Maximum	14	8	12	10

Table 16: Frequency of breaks by surgical task and minimum/maximum.

6.4. Discussion

After training with the haptic simulator, participants were more accurate at producing target levels of force, implying that training on the haptic simulator improved participants' skill in applying precise forces. Improvement in this skill was more pronounced at the lowest value of force tested, where a significant improvement with training was demonstrated for all three salient tasks. Generally, participants applied higher forces initially (before training) but decreased the forces applied with the tool after training.

This result is extremely relevant to surgical proficiency training, where force-related errors are a major cause of surgical mishaps [23]. One study noted that 55% of all errors caused during the performance of common laparoscopic procedures was due to the over-application of force [24]. It is imperative, therefore, that novice surgeons learn to apply controlled forces using their tools to enable safe surgical outcomes by preventing tissue damage. Learning to apply a precise range of forces seems to be a particular challenge for novice residents whose force behavior has been documented to be significantly different from that of surgeons. Wagner and coworkers, for example, examined the force application behavior of novices and surgeons using a custom haptic setup for a simulated surgical task [25]. Their results demonstrate that surgeons applied greater forces than novices when dissection real and simulated tissues. Similar differences in applied force magnitudes between surgeons and novices have been demonstrated in other studies with real tissues ([20], [26–29]) as well as on this simulator [13].

In terms of measured force magnitudes, novices tend to be quite tentative in applying forces when probing real tissues, maybe due to the fear of damaging tissue and not knowing experientially at which force irreversible tissue damage occurs [12]. On the other hand, when manipulating tissues using lateral motions, novices apply higher magnitudes of forces than surgeons that may lead to tissue damage [12]. An efficient haptic surgical simulator must therefore teach the novice user to learn to apply controlled and precise forces. In this study, it has been demonstrated that when intentional feedback on the error in force magnitude is given to participants during training, their skill in applying precise forces improves significantly (in some ranges in the study).

In this study, standard deviations of participants' force estimates also generally improved with training. This may point to the aspect of training the repeatability of precise forces and not just force magnitudes.

Another significant result from the study pertained to the minimum force required by the participant to perceive contact with the virtual material; after training the participants applied a significantly lower minimum force for both grasping and probing, implying an improvement in perceptual sensitivity to force when using the simulator. This correlates with an earlier study by Zhou and coworkers who reported that expert surgeons could perceive contact with tissue by applying lesser forces than novices using laparoscopic tool [20]. Haptic skills training may thus improve even the threshold at which reaction force from the tissue is first felt.

The balance of applying controlled and precise forces lies at the heart of haptic surgical skills training, where over- or under- application of force results in inefficiency and morbidity. To our knowledge, this is the first study to objectively demonstrate the viability of a haptic simulator for basic haptic surgical skills, including those involved in probing, grasping and dissection. There are some limitations of the study, however. Only one force-based metric was used in the study. In the future, more time-, motion- and force- based metrics will be examined for validity. We also plan to use more varied virtual material models including non-linear and mass-spring-damper models.

The training of force skills for laparoscopic surgery is neglected in current trainers. The most widely used FLS curriculum in the United States does not include precise force skills training for important surgical maneuvers. Some recent VR simulators have sought to include haptic feedback, but studies generally demonstrate poor results. Salkini and coworkers, for instance, examined the effect of simulator force feedback for performing two common FLS tasks. No major differences were evidenced between the haptic and no-haptic trained groups [30]. Several other studies examining the effect of popular haptics-enabled VR trainers have also shown poor results [2], [31], [32].

In our estimation, the reason for the poor performance of current haptic VR trainers is the skill set that is addressed for training. All of the above-cited studies examine the effect of haptic feedback on learning basic FLS-like tasks. The primary skill set required for proficiency in these tasks is visual perception and hand-eye coordination. Recent studies have demonstrated that haptic feedback may not be critical or even necessary when performing basic FLS tasks like peg transfer [18], [33]. Haptic feedback has been shown to be critical, however, for some other tasks. In a seminal study by Richards and coworkers, significant differences in the magnitude of force applied were evidenced between expert surgeons and novices on three force-based tasks: probing, grasping and sweeping [12]. *These* tasks require the skilled application of force. In an earlier work, the basis for specialized haptic skill set consisting of salient or core haptic skills, including the skills of grasping, probing and sweeping was presented. We suggest that force training should focus on skills where haptic feedback is critical for the successful performance of the task (i.e. salient haptic skills) rather than skills where haptic feedback is a complementary sensory modality. Following this logic, custom force simulators were developed and tested in the current study for their efficacy in training the haptic skill of novices.

6.5. Conclusions

There is a pressing need to design and validate surgical simulators that efficiently train force-based (haptic) skills. In this pioneering study in haptic skills training, we examined the effect of using a custom haptic simulator for training novices' force skill in three salient force-based skills: grasping, probing and sweeping. Results demonstrated that, for all three skills, training improved the accuracy of scores applied using the simulators, particularly at lower force ranges. After training, participants applied significantly lower forces and were more sensitive to the threshold at which force from the simulator is first felt. Standard deviation of force metrics also improved after training. These results suggest that haptic training simulator may be used for training specific force-based surgical skills of novice residents. Future work will involve designing and testing a simulator-based training curriculum for haptic skills training of novice residents. Attention will also be given to improving the overall design and metrics used to assess haptic skills.

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CHAPTER SEVEN

CONCLUSIONS

The need for efficient simulators to teach advanced surgical skills to novice laparoscopic surgeons is a topic of great interest in surgical education. There is an almost unanimous consensus in current literature for the need for developing advanced skills simulators, which are capable of objectively assessing trainees and which are ethically more desirable and inexpensive when compared to operating room-based training.

Based on the studies presented, several conclusions can be drawn. Using a mechanical haptic device, rendering force information necessary for accurate human perceptual human—i.e. perceptually salient rendering—facilitates efficient force skills training. Haptic information may not be crucial for performing basic laparoscopic tasks, as embodied in the hand-eye coordination skills that dominate the FLS peg-transfer task. Consequently, when teaching surgical tasks that primarily involve hand-eye coordination skills or visual perceptual skills, the presence of haptic information may not be necessary. This could explain the success of the FLS curriculum in imparting basic laparoscopic skills despite low realism in comparison to the surgical environment and no tissue-like haptic feedback. Haptic simulators can quantify and distinguish the haptic surgical skills of surgeons and novices. Even when a commercial haptic device that was not specifically designed for laparoscopic applications was used in one of our studies to capture surgeon and novice force behavior, force measurements distinguished between the two groups. One of the critical components in simulator-based haptic skills testing and training is choosing what skills are *really* haptic skills, i.e., skills where haptic feedback is critical, even necessary for successful task outcomes.

The three salient haptic skills proposed in this work—grasping, probing and dissection—were shown to be part of the salient haptic skill set. Therefore, haptic simulators designed to train force skills of users must account for training of these core haptic skills. On the other hand, the popular approach of just adding ill-defined "haptic feedback" to expensive VR trainers as a complementary sensory modality to teach hand-eye coordination skills will continue to yield poor results because haptics may not be necessary or even useful for successful learning of these tasks. The simulator system—hardware, tasks, metrics, etc.—presented in this research may be used as an objective means for testing the haptic skill of residents at various levels in their training. This may prove to be a means of motivation, as proficiency-based curricula have shown praiseworthy results with the FLS.

In summary, simulator-based haptic training can improve the haptic skill of novice users with little to no experience with laparoscopic surgery. To our knowledge, this is the first study that successfully used custom haptic simulators to train novice users for the three salient haptic tasks. It is hoped that future work will lead to the implementation and use of efficient simulator-based training in skills labs across the world, leading to safer surgeries and satisfied surgeons and patients.

CHAPTER EIGHT

RECOMMENDATIONS FOR FUTURE WORK

- Examine the research question, does training novices on the haptic simulator provide an enhanced skillset that translates to the operating room? That is, do simulator-trained users perform significantly better than those not trained on the simulator when applying their force skill performance to real tissues?
- Devise and test a larger range of assessment metrics including, force-, time- and motion-based metrics used to assess haptic performance.
- Develop a more intuitive graphical user interface that is more inviting to users. Three-dimensional graphics with physics-based object interaction may be a step in the path to developing a more complete system.
- Track the learning curves of participants as they progress in their learning on the simulator. This will require a wide range of metrics to assess process and outcome measures, as well as subtle differences in skill levels.
- Objectively measure the force skill of residents at all levels of training (Post-graduate (PG) year 1 through 5), and use that to devise a quantitative scale.
- Expert surgeons' haptic skill can be quantified using the Core Haptic Skills simulator to identify proficiency targets for residents.
- Devise and test a training curriculum for simulator-based haptic skills training and test transfer of training to the operating room.

APPENDICES

Appendix A

Mathematical Derivation of Three Dimensional Mass-based Rendering of Objects

The dynamical equations for the motion of a handheld rod were derived by defining two frames of reference; a static inertial (*i*) frame and a body (*b*) frame which moves with the moving rod. The rotation from *i*- to the *b*- frame is defined by the rotation angles θ and φ, with the sequence of rotation being rotation about the y_b-axis using the θ angle first, followed by rotation about the x_b –axis using the φ angle. The rotation matrix, C_i^b, from the inertial to the body frame is

$$C_i^b = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\varphi & s_\varphi \\ 0 & -s_\varphi & c_\varphi \end{bmatrix} \begin{vmatrix} c_\theta & 0 & -s_\theta \\ 0 & 1 & 0 \\ s_\theta & 0 & c_\theta \end{vmatrix} = \begin{vmatrix} c_\theta & 0 & -s_\theta \\ s_\varphi s_\theta & c_\varphi & s_\varphi c_\theta \\ c_\varphi s_\theta & -s_\varphi & c_\varphi c_\theta \end{vmatrix},$$

where $c(\theta) = \cos(\theta)$ and $s(\theta) = \sin(\theta)$. Using Newton-Euler equations for dynamic equation formation, the total torque applied on the virtual rod is the sum of the gravitational torque and torque applied by the user; $M_{total} = M_{gravity} + M_{applied}$.

On the left hand side of the moments equation, the total torque consists of two sub moments; torque due to angular acceleration and torque due to translation of the bottom of the rod. The angular momentum, H^b, in the body frame is defined as $H^b = \boldsymbol{I} w_{ib}^b$, where $\boldsymbol{I}$ is the diagonalized inertia tensor,

$$\boldsymbol{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix},$$

with $I_{xx} = I_{yy}$ because the rods are cylindrical. w_{ib}^b is the angular velocity of the body with respect to the inertial frame, expressed in the body frame;

$$w_{ib}^b = \begin{bmatrix} p \\ q \\ r \end{bmatrix}.$$

Since the rod rotates only about the x_b- *and* y_b-axis, the z_b-component of w_{ib}^b is zero ($r = 0$). The moment due to angular acceleration M^i in the inertial frame is obtained by differentiating the angular momentum

$$M_{acc}^b = \frac{d}{dt}H^i = \frac{d}{dt}\left(C_b^i H^b\right) = \left(\frac{d}{dt}C_b^i\right)H^b + C_b^i\left(\frac{d}{dt}H^b\right) = C_b^i \Omega_{ib}^b H^b + C_b^i\left(\frac{d}{dt}H^b\right),$$

where Ω_{ib}^b is the skew symmetric matrix of the vector w_{ib}^b. Transforming the total moment with respect to the body frame yields

$$M_{acc}^b = C_i^b M_{acc}^i \quad \frac{d}{dt}H^b + \Omega_{ib}^b H^b$$

$$M_{acc}^b = \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ I_{zz}\dot{r} \end{bmatrix} + \begin{bmatrix} -rqI_{yy} + qrI_{zz} \\ prI_{xx} - prI_{zz} \\ -pqI_{xx} + pqI_{yy} \end{bmatrix} = \begin{bmatrix} I_{xx}\dot{p} - qr(I_{yy} - I_{zz}) \\ I_{yy}\dot{q} - pr(I_{zz} - I_{xx}) \\ I_{zz}\dot{r} - pq(I_{xx} - I_{yy}) \end{bmatrix}.$$

Since $r = 0$, $\dot{r} = 0$ and $I_{xx} = I_{yy}$, moment due to angular acceleration with respect to the body frame is given by

$$M_{acc}^b = \begin{bmatrix} I_{xx}\dot{p} \\ I_{yy}\dot{q} \\ 0 \end{bmatrix}.$$

Moment due to translation of the bottom of the rod causes the moments M_{tr}^b

$$M_{tr}^b = -r_{AG}^b \times F_A^b = r_{GA}^b \times F_A^b$$

$$F_A^b = m\left(C_i^b \begin{bmatrix} \ddot{x}^i \\ \ddot{y}^i \\ \ddot{z}^i \end{bmatrix} + \dot{\omega}_{ib}^b \times r_{AG}^b + \omega_{ib}^b \times \left(\omega_{ib}^b \times r_{AG}^b\right)\right)$$

$$M_{tr}^b = m\begin{bmatrix} 0 & -\frac{l}{2} & 0 \\ \frac{l}{2} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\left(\begin{bmatrix} c_\theta & 0 & -s_\theta \\ s_\phi s_\theta & c_\phi & s_\phi c_\theta \\ c_\phi s_\theta & -s_\phi & c_\phi c_\theta \end{bmatrix}\begin{bmatrix} \ddot{x}^i \\ \ddot{y}^i \\ \ddot{z}^i \end{bmatrix} + \begin{bmatrix} 0 & -\dot{r} & \dot{q} \\ \dot{r} & 0 & -\dot{p} \\ -\dot{q} & \dot{p} & 0 \end{bmatrix}\begin{bmatrix} 0 \\ 0 \\ -\frac{l}{2} \end{bmatrix} + \begin{bmatrix} 0 & -r & q \\ r & 0 & -p \\ -q & p & 0 \end{bmatrix}^2\begin{bmatrix} 0 \\ 0 \\ -\frac{l}{2} \end{bmatrix}\right)$$

$$= \frac{ml}{2}\begin{bmatrix} -s_\phi s_\theta \ddot{x}^i - c_\phi \ddot{y}^i - s_\phi c_\theta \ddot{z}^i \\ c_\theta \ddot{x}^i - s_\theta \ddot{z}^i \\ 0 \end{bmatrix} + \frac{ml^2}{4}\begin{bmatrix} -\dot{p} + qr \\ -\dot{q} - pr \\ 0 \end{bmatrix}.$$

The next moment to be considered is torque due to gravity. Assuming that the gravity is transmitted to the lower end of the rod along the z_b-axis in the body frame, the z_b-component of the gravity term causes a force F_g^b given by

$$F_g^b = C_i^b \begin{vmatrix} 0 \\ 0 \\ mg \end{vmatrix} = \begin{vmatrix} -s_\theta \\ s_\varphi c_\theta \\ c_\varphi c_\theta \end{vmatrix} mg,$$

where m is mass of the rod. The gravity term causes the moment, M_g^b, defined by $M_g^b = -r_{GA}^b \times F_g^b$. Using $r_{GA}^b = [0\ 0\ \frac{l}{2}]^T$ (where l is the length of the rod) and F_g^b,

$$M_g^b = -\begin{bmatrix} 0 & -\frac{l}{2} & 0 \\ \frac{l}{2} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}\begin{vmatrix} -s_\theta \\ s_\varphi c_\theta \\ c_\varphi c_\theta \end{vmatrix} mg = \begin{bmatrix} s_\varphi c_\theta \\ s_\theta \\ 0 \end{bmatrix}\frac{lmg}{2}.$$

The external applied moment of the hand is defined as M_T^b. Using Newton-Euler balance equations, $M_{acc} + M_{tr} = M_{gravity} + M_{applied}$, the equilibrium of the body about the x_b- and y_b- axis results in the following equations

$$\left(I_{xx} + m\frac{l^2}{4}\right)\dot{p} - m\frac{l^2}{4}qr = s_\varphi c_\theta \frac{lmg}{2} + \left(-s_\varphi s_\theta \ddot{x}^i - c_\varphi \ddot{y}^i - s_\varphi c_\theta \ddot{z}^i\right)\frac{ml}{2} + M_{Tx}^b$$

$$\left(I_{yy}+m\frac{l^2}{4}\right)\dot{q}+m\frac{l^2}{4}pr = s_\theta\frac{lmg}{2}+(c_\theta\ddot{x}^i - s_\theta\ddot{z}^i)\frac{ml}{2}+M_{Ty}^b.$$

Since the angular rates of the rod can be expressed as the time derivatives of Euler angles using

$$\begin{bmatrix}p\\q\\r\end{bmatrix}=\begin{bmatrix}1 & 0 & -s_\theta\\0 & c_\varphi & s_\varphi c_\theta\\0 & -s_\varphi & c_\varphi c_\theta\end{bmatrix}\begin{bmatrix}\dot{\varphi}\\\dot{\theta}\\\dot{\psi}\end{bmatrix},$$

torque balance equations about the *x* and *y* axis are

$$I_{xx}\ddot{\varphi} = s_\varphi c_\theta\frac{lmg}{2}+\left(-s_\varphi s_\theta\ddot{x}^i - c_\varphi\ddot{y}^i - s_\varphi c_\theta\ddot{z}^i\right)\frac{ml}{2}+M_{Tx}^b$$

$$I_{yy}(c_\varphi\ddot{\theta}-s_\varphi\dot{\varphi}\dot{\theta}) = s_\theta\frac{lmg}{2}+(c_\theta\ddot{x}^i - s_\theta\ddot{z}^i)\frac{ml}{2}+M_{Ty}^b.$$

The vector $[-M_{T_x}^b\ \ 0\ -M_{T_y}^b]$ defines the output response torque and is applied to the 5 DOF haptic device.

Appendix B

Perceptual Metrics: Towards Better Methods for Assessing Realism in Laparoscopic Simulators

Introduction and Background

The number of laparoscopic procedures performed in the United States has seen a continual increase in the last decade. Consequently, there is a need to devise training systems that enable faster and more efficient skills training for novices in laparoscopy [1]. Though several Virtual Reality (VR) trainers are currently available, they have not been widely adopted in surgical skills labs [2]. One of the main reasons for this is the lack of realism in VR trainers [3]. Though computer-based trainers feature realistic graphics, most trainers do not simulate the haptic "feeling" arising from tool-tissue interactions [4]. The few simulators that have sought to incorporate simulated haptics have produced only a slight benefit in task performance [5],[6]. For example, Salkini and coworkers demonstrated that the addition of haptic feedback in a specific laparoscopy simulator produced no significant performance benefits [7]. One suggested reason for this is inaccurate or unrealistic haptics.

Methods for the assessment of "face validity", the degree of realism of the simulator, are not well established in the current literature. Most studies reporting face validity for simulators have used a questionnaire-based approach. Subjects were asked to use a Likert-type scale to rate aspects of the simulators' realism and "feel" [8]. This approach to measuring realism suffers from lack of objectivity and other biases. However, to design better simulators, better metrics for realism need to be designed and evaluated [9]. This work proposes a method to measure the haptic realism of VR simulators using "perceptual metrics."

Materials and Methods

Several studies have shown that humans are capable of accurately estimating length of unseen sticks by holding and wielding them [10],[11]. In this study, sticks of various lengths were rendered using a haptic device and subjects were asked to estimate their lengths based on feeling alone. Eight wooden rods which varied in the lengths and inertial properties were selected for this experiment (Table 1).

The haptic interface device used in this experiment was the 5 degree-of-freedom Haptic Wand (Quanser Inc., Canada). Euclidean position and orientation of user's motion is sensed and is used by the dynamic model of the stick. Force and torque are then calculated based on Newton-Euler laws for 6D motion. The software platform controlling the device consisted of MATLAB (v 7.1) with Real Time Workshop (v 2.1) and Wincon (v. 5.0).

The experiment had two sessions: real sticks and virtual sticks. In the real sticks session subjects were given physical sticks that were occluded by a black curtain that eliminated visual feedback. Subjects were asked to wield the stick and estimate its length on a reporting scale. The reporting scale consisted of a sliding pointer, movable by the user to a position from 0-120 cm from the origin of the scale. No markings were visible on the user's side; the other side had a centimeter scale and when the user estimated the stick length, the reading was noted. In the virtual sticks session, the same set of sticks were rendered by the haptic device and users were asked to wield the virtual stick to estimate length using the same reporting scale. The haptic device was occluded with a black curtain and was not visible to the user.

Eight subjects participated in this experiment after providing informed consent. The participants were students between 18-25 years of age. Each user was randomly assigned to receive either the real or virtual session first. Within each session the eight sticks were given twice in a random order.

Results and Discussion

After data was collected, correlation analysis was performed separately for each of the sessions. In both sessions, actual length was correlated with estimated length. Results of the eight subjects are shown in Table 1, all values are correlation coefficients. The mean value of correlation coefficient for the real sticks was 0.921, while for the virtual sticks it was 0.845. All correlation coefficients had a p-value of < 0.01. It was expected that the correlation coefficient for real sticks would be high (approximately .90) in keeping with previous results. The correlation coefficient of virtual sticks was expected to be lower than for real sticks. However, the closer the virtual correlation value is to the real value, the greater the haptic realism of the simulator. The high virtual value (0.845) in this experiment validates the realism of the haptic device and rendering algorithm.

Conclusions and Future Work

Can a haptic device accurately render the feel of real surgical instruments and tool-tissue interaction? How can the degree of realism of the simulator be accurately measured? This work points to a paradigm for measuring haptic realism using "perceptual metrics." In this study, the degree of realism of the virtual stick was measured by comparing it with real sticks using the perceptual metrics of perceived length. Face validity of haptic simulators can thus be measured using this paradigm, with other haptic perceptual metrics such as stiffness and texture estimation being used to measure other aspects of simulator realism.

Subject	Correlation Coefficient **Virtual** Sticks	Correlation Coefficient **Real** Sticks
1	0.851*	0.934*
2	0.762*	0.884*
3	0.874*	0.903*
4	0.892*	0.964*
5	0.769*	0.949*
6	0.866*	0.837*
7	0.841*	0.970*
8	0.921*	0.936*
		* = *p-value < 0.01*

Stick	Length	Mass	Inertia	Density	Moment
1	0.50	0.0312	0.0026	0.0624	0.0078
2	0.57	0.0384	0.0042	0.0674	0.0109
3	0.69	0.0508	0.0081	0.0736	0.0175
4	0.80	0.0665	0.0142	0.0831	0.0266
5	0.85	0.0474	0.0114	0.0558	0.0201
6	0.90	0.0689	0.0186	0.0766	0.0310
7	0.95	0.0613	0.0185	0.0645	0.0291
8	1.00	0.0726	0.0242	0.0726	0.0363

***Table B-1. left**, correlation coefficients of 8 participants, **right**, rendered virtual "stick" properties*

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Appendix C

Demographics Questionnaire For Study Participants

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Demographics

Age:

Sex:

1. Do you currently have any problems with your hands, arms, or neck? **Yes** **No**

If yes, please describe:

2. Have you ever required surgery on your hands or arms (including fingers and wrists)? **Yes** **No**

If yes, please describe (including which hand or both):

3. Do you currently have any vision problems aside from corrected vision? **Yes** **No**

If yes, please describe:

4. Do you have any experience with videogames? **Yes** **No**

If yes, estimated past usage or current hours per week:

If yes, list/describe your 3 most commonly played games and their respective consoles.

5. Does this include first-person perspective games (e.g. first-person shooter)? **Yes** **No**

If yes, estimated past usage or current hours per week:

6. Are you a Surgeon or Resident? **Surgeon** **Resident**/Year **1 2 3 4 5**

7. Total number of laparoscopic procedures performed

Appendix D

Informed Consent Form For Study Participants

Consent Form for Participation in a Research Study
Clemson University

Haptic Devices for Virtual Displays

Description of the research and your participation:
You are invited to participate in a research study conducted by Dr. Chris Pagano, Dr. Timothy Burg & Joseph Singapogu. The purpose of this research is to investigate how haptic (touch) devices can be employed to create more useful virtual displays.

Your participation will involve the performance of a task in a virtual environment, such as navigating though a virtual path, manipulating a virtual object, and/or communicating with another subject through the virtual display. Depending on the experimental group to which you are assigned, you may perform the task by operating a computer mouse, keyboard, haptic wand, or similar device while viewing a computer monitor or a large screen projection. (A haptic wand is a device with a pen-like handle that is attached to small motors. When the handle is grasped the motors provide force-feedback to the hand. If you will be using this device, it will have already been shown and described to you). As we wish to compare performance with and without the use of the haptic device, and with and without the aid of vision, you may be asked to perform the task while viewing a display on a computer monitor while simultaneously receiving force feedback from the haptic wand, or you may perform the task without one or both of these. In some conditions you may be asked to manipulate real objects, as we wish to compare the performance of our virtual device with that of real objects. You may be asked to complete a breif assessment of your spatial abilities.

Depending on the nature of the tasks that you are assigned, the amount of time required for your participation will be between one or two hours. Depending on the task that you will be testing, you may be asked to participate in multiple research sessions. You have already been informed about the number of sessions that you will be asked to participate in, and you already have been given a more specific estimate of the duration of each session.

Risks and discomforts:
There are no known risks associated with this research.

Exclusion Requirements:
Participants must have normal, or corrected to normal, vision and full use of their neck, arms, and hands.

Potential Benefits:
There are no known benefits to you that would result from your participation in this research. Information that is obtained from this study may be used scientifically and may be helpful to others. Possible benefits you attain may include extra credit towards a course grade at Clemson University, and may also include the satisfaction of contributing

This form is valid only if the Clemson University IRB stamp of approval is shown here:

CLEMSON UNIVERSITY
IRB CONSENT FORM
APPROVED 7·10·11
EXPIRES 7·9·12

Revised: June 2011
Page 1 of 2

to the advance of science and technological innovation. This research may help us develop more effective interfaces for virtual systems that may eventually be used to design improved systems for laparoscopic surgery, urban search and rescue robots, teleconferencing, etc.

Incentives/Compensation:
Subjects will receive $10 or course credit at Clemson University. For some experimental conditions involving multiple sessions subjects will receive payment of $10 per session.

Voluntary Participation:
Participation in this study is voluntary. You may choose not to participate. Your participation in this research study is voluntary. You may choose not to participate and you may withdraw your consent to participate at any time. You will not be penalized in any way should you decide not to participate or to withdraw from this study.

Confidentiality:
We will do everything we can to protect your privacy. The records of your participation are confidential. The investigator will maintain your information, and this information may be kept on a computer. Your identity will not be revealed in any publication that might result from this study.

In rare cases, a research study will be evaluated by an oversight agency, such as the Clemson University Institutional Review Board or the federal Office for Human Research Protections, that would require that we share the information we collect from you. If this happens, the information would only be used to determine if we conducted this study properly and adequately protected your rights as a participant.

Contact information:
If you have any questions or concerns about this study or if any problems arise, please contact Chris Pagano at Clemson University at 864.656.4984. If you have any questions or concerns about your rights as a research participant, please contact the Clemson University Institutional Review Board at 864.656.6460.

Consent:
I have read this consent form and have been given the opportunity to ask questions. I give my consent to participate in this study.

Participant's signature: ______________________________ Date: ____________

Participant's name printed: ___________________________

A copy of this consent form should be given to you.

This form is valid only if the Clemson University IRB stamp of approval is shown here:

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Page 2 of 2