

Perception of Compliance in Laparoscopic Surgery

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Hao Xin

Abstract

Laparoscopic surgery provides major benefits to patients in terms of decreased pain and post-operative hospital stays, but also increases their risks of intra-operative injuries because of the reduction in force feedback. Although the limitations of laparoscopy have been studied, the specific role of force feedback in laparoscopic surgery performance is not well understood.

The purpose of this thesis is to determine the effect of force feedback on the ability to accurately discriminate tissue compliance by comparing subjective tissue compliance assessment, force output, and subjective force assessment, in conventional and laparoscopic setups. The experimental trials involved eleven participants providing evaluations of a range of compliant samples, and analyzed their force output as well as their subject evaluation of force output.

The results of this investigation the accuracy of compliance discrimination is worse when using indirect probing compared to direct probing, and that the force used in direct probing is lower than that in indirect probing. Further, the subjective assessment of force output in direct probing is not significantly different compared to indirect probing. Further research is recommended to better understand our awareness of the subjective force output.

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As I look back on my journey, I can't help but think that I could have done something better, or differently all together. But as I look forward to the future, I am reminded of how lucky I am to have my wonderful mentors, family, and friends in my life.

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1 Introduction:

Laparoscopic surgery is a type of minimally invasive surgery performed by inserting laparoscopic instruments through trocars (a hollow cylinder with a sharp and pointed end) via small incisions, usually into the abdominal cavity. As Figure 1 illustrates, laparoscopic surgery require much smaller incisions compared to traditional open surgery.

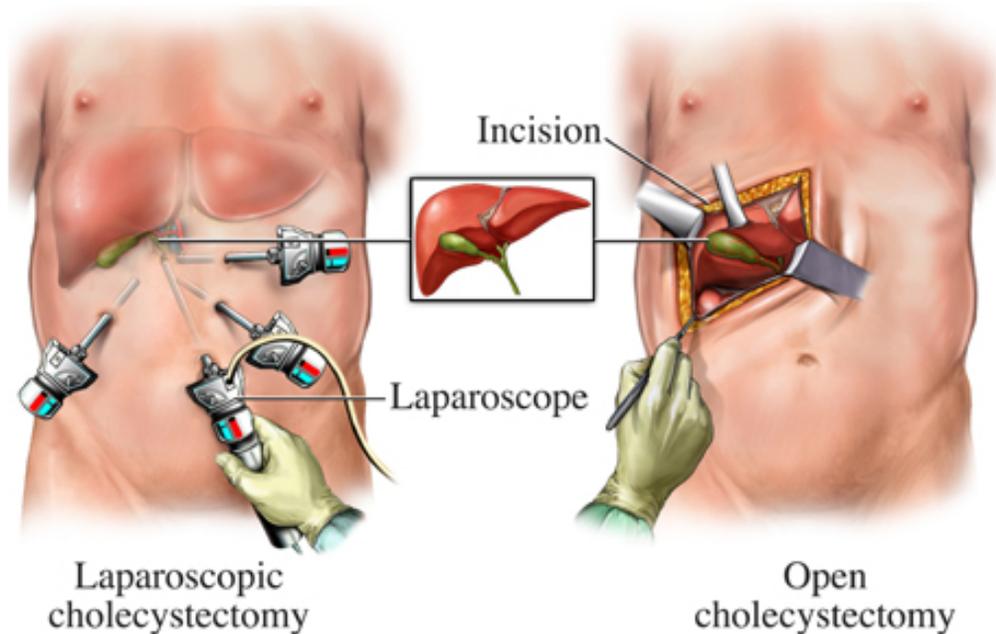


Figure 1: Laparoscopic versus open abdominal procedure

Since the first laparoscopic cholecystectomy (removal of the gallbladder) was performed in the United States in the mid 1980s (Reddick & Olsen, 1989), it has been adapted as the standard procedure in cholecystectomy (Soper et al., 1992), splenectomy (removal of the spleen) (Friedman et al., 1996), adrenalectomy (removal

of one or both of the adrenal glands) (Smith, Weber, & Amerson, 1999), and many other surgical sub-specialties.

The primary benefits of laparoscopic surgery are reduced postoperative pain, shorter postoperative hospital stays, and faster recovery time for the patients (Reddick & Olsen, 1989; Soper et al., 1992). Although laparoscopic surgery could be more cost-effective than traditional open surgery (Bass, Pitt, & Lillemoe, 1993) due to reduced hospital stay, the savings in *total* hospital cost with laparoscopic surgery is insignificant because the procedure incurs more theater cost due to significant longer operating time (Ortega et al., 1995; Bergamaschi & Arnaud, 1997). Nevertheless, laparoscopic surgery indirectly benefits society by allowing the patient to return to work more rapidly (Bass et al., 1993), though this social cost might be difficult to calculate.

Laparoscopic surgery has become very popular – for instance, there has been a dramatic increase in the number of laparoscopic cholecystectomies performed since its introduction (Nenner et al., 1994; Aslar et al., 2003). Despite its benefits and popularity, laparoscopy has many limitations compared to conventional open surgery. The setup of laparoscopic surgery, shown in Figure 2, is very different from that of open surgery. In an open abdominal operation, the surgeon looks down at his/her hands and the instruments while simultaneously observing the organs/tissues directly. In laparoscopic surgery, image of the operating environment is captured by inserting an endoscopic camera into the body cavity, and shown on a 2-dimensional monitor. The surgeon views his/her operating environment indirectly and performs the surgical tasks using laparoscopic instruments extended into the patients. Changes in the

laparoscopic image viewed are controlled by a camera assistant, as the surgeon performs the surgery ambidextrously. This particular setup, while beneficial to the patients, increases the cognitive and physical load of the surgeons, and consequently the potential for error, to the detriment of the patients.



Figure 2: Laparoscopic surgery setup

The limitations of laparoscopy and their consequences require a different motor and perceptual skill-set compared to open surgery, and training and significant experience is needed to attain competency (Dent, 1992; Soper & Hunter, 1992). For instance, surgeons must perform with reduced depth perception (Shah et al., 2003) because the monitor filters and removes 3-dimensional depth cues from the operative field. Laparoscopic surgeons must also overcome poor hand-eye coordination due to the location of the monitor that prevent the surgeons from looking at their hands and the monitor simultaneously, the variable amplification or magnification caused by the laparoscopic camera that present inaccurate size/distance of internal organs, the

rotation of the instruments around the incision point and further angle distortions caused by the laparoscopic camera, and the misorientation or mismatch between the line-of-sight of the surgeon and that of the camera (Breedveld & Wentink, 2001). Furthermore, laparoscopy limits the freedom of movement because it reduces the degrees of freedom of motion from six to four as the trocars act as invariant points (Schurr et al., 1996). Finally, surgeons must perform with reduced haptic feedback due to the use of long and slender laparoscopic instruments. The environmental factors could contribute to the increased incidents of intra-operative injury in laparoscopy when compared to open surgery (Deziel et al., 1993; Adamsen et al., 1997; Fletcher et al., 1999).

While all the above factors are limitations in laparoscopy, haptic feedback is especially relevant to surgical performance. The excessive use of force has been found to be an important underlying factor contributing to intra-operative errors (Joice, Hanna, & Cuschieri, 1998; Tang, Hanna, & Cushieri, 2005). Yet, “the exact contribution of ... tactile or force feedback in laparoscopic procedures remains poorly understood” (Shah & Darzi, 2003). Indeed, to quantify the surgical experience is difficult, since measuring and recording the force in any laparoscopic procedure is difficult and expensive due to the size and accuracy of sensors required. The role of force in laparoscopic surgical performance is therefore a worthwhile research topic that will further our understanding of haptic perception as well as ways to improve laparoscopic surgery performance.

Unfortunately, research on the impact of laparoscopy on the control of force has been sparse due to the relatively short history of laparoscopic surgery. Also, force

is a part of all interactions between the tissue and the instrument. To record and analyze force data in a surgical operation is a large and complex task due to the duration and the complexity of any given procedure. However, it is much more convenient to breakdown the basic tasks involved in surgical procedures and examine how force is used, and how it is affected by the laparoscopic instruments in a more limited context. Furthermore, looking at force within the scope of a basic surgical task leads to more applicable results, since the task of grasping, for instance, is the same whether it is performed during a cholecystectomy or a splenectomy.

The tasks in laparoscopic surgery include probing, grasping, cutting, and suturing, the simplest of which being probing. Although an easy task, probing is crucial in providing haptic information that help surgeons differentiate tissues and navigate. Surgeons interact with the tissues and organs not only to manipulate it, but also to detect physical properties such as texture, compliance, and temperature – properties that are otherwise difficult if not impossible to assess using purely visual cues. Tissue softness is an especially important property, because different organs and tissues have different softness; for example, tumors are often harder than healthy tissue. Palpation is used in breast cancer screening precisely because carcinoma breast tissue has a stiffness of 456 ± 208 kPa, compared to 66 ± 17 kPa for normal breast (Konofagou et. al, 1997).

In traditional open surgery, palpation could provide useful information regarding the location of tumors if they are not visually identifiable. As others have emphasized, “colour, texture, and visible aspects of tissue deformation in the surgical field convey important anatomical information, palpation may be critical in

identifying otherwise obscure tissue planes, arterial pulsations, and regions of tissue thickening that may signify pathologies such as infection or cancer” (Rosen et al., 1999). In laparoscopy, probing is the form of examination closest to palpation due to the absence of direct touching. It is also the safest, since the blunt end of a laparoscopic probe is designed to be atraumatic – even grasping could cause tissue damage due to mechanical stress (De et al., 2006) between the jaws of graspers. Probing provides an ideal starting point for force-related research in laparoscopy since it is simple yet relevant: simple because probing involves only one instrument and very basic skills that do not require training, and relevant because the discrimination of tissue softness is necessary in the exploration and navigation of the surgical environment.

The objective of this research is to quantify force feedback in laparoscopy in the context of compliance discrimination using the laparoscopic probe. This involves a comparison of compliance discrimination between bare-hand and laparoscopic methods of probing, and the magnitude of force exerted under each condition. The effect of instrumentation on force output, if any, will provide further insight into the nature of intra-operative injuries in laparoscopy. The results could be used to develop a transfer function for how force is transformed by laparoscopic instruments from the tip to the handle. The results will also contribute to the body of knowledge concerning the perception of softness in using laparoscopic instruments.

The following chapters provide a review of the literature in related research, the methods and apparatus used in the experiments, the results and analysis, and conclusions.

2 Literature Review

The purpose of literature research is to find the results obtained in previous studies that could apply to laparoscopy and help form the hypotheses to the questions that this research seeks to address, namely, the accuracy of softness-perception using laparoscopic instruments, and the effect of laparoscopic instruments on the magnitude of the applied force. The literature research provides a general background on the haptic perception and haptic feedback, past results on compliance discrimination, active force exertion under direct and indirect modes of interaction, and perception of applied force. It helps us frame our experiments within this context and therefore illuminates our contributions.

2.1 Haptic Perception and Feedback

The haptic perception system allows us to perceive characteristics such as shape, size, weight, texture, and temperature. Although vision and hearing provide many environmental cues, the sense of touch is essential to object identification. The terms haptic and tactile seem interchangeable, but haptic perception uses both tactile/cutaneous as well as kinesthetic stimuli. The cutaneous stimuli come from the mechanoreceptors – cells sensitive to mechanical pressure or deformation of the skin – under the skin, while the kinesthetic stimuli are provided by a network of muscles, tendons, and joints that give information about the movement and position of the body and its limbs (Sekuler et al., 2002). Thus cutaneous stimuli require direct contact with the skin, while kinesthetic stimuli require the movement of the body. The perception essential in the determination of properties such as shape, texture, and

compliance is haptic in nature, as they require both cutaneous and kinesthetic feedback. This is especially true in surgery, open or otherwise, since surgeons use their hands and the instruments to manipulate tissues.

Traditionally, the study of the human haptic system has been focused on the relative contribution of the different classes of receptors. The study of tactile perception attempts to explain how the different types of cells – the Meissner corpuscles, the Pacinian corpuscles, the Merkel disks, and the Ruffini endings (also referred to as rapid adapting (RA) and slow adapting (SA) receptors in some literature) – provide information to the central nervous system (CNS) and the unique manner of provision by each type of receptor. The study of kinesthetic or proprioceptive system focuses on establishing the exact role of muscle, cutaneous, and joint receptors to the body's awareness of its movement and position. Other studies have also tried to separate haptic stimuli from visual and auditory stimuli in order to isolate the perception of tactile and kinesthetic cues independent of the other senses. While these studies are essential to the biological and neurological understanding of haptic perception, it is not a focus of this research project. Instead, this research focuses on comparing a small and restricted aspect of haptic feedback to laparoscopic surgery.

2.2 Compliance Discrimination

Softness is a subjective perception. We perceive some thing as soft when the surface gives away under applied force. Typically, soft objects are deformable, like a teddy bear, or a pillow. However, softness is not a measurable quantity, and must be represented by compliance in scientific research.

Compliance is a physical and measurable property, and it is quantified by the amount of depression when the same force is applied to materials of different compliance. Though the terms *compliant* and *soft* are used interchangeably, a compliant object is not necessarily soft: a spring or the keys on a keyboard are compliant – they give away when compressed, but their surfaces remain rigid.

To study the perception of compliance, one must be able to quantify both the compliance as well as the subjective perception. Harper and Stevens (1964) used a range of compliant materials and asked their participants to rate the relative softness/hardness of the specimens. They quantified the compliance of materials by measuring indentation on the material surface using the same weight, and were able to relate subjective perception of hardness as a function of the physical compliance with a coefficient of 0.8 – i.e., as the physical compliance decreased by 1 (the material becomes harder), the subjective ranking of the compliance decreased only by 0.8. The results of this study suggest that our ability to discriminate compliance is limited, especially at the higher levels of stimulus, since the coefficient of the matching function is 0.8 – as the actual compliance of a material increases or decreases, the perceived ranking would be approximately 0.8 of the compliance. The difference between the objective measure and the subjective judgment would become more pronounced for the more extreme values of compliance. The use of compliance and of numerical ranking of perceived softness enabled the researchers to relate the objective measure (compliance) and the subjective sensation (perceived softness) and allowed for a quantifiable model of compliance discrimination.

One shortfall of the Harper and Stevens (1964) study is that it quantified compliance in a consistent manner, but did not control for surface texture – the specimen used included close-textured sponge rubber, open-textured sponge rubber, and Neoprene (Harper & Steven, 1964). The impact of the different materials and surface properties such as coarseness on the subjective ranking of compliance in this study is unknown, but it is possible for one physical property to affect the perception of another. For instance, the texture of a surface could affect the normal and tangential forces used in exploration (Smith et. al, 2002), and which could in turn influence the perception of material softness.

Another study of stiffness perception as quantified by spring constants adds to the body of knowledge regarding compliance discrimination by controlling kinesthetic stimulus. Jones & Hunter (1990) studied the perception of stiffness using electromagnetic linear motors that behaved like rotational mechanical springs. The participants were asked to match the stiffness of one motor to that of a reference motor, each attached to a different arm, while blindfolded. This matching exercise investigated the ability to accurately perceive stiffness using mainly kinesthetic input from the force and the displacement outputs of the motors. The coefficient of the matching function for stiffness from this study was determined to be 0.91, compared to 0.84 for force (Jones & Hunter, 1982) and 0.95 for position (Erickson, 1974). The matching functions Similar to the results obtained by Harper and Stevens (1964), the values of the coefficients show that human haptic perception is limited in sensitivity and resolution. In addition to the matching function, Jones and Hunter also used that the Weber's fraction as a measure of the perception of compliance. The Weber's

fraction, k , which expresses the just noticeable difference (JND) for any physical stimulus as a ratio of the reference stimulus, I , and the difference to the reference required to be perceived, ΔI . Smaller values of k indicate that our perception is more sensitive to a particular stimulus, as less change to the reference is required to enable detection. In this study, the Weber's fraction for compliance was 0.23.

Another useful group of studies came from the investigation of compliance discrimination, where the objects have a rigid planar surface (Pang et al., 1991; Tan et al., 1992; Tan et al., 1993), and compliance was simulated by using a modified caliper with a fixed and a moving plate. The participants would grasp the plates mounted on the modified caliper between the thumb and the forefinger, and squeeze to match a reference stimulus of force, position, or compliance. The squeezing action employs both tactile and kinesthetic stimuli, from the direct contact and the movement of the fingers, respectively. The resultant Weber's fraction for compliance discrimination was 0.17 (Pang, Tan & Durlach, 1991). This means that given any reference compliance, people can begin to notice that the compliance has changed if the change is 17% of the reference. Compare this to the Weber's fraction of 0.23 obtained by Jones and Hunter (1990), which relied on only the kinesthetic information from moving the forearm and elbow/shoulder joints, one might be inclined to conclude that the availability of both the tactile and the kinesthetic information improves the discrimination of compliance. However, later studies reported JND of 0.06 – 0.08 (Tan et al., 1992) to 0.15 – 0.99 (Tan et al., 1993), showing a large variance in the value of the Weber's fraction. Difference in methodology and apparatus used in the studies could certainly contribute to the

differences in Weber's fraction. However, since the hand possesses more mechanoreceptors than other parts of the body, using the hand in the compliance discrimination task rather than the elbow (Jones & Hunter, 1990) could possibly enhance the accuracy of discrimination.

The apparatuses in the above studies used the fingers as part of the discrimination task, and successfully simulated different compliance but not softness – the subjects were in direct contact with rigid plates (Pang, Tan & Durlach, 1991; Tan et al., 1992; Tan et al., 1993). The surface of organs, however, is deformable. Further, the indentation of a deformed surface provides visual cues about its compliance and is absent for rigid surfaces.

Srinivasan and LaMotte (1995) conducted an extensive investigation of perceived softness using different stimuli and conditions. This study used both deformable and rigid objects to represent compliant materials. The deformable objects were made from transparent rubber specimens with various compliances, while the rigid objects were constructed using springs and hollow cylinders. The compliance variations in the deformable and rigid objects were achieved by varying the amount of diluents while making the rubber specimens, and by changing the spring constants of springs inside the hollow cylinders in the rigid objects, respectively. Each of the deformable and the rigid groups had the same colour, shape, and surface characteristics – i.e., all deformable specimens looked and felt the same, and the same applies to all rigid specimens.

Recognizing the fact that both cutaneous and kinesthetic information are used to perceive softness, Srinivasan and LaMotte isolated the effects of cutaneous and

kinesthetic perception using active/passive exploration conditions and local anesthesia. The study allowed subjects to touch compliant materials under three conditions: active exploration with a normal finger where both cutaneous and kinesthetic information are present, active exploration with local anesthesia of the finger pads such that only kinesthetic information is available, and finally, passive exploration where only cutaneous information is available. In the active scenarios, the participants applied force to the objects, while in the passive scenario, the objects were brought down to the stationary finger at a constant velocity.

Srinivasan and LaMotte concluded that human participants showed excellent compliance discrimination with deformable objects (the rubber disks), but fared poorly when it came to the compliant but rigid objects (the hollow and spring-loaded cylinders). Furthermore, to distinguish between a pair of deformable objects, tactile information alone was sufficient, while kinesthetic information alone is not. This means that passive exploration where the rubber specimens were pressed down at the immobile fingers produced better discrimination results than active exploration with the fingers under the effect of local anesthesia. To distinguish between a pair of compliant and rigid objects, both cutaneous and kinesthetic information are necessary, meaning that pressing the spring-loaded cylinders down at an immobile finger, or pushing them with an anesthetized finger, produced poorer performance compared to active pushing with an unaffected finger.

Srinivasan and LaMotte reasoned that the deformation on the finger pad depends on the compliance of deformable objects, but the same is not true for rigid objects. When an object is deformable, its compliance will affect the indentation of

the finger pad. However, when an object is rigid, the finger pad will already be compressed, and the compression will have less correspondence to the compliance. Essentially, if one were to model the finger pad itself as a deformable object, then the deformation of the finger pad will provide additional information when pressed against other deformable objects. Against a rigid object, the finger pad will already be deformed, so no information can be derived from the deformation itself. Hence, discrimination of rigid objects requires both cutaneous and kinesthetic information while discrimination of deformable objects requires only cutaneous information, though both are compliant.

The experiments of Srinivasan and LaMotte only dealt with direct tactile exploration since the participants were always able to touch (or be touched by) the compliance objects. In contrast, the laparoscopic surgery environment does not permit direct contact at all. How would compliance discrimination be affected by the use of laparoscopic instruments? In the context of laparoscopy, it has been established that haptic feedback is present during laparoscopic surgery (Bholat et al., 1999). Bholat researched texture, shape, and consistency (softness) discrimination using direct palpation (DP), conventional surgical instruments (CI), and laparoscopic instruments (LI). This study is notable because it uses actual laparoscopic instrument in the experiment. Not surprisingly, direct palpation shows the greatest accuracy in shape, texture, and consistency discrimination. However, the performance difference observed between DP, CI, and LI in consistency determination is *not* statistically significant. One drawback of this study is that the consistency was represented by a series of springs as supposed to deformable surfaces. Although the spring constants

easily simulate a range in stiffness, it is not a realistic representation of the organ tissues.

LaMotte (2000) investigated not only the accuracy of compliance discrimination, but also different exploration conditions involving the index finger and a stylus. Using deformable rubber silicone samples with a range of 10 different compliances, the participants in this study were able to explore the compliant specimen using active tapping of the index finger, active tapping using a stylus with the index finger on top of the stylus, active tapping with two fingers gripping the stylus, and passive tapping with the specimen being pushed down on the stylus to the index finger (LaMotte, 2000). Besides tapping, participants also explored the specimen using a pressing strategy as well. This study quantified the force involved in tapping and pressing of the specimen when using the stylus by measuring and recording the force between the stylus and the specimen.

The results showed no significant difference in compliance discrimination between direct (finger tapping) and indirect (stylus tapping) contact. The exploration strategy, on the other hand, has a significant effect on the accuracy – tapping appears to be a more effective method of exploring a surface when it comes to compliance discrimination. The method and apparatus used are not very comparable to laparoscopy - the stylus used is significantly shorter and very different from a laparoscopic instrument, and it is very unlikely that surgeons will employ a tapping strategy when interacting with the tissues (tapping requires rapid contact that might bruise the tissue, especially with a probe). Nevertheless, the direct and indirect aspects of exploration in this study are useful for comparison. The results regarding

compliance discrimination are similar to those obtained by Bholat et al. (1999) – overall, there is no significant difference in the accuracy of compliance discrimination between direct and indirect contact.

The results of LaMotte (2000) and Bholat (1999) studies suggest that the use of indirect method of tactile contact does not affect the accuracy of compliance discrimination compared to direct contact, and contradicts the results of other studies that clearly show the decrease in accuracy when an instrument is used (McFarlane et al., 1999; Rosen et al., 1999). MacFarlane et al. (1999) used six silicone specimens of different compliance and tested the ability of the participants to accurately rank the specimen hardness by palpating using surgically gloved hand, a standard Babcock laparoscopic grasper, and a force-feedback grasper. The results showed that direct palpation using a surgical gloved hand had the least amount of error in ranking the specimen hardness compared to using the laparoscopic grasper or the force-feedback grasper. Similarly, Rosen et al. (1999) again tested the ranking of stiffness using different tools (surgically gloved hand, standard laparoscopic grasper, force-feedback grasper) and found that the hand had the best performance in ranking the stiffness of the specimen in the correct order.

The McFarlane et al. and Rosen et al. studies clearly show that direct contact using the hand produces better accuracy in compliance discrimination compared to standard laparoscopic graspers. Further evidence supporting the superior performance of direct tactile contact to indirect contact comes from Tholey et al. (2005). Using a PHANTOM haptic device to control a laparoscopic grasper and provide force feedback and a video screen for vision feedback, Tholey et al. (2005) compared the

accuracy of ranking three tissue samples of varying hardness under the conditions of vision feedback, force feedback, and vision plus force feedback. The researchers found that simultaneous vision and force feedback leads to better performance in tissue characterization when compared against using only vision or only force feedback (Tholey et al., 2004). In direct probing, both vision and force feedbacks are available. In indirect probing, both vision and force feedback will be reduced through the use of a video monitor and laparoscopic instrument. In actual laparoscopic surgery, without the aid of haptic devices to improve force feedback from the tool/tissue interface to the hand, it is likely that the performance in tissue characterization will be negatively impacted.

2.3 The Application of Force

Force is an essential component of compliance discrimination, since the particular task is conducted under active haptic exploration, involving both tactile and kinesthetic stimuli. It is important to know if the force exertion is different during direct and indirect probing.

If the use of the laparoscopic probe also affects the force exertion, it is equally important to quantify the difference. Does the instrument have an attenuating or amplifying effect on the force transfer between the tip and the handle? Knowing the answer to this question will further clarify the root cause of the excessive use of force and the increase in intra-operative injury in laparoscopy. Furthermore, being able to quantify the force transfer effect of the laparoscopic instruments will aid in the design of instruments with better force feedback in laparoscopic as well as robotic and tele-surgery.

The literature on force exertion in laparoscopy is sparse. It has been shown that the force at the tissue/instrument interface is lower than that measured at the handle for laparoscopic grasper – the ratio of maximum tip force to handle force ranged between 0.117 ± 0.012 and 0.853 ± 0.076 (Sukthankar & Reddy, 1994). The task of the participants was to squeeze the materials (hard, medium, or soft), so the force at the tip is from the grasper jaws clamping down on a surface. Despite large individual variation between the participants, all coefficients of the peak tip force versus handle force were less than 1. Another study between conventional and laparoscopic surgical forceps (or graspers) also showed that the force at the handle was significantly higher while the force at the tip was significantly lower using laparoscopic forceps (Gupta et al., 1996). Compared to conventional surgical forceps, the variation in tip force is insignificant in laparoscopic forceps. These results indicate that the laparoscopic forceps do not effectively translate force from the tip to the handle or vice versa. The inefficiency of force transfer between the tip and the handle of laparoscopic forceps could be viewed as a large distortion effect on force, making it more challenging for surgeons to “feel” through them. However, it is important to note that the design of graspers is much more complex than that of the probe.

In the studies by Sukthankar & Reddy (1994) and Gupta et al. (1996), the force at the handle is a result of the participants manipulating the grasper or forceps handles. Both the end-effector and the handle of the grasper/forceps are very different from those of the laparoscopic probe. The contact area when handling a laparoscopic grasper is closer to the joints below the fingertips, while the contact area when using a

probe is directly on the tips of the thumb and forefinger, which are more tactually sensitive. Further, the handle of the grasper is bent from the body, where as the handle of the probe extends straight out from the body of the probe, resulting in the creation of torque. Finally, the probe is made of a single solid piece of material, while the grasper is constructed from many smaller components. The effects of the usages and the designs of the grasper and the probe on force transfer between the tip and the handle is unknown. Although Zelek and Xin (2007) found preliminary evidence that force measured at the tip of a laparoscopic grasper is smaller than that measured at the handle during probing tasks, more evidence is needed regarding the effect of a laparoscopic probe on force exertion.

LaMotte (2000) studied compliance discrimination using a stylus and two different exploration methods. The exploration strategies were tapping briskly or pressing slowly onto the compliant surface. The stylus used was very short in length and not at all similar to a laparoscopic probe. Even though the apparatus and the motion of the stylus are not comparable to laparoscopic probing, the grip force on the stylus and the compression force at the tip showed a similar pattern compared to the studies with laparoscopic graspers – the maximal grip force was always greater than the maximal compression force, regardless of the tapping or pressing strategy used.

The combined results from Sukthankar & Reddy (1994), Gupta et al. (1996), and LaMotte (2000) suggest that the use of an instrument does have a significant effect on the force transfer between the hand and the material under contact. It is likely that the laparoscopic probe will have similar effect, and the force at the tip will not be effectively transferred to the hand.

The above studies provide clues as to *how* the instrument might affect the force transfer between the tip and the handle of a probe, but not by *how much*. Simply knowing that the force between the hand and the handle is higher compared to the force at the instrument-tissue interface does provide more insights into the nature of excessive use of force. If the force at the handle is lower, why then, are injuries caused by excessive force? Furthermore, the force at the tip of a laparoscopic grasper is actually lower compared to conventional forceps (Gupta et al., 1996). What is really of interest is the difference in magnitude between the force exerted by a fingertip and that of a laparoscopic probe: between direct and indirect probing.

The literature offers a conflicting picture of force exertion during direct and indirect tactile exploration. In the estimation of surface roughness, the tangential and normal forces as subjects explored different grades of sand paper using a laparoscopic instrument is *lower* compared to using their fingertips (Brydges et al., 2005). The task involves stroking the specimen surfaces using either the laparoscopic grasper or the index finger. Although the participants had the tendency to underestimate the roughest surface and overestimate the other surfaces compared to using the index finger, the results did show that the roughness estimation is possible using a laparoscopic instrument. Unfortunately, there are no similar studies involving compliance discrimination.

The Brydges et al. (2005) study showed that force exerted using a laparoscopic instrument was lower compared to that of a bare finger for the same task. Evidence from studies of force control, however, paints a conflicting picture. Jones (2000) showed that the error in fine force control was just less than 1N for the

index finger flexors over a range of 2 – 6N, and 4.5N for the elbow flexors over a range of 10 – 30N. This is very relevant to force exertion using a laparoscopic probe because the elbow flexors are involved (in combination with the wrist) in the output and the control of force when manipulating laparoscopic probes, especially since the finger flexors will only be used to grasp the handle. The index finger flexors are capable of finer force control compared to the elbow flexors, but they will be used to grasp the handle, and not to vary the force when using a laparoscopic probe. The force control range of 2 – 6N and 10 – 30N are typical operating ranges of the index finger and the elbow, respectively (Jones, 2000). Thus, we cannot ignore the fact that the elbow will usually exert more force than the finger, and that the absolute error in force control is higher for the elbow as well. In a separate study, Lederman et al. (2004) asked the participants to exert a constant level of force (light or medium) using their index finger and a probe, and the results showed that the effect of the end-effector is statistically significant in the control of force – the force output using the probe is consistently higher than with the bare finger.

Why is the fingertip force higher in roughness estimation, but lower in a force control task? One reason is that in the roughness estimation task, the vibration from the tip of the laparoscopic instrument as it passed the surface provides important information on the surface roughness. This vibration is not present during direct tactile exploration. Rather, participants must press into the surface to feel the number of raised bumps to accurately discriminate between different grades of surface roughness. In the task of compliance discrimination, it is unlikely that vibration will be present due to surface texture, since tissues and organs usually have smooth

surfaces. The only other way vibrations could arise is if the probe is used in a rapid tapping manner and the tip of the probe is bounced off of difference surfaces (similar to how the visually impaired use a long cane to make contact with obstacles), and this is extremely unlikely since such an exploration strategy could cause damage to the internal organs. In the task of compliance discrimination, it is more likely that the probe will be pushed into a deformable surface to create indentations. In such cases, it is more logical to assume that the force exerted using direct contact will be lower given the sensitivity of the fingertips and the fact that there will be no distorting factors to the transmission of the exerted force.

Based on the results from the above studies, we can hypothesize that laparoscopic instruments do have an attenuating effect on force when it is transferred from the tip to the handle, and that the sensitivity is decreased. This might affect how accurately humans can perceive and subsequently interpret force information, and how accurately they can estimate tissue compliance.

2.4 Subjective Perception of Force Output

There has not been any research concerning how people perceive their own force output without any external (visual or otherwise) feedback. In most situations requiring force exertion, external feedback is readily available from the effect of the force – verbal and non-verbal cues from touching others, visual and/or force feedback from controlling a machine, etc. In laparoscopic surgery, however, it is very difficult to tell when too much force is applied, unless damages become visible to the surgeons. And, if damage is observed, could the surgeon adjust his/her force output accordingly? Moreover, could the surgeon remember the safe level of force output in

future operations? This leads to the question of whether we have accurate awareness of our own force output. There have been studies on the ability and accuracy of maintaining a constant level of force using different muscle/joint groups, but how well do we know our own force with no external feedback and no reference point?

Past studies have already offered indirect evidence that we do not have an accurate idea of our own force output. When participants are asked to maintain a constant level of force, the presence of error shows that our perception is not sensitive to small fluctuations in our force output (Jones, 2000). The higher level of force exertion when using a probe versus a finger (Lederman et al., 2004) further illustrates the effect of instruments on the perception of self-generated force. People could be consistently underestimating their own force output even in direct tactile contact, given how easy it is to escalate physical conflicts. One particular study showed that given an externally generated force stimulus, people quickly increased the perceived force when asked to reproduce the external force on another (Shergill et al., 2003). As each participant took turn to match the “reference” force, the researchers saw a 38% mean escalation in the magnitude of force *in each turn*. This seems to suggest that we possibly tend to overestimate the reference force. However, the fact that the force match was applied to another person means that the person applying the force does not have feedback to compare to his/her reference stimulus – e.g., the force applicant does not have the opportunity to apply a force to him/herself first so that the reference and the match could be compared. This could undoubtedly cause an increase in error. Nevertheless, there is evidence that we cannot accurately produce an *externally-directed* force output based on an *external* force input. This in turn implies

that we might not have accurate knowledge about the magnitude of force we produce onto others. If this is the case, then it could be part of the reasons for the excessive use of force in laparoscopy.

When Pang et al. (1991) investigated manual discrimination of force by asking their participants to actively adjust two plates (one fixed, one movable) between the thumb and the forefinger to match a reference force, they found the just noticeable difference (JND) to be 7% of the reference force. Similar results were obtained in later studies where the JND of force ranged from 5 – 10% (Tan et al., 1992) to 5.15% (Tan et al., 1993). The JND for force perception through the elbow flexor muscles were very similar, ranging from 5.2 % to 8.8% with a mean of 7.3% (Jones, 1988). So, when a person has feedback on both the reference and the self-generated stimulus, the difference in the matching task is smaller. Unfortunately, other than the reaction force from handling the instruments, the laparoscopic surgeons will not have haptic feedback on the force that they produce. Since the JND is based on a reference stimulus, regardless of the actual magnitude of the reference stimulus, it still requires the same relative difference in stimulus intensity to cause a perceived difference. Thus, the bigger the reference stimulus, the bigger the difference needs to be to be perceived differently. So, given that the typical force operating range of the elbow flexors is 10 – 30N, and that the elbow plays a more significant role in instrument control in laparoscopy, it is important to study the subjective assessment of the magnitude of force output. If people tend to apply a higher level of force while using a laparoscopic instrument, yet have poor awareness of the fact, then they could be more likely to cause intra-operative injury through the excessive use of force.

2.5 Hypothesis Statements

The results of the literature review helped formulate three hypotheses that will be the focus of this research. First, the accuracy of compliance discrimination will be worse when using indirect probing with a laparoscopic surgical probe compared to direct probing with a finger. Second, the force used in direct probing will be lower than that used in indirect probing. Third, the subjective assessment of force output is more accurate in direct probing compared to indirect probing using a laparoscopic probe.

An experiment was designed to gather the necessary data to validate the above hypothesis.

3 Methodology

The methodology of this study experiment aims to retain realistic simulation of the laparoscopic surgery environment, and make the results relevant to laparoscopy. Also, the methods should be relatable to previous studies to allow for comparison of results.

3.1 Participants

Eleven volunteers participated in this study. The University of Waterloo's Office of Research Ethics gave ethics approval, and each participant completed an informed consent form prior to participating in the study. Appendix A shows the documents submitted to the Office of Research Ethics. The participants were aged 24 to 35 with nine males and two females.

3.2 Materials and Apparatus

The task of the study was to probe compliant surfaces with the tip of the index finger (of the preferred hand) or a laparoscopic instrument. A Richard Wolf Co. blunt laparoscopic probe – Model no. 8384.661 – measuring 48 cm in length and 5 mm in diameter, was used to probe the surfaces. This instrument is used by surgeons to atraumatically move various organs out of the way to allow inspection or manipulation of other organs. The probe has a blunt tip and centimeter markings along the shaft of the probe to provide an objective estimation of physical size. The handle of the probe is a hexagonal cylinder. The appearance of the laparoscopic probe is depicted below.



Figure 3: Laparoscopic probe with force sensor

Figure 3 also shows how a Teckscan Flexiforce sensor is used to record the force. Both the tip of the probe and the sensor itself are wrapped with Glad[®] Press n' Seal plastic sheet. The plastic sheet acts as a protective layer for the force sensor. More importantly, when wrapped around both the force sensor and the probe tip, the sheet allows the two objects to be secured together by Super Glue[®], an otherwise impossible feat due to the smooth metal surface of the probe. The additional wrapping around the tip of the probe does not change the shape or hardness of the tip. Figure 4 shows a closer view of the tip and how the force sensor is attached to the tip. The bond between the sensor and the probe does become loose due to usage, and is replaced with new wrappings and glue.

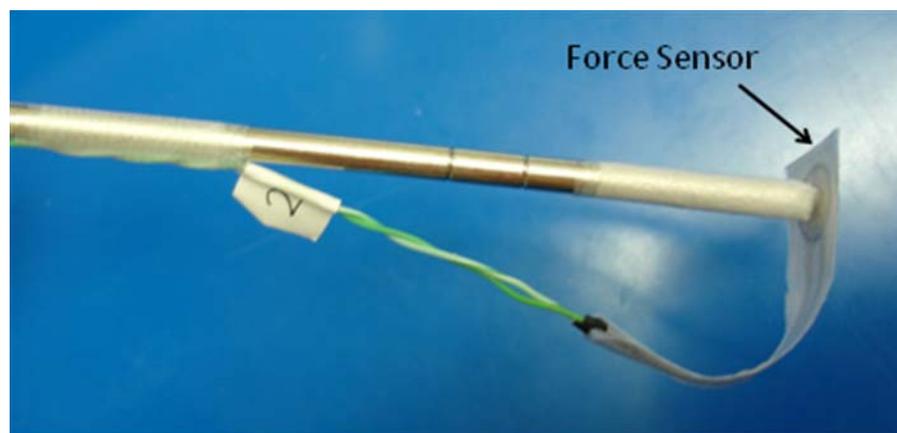


Figure 4: Tip of the laparoscopic probe

Five compliant and deformable silicone disks served as the compliant surfaces. The disks are made from Smooth-On silicone compounds EcoFlex00-10, EcoFlex00-30, DragonSkin, MoldMax20, and SmoothSil930, and have the compliance of 10, 35, 55, 70, and 80 on the Shore 00 scale (Smooth-on.com, 2007), respectively. All disks are created by mixing the required compounds according to instructions provided by the manufacturers, and pouring equal volumes into 8 oz. plastic containers. In addition to having the same shape and size, the discs also have nearly identical colour by adding blue silicone pigments into the liquid silicone mixtures prior to casting the molds. The EcoFlex00-10 silicone has a slightly tacky texture once solidified, so all discs have an added layer of EcoFlex00-30 on top to ensure that all testing materials have the same surface texture as well. The extra layer was painted on with a thickness of 2-3 mm once dried, and did not change the compliance of the discs. Prior to the experiment, volunteers verified that the slight differences in colour cannot be used to help rank the discs in terms of compliance. With the variance in colour being insignificant, the only distinguishable difference between the disks is their compliance. To record the force output of the finger, the sensor is secured to the index finger in contact with the probe using masking tape, as shown in Figure 5. Figure 5 also shows all 5 deformable rubber disks and the uniformity in shape, size, and colour.

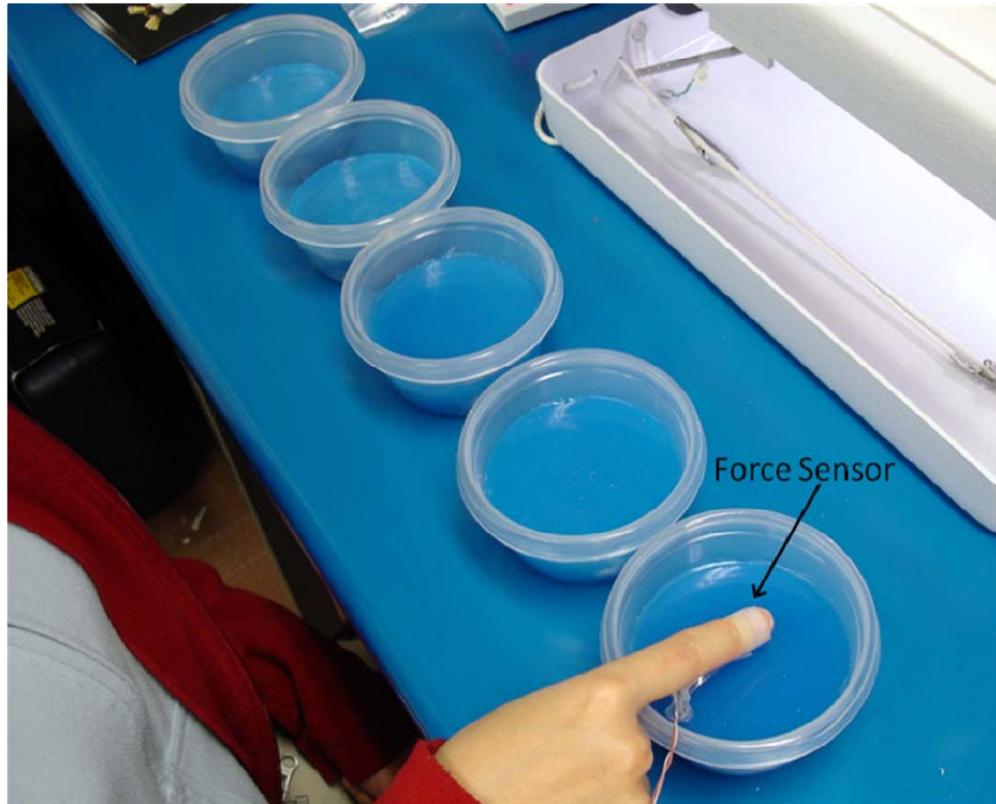


Figure 5: Sensor on index finger

The sensors require calibration by repeatedly loading them with 110% of the maximum pressure prior to actual usage (Tekscan, 2008). The calibration was performed prior to each experiment trial with a compressive force of 9.81 N, achieved with a 1 kg weight loaded on top of the sensor and a flat rubber material with the same surface area as the sensor (used to ensure that the weight is equally distributed over the area of the sensor and nowhere else). Although the maximum force that participants could exert were not known prior to the actual trials, based on the compressive and normal force as reported by previous studies to be in the range of 3-5N (LaMotte, 1995; Dubrowski & Carnahan, 2005), it is reasonable to assume that 9.81 N is adequate to represent the 110% of maximum force required as the calibration force. It should be noted that in this experiment, the sensors can only

measure the normal force as the fingertip or the probe deforms the object surfaces, and between forefinger and the handle of the probe. The tangential force or shear force cannot be measured.

The sensors are connected to an analogue to digital converter circuit and the output from the sensors is recorded into digital format using a Matlab program. The sensors sample at a rate of 100 Hz (one sample every 0.01 s) and the Matlab program records the output from the sensors. Also, the sensors measure in voltage while the analysis is performed on force. The equation used to translate voltage into force is derived from data points obtained during the calibration process is:

$$F = 2.256V - 1.133$$

where F is the force in Newtons and V is the voltage in volts. The variance of this equation is 0.787.

An FLS laparoscopic trainer box (Fundamentals of Laparoscopic Surgery, 2008) was used to simulate the laparoscopic environment. The FLS kit, shown in Figure 6, resembles a box with a soft cover, with small openings on the cover simulating surgical incisions. The laparoscopic probe is inserted through the right-hand opening in the figure below.



Figure 6: FLS laparoscopic training kit

The laparoscopic probe is inserted through the left or right opening, depending on the left or right-handedness of the participant, respectively. The camera inside the FLS system provides an image of the environment inside the FLS kit, and an LCD monitor, as shown in Figure 7, provides the view. Figure 7 shows one of the rubber discs already inside the laparoscopic training kit.

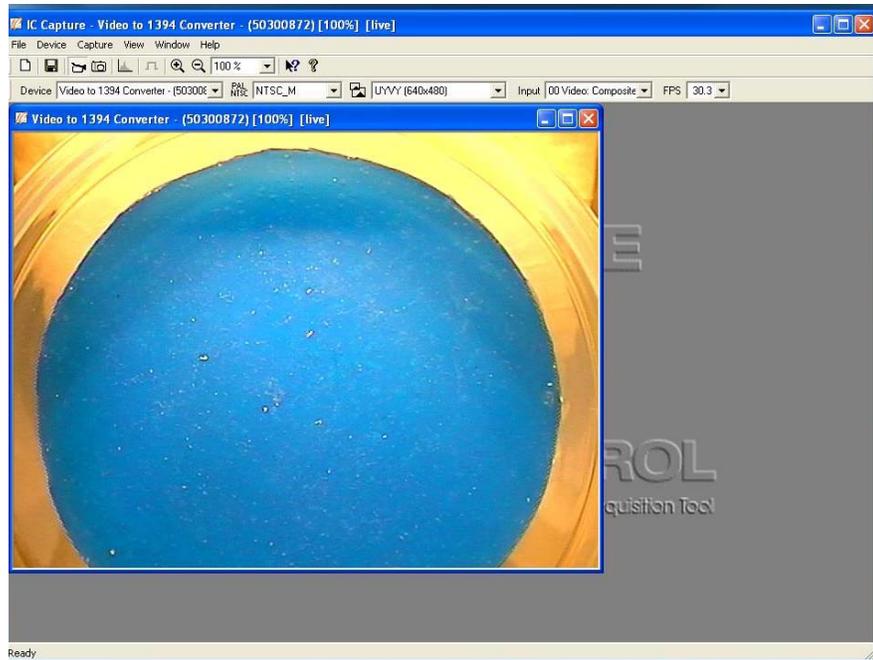


Figure 7: View provided by laparoscopic training kit

Inside the training kit, to ensure that the probe comes into contact with the rubber specimen at angles that are as perpendicular as possible and thus transmit as much normal force as possible, a stand has been constructed from cardboard and masking tape to prop the containers holding the discs such that the contact angle is very close to 90° (actual angle cannot be controlled when the participants are performing the probing tasks). See Figure 8 for the diagram illustration.

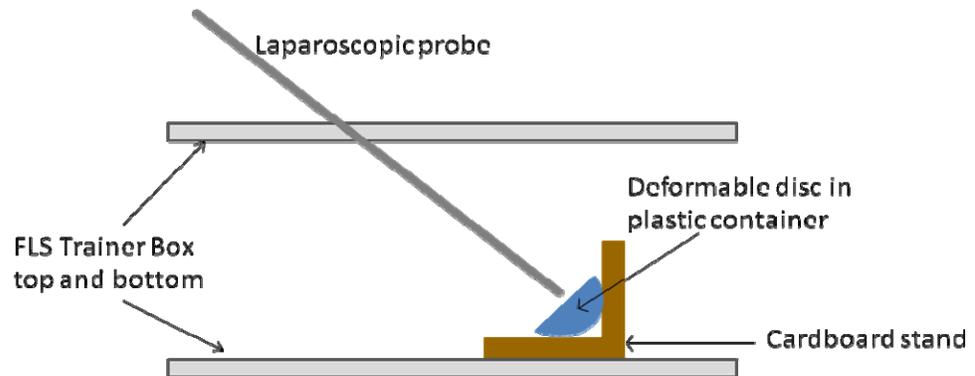


Figure 8: Diagram of the inside of the FLS Trainer Box

3.3 Procedure

The participants took part in two trials – direct and indirect probing trials. The order of the trials was randomized by coin toss. The participants sat for the direct (index finger) probing trials and stood in front of the laparoscopic training kit for the indirect (laparoscopic) probing trials. For the indirect probing trials, the participants held the probe between the index and the thumb and ensured the full contact of the Flexiforce sensor with the handle.

At the start of each trial, the participant holds either his/her index finger or the tip of the probe 1-2 cm above the surface of the compliant object without touching. At the notification of the experimenter, the participant begins to probe the compliant surface. Each participant explored the surfaces in his or her own speed, and was not instructed to follow any rhythm or pattern of exploration, or alter his/her tactile exploration in anyway. Although other studies have controlled the speed of exploration using metronome (Bridges et al., 2005) or computer programmed visuals (Lederman et al., 2004), LaMotte (1995) showed that no significant differences in sensory performance resulted from considerable differences in duration, rate, and magnitude of applied forces of individual subjects. Also, individual surgeons will interact with the surgical environment with different speed, duration, force level. Using a prescribed manner of manual exploration here would make the interaction less realistic and less applicable to laparoscopy.

When the data collection program finished recording the force information, the participants were instructed to stop and to prepare for the next sample. The

participants were not allowed to touch the disks directly or indirectly between the probing tasks. After all five disks were probed, the participants could choose to explore the compliant objects again, and fill out a questionnaire providing the subjective ranking of the object's hardness, as well their assessment of their own force output when exploring each disk (see Appendix A for a sample questionnaire). Both the object hardness and the self-applied force are ranked on a numerical scale of 1 to 10, 1 being the softest object or the lightest force exertion, and 10 being the hardest object or the strongest force exertion. The participants had to be instructed to anchor the opposite ends of the scale such that the softest material is ranked 1 and the hardest material is ranked 10. For the ranking of force output, the participants also had to anchor the extremes if there is a difference in the magnitude of force output. The participants had the choice to rank the force magnitude if they truly cannot distinguish their own force output. The purpose of anchoring the responses was so that all subjective rankings could be compared according to the same scale. If participants were asked to merely provide a numerical ranking of the object softness or their force exertion, they might be confused as to the "correct" response they should be given. Also, it would require all subjective rankings to be normalized so that all rankings are on the same scale; however, doing so would introduce more variability into the data.

Prior to the first round of exploration, the order of the presentation of the discs was randomized so that each participant probed the five disks in a unique order. Each participant's disk order was repeated between the first and the second trial. There was

no repetition of conditions – e.g., each participant only performed the direct and indirect probing once, for a total of two trials per participant.

Other studies have introduced more conditions into the experiment, such as performing the task under the conditions of with vision and without vision. No attempts were made to remove visual feedback during the task performance, since in surgery, vision will always be available to the surgeons, and how vision affects the perception of compliance is not a focus for this research. It should be noted that the participants could use visual cues from the amount of indentation due to the direct or indirect probing and help them rank the compliance of the rubber discs, much like in real world scenarios of tactile exploration.

Similarly, there were no attempts to block out the auditory cues from probing tasks, because there was very little noise from the compression of the silicone discs. Furthermore, there was no differentiable sound from the direct or indirect probing of the discs that are correlated with the disc compliance.

4 Results and Analysis

15 volunteers participated in the study, but only 11 participated in both the direct and indirect probing trials. Furthermore, corruption of sensor data resulted in loss of data for one participant. For compliance discrimination, data from 11 participants were used. For force-related analysis, data from 10 participants were used.

The force data from the sensors were collected in Matlab and exported to Excel for further analysis. The data from the completed questionnaires were transcribed into Excel for statistical analysis.

4.1 Compliance Discrimination

Eleven participants aged 24 – 35 participated in both the direct and indirect probing sessions and completed their assessment of compliance as well as force output for each trial. Twenty-two sets of data, 11 each for each condition of probing – direct (bare finger) and indirect (laparoscopic probe) – were collected. After tabulating the subjective compliance ratings from 11 participants, the accuracy of compliance discrimination is analyzed by ranking – e.g., how closely can the participants rank the rubber discs compared to the actual order of compliance? Each time a specimen is correctly ranked, the associated score increases by 1. The results show that direct probing yields a higher accuracy rate than indirect probing – the success rate for direct probing is 85.5% versus 67.3% for indirect probing. The difference in accuracy due to probing condition is statistically significant. This is comparable to the results obtained by Bholat et al. (1999), where the accuracy of consistency determination was 96.7% for direct palpation and 63.3% for palpation using laparoscopic instrument.

Table 1: Accuracy of compliance discrimination

Participant	Hand	Probe
2	100.0%	60.0%
3	100.0%	100.0%
4	80.0%	100.0%
6	100.0%	100.0%
7	100.0%	40.0%
8	60.0%	40.0%
9	40.0%	80.0%
10	100.0%	60.0%
11	60.0%	40.0%
12	100.0%	60.0%
15	100.0%	60.0%
Average	85.5%	67.3%

A further breakdown of the accuracy by the actual compliance, shown in Table 2, shows that the accuracy rate is significantly lower for the DragonSkin and MoldMax 20 samples, with a true compliance of 6.875 and 8.75, respectively. Participants had less than 60% accuracy rate for each of these two compliances. Compliance discrimination was poorest in the case of indirect probing of DragonSkin and MoldMax silicon samples. This is similar to the results obtained by LaMotte, who concluded that most mistakes in softness discrimination occurred between samples within a neighborhood – e.g., samples that are next to each other in the softness rankings (1995). Also, in terms of their real compliance as defined by their respective Shore 00 durometer ratings, DragonSkin has a rating of 70 while MoldMax has a rating of 80. The difference between the compliance of DragonSkin and MoldMax is smaller than the difference between other neighboring pairs (10 versus 20 or 25), and is also a factor in the lower accuracy rate of compliance discrimination.

Table 2: Accuracy of compliance discrimination by ranking

Compliance (Shore 00 Rating)	Hand	Probe	Average
1 (10)	100.0%	90.9%	95.5%
3.75 (30)	93.3%	81.8%	90.9%
6.875 (55)	81.8%	36.4%	59.1%
8.75 (70)	63.6%	45.5%	54.5%
10 (80)	90.9%	81.8%	86.4%
Overall	85.5%	67.3%	77.3%

Compliance is a significant factor in the accuracy of compliance discrimination ($P > 0.001$). However, the interaction effect of probing condition and compliance is insignificant ($P > 0.05$).

One issue concerning the discrimination of compliance is the use of a discrete scale to rank the perceived softness. Even though the participants were instructed to write any number between 1 and 10 to express their perceived softness, the absence of a continuous line for marking (similar to the method used by Bridges et al., 2005) could influence the participants to use only discrete numbers. However, the result shows that on average, the rankings provided by the participants are very close to the true compliance of the silicone samples, despite the use of numerical scale. Figure 9 shows the difference between the subjective rankings from the direct and indirect probing conditions and the true ranking.

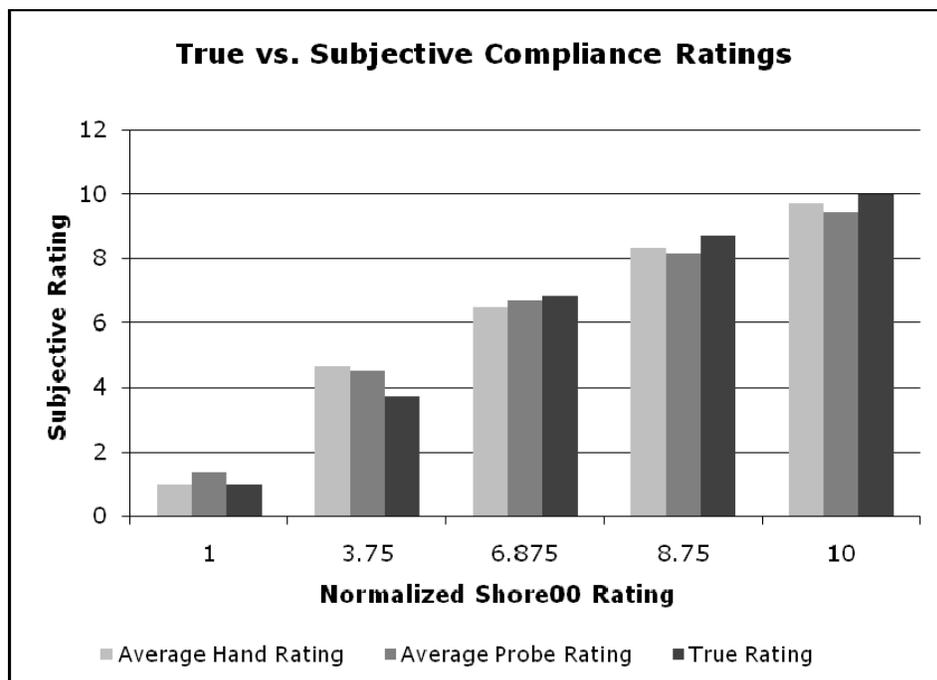


Figure 9: True compliance versus subjective assessment

In summary, both the probing condition and the compliance of the material are significant factors in the accuracy of compliance discrimination. However, there are no significant interaction effects between the probing condition and the material

compliance. The results also confirm the first research hypothesis, that the accuracy of compliance discrimination is higher in direct probing compared to indirect probing.

4.2 Average and Peak Force Analysis

The force data was obtained at three points: at the finger tip during direct exploration, and at the two end points of the probe during indirect exploration. The probing forces are the direct and indirect normal contact forces measured at the finger tip and at the probe tip, respectively, while the handle force refers to grip force used by the participants to secure and manipulate the laparoscopic probe. The analysis examines the average as well as the peak force measured during the experimental trials. The average force here means the numerical average of the 100 data points collected for each direct and indirect exploration, and the peak force is the maximum force measured during each trial.

4.2.1 Effect of probing condition on probe force

As hypothesized, the normal force measured between the rubber discs and the probe tip is significantly greater than that between the discs and the finger tip ($P > 0.01$). The average force measured in the direct probing condition is 1.32 N ($\sigma = 2.04$) while the average force between the silicone materials and the laparoscopic probe during the indirect probing condition is 3.32 N ($\sigma = 1.72$) (Figure 10).

Similar to the average normal force, peak force also differs significantly between probing conditions ($P > 0.001$), with the average peak force during direct probing and indirect probing of 5.15N ($\sigma = 2.68$) and 8.13N ($\sigma = 1.03$), respectively. Figure 10 graphically illustrates the difference.

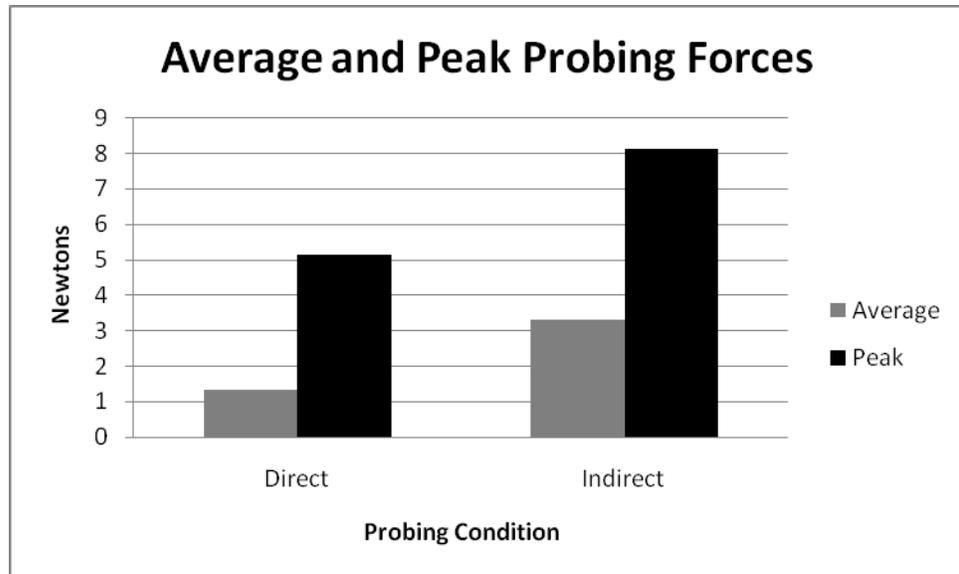


Figure 10: Average and peak forces under different probing conditions

The difference in average and peak force in compliance discrimination found here is opposite of Brydes et al. (2005) study of roughness estimation. Bridges et al. (2005) found that the normal force is *lower* when exploring sandpapers of various grids using a laparoscopic grasper compared to the bare finger. One explanation for this contradictory results in two textual properties is that compared to compliance, roughness provides vibration information during surface exploration with a probe. This vibration information is absent during direct tactile exploration, and subjects must rely on the compression of the grids into the finger to discriminate roughness, and hence tends to press harder in order to obtain accurate assessment of roughness. It can be argued that in the exploration of rough surfaces, laparoscopic instrument or rigid probes actually provide *more* information rather than reducing it. Compliance, on the other hand, does not stimulate vibration regardless of the mode of exploration. Therefore, for the task of compliance discrimination, the use of laparoscopic

instrument does reduce haptic information and leads to an increase in force in order to compensate for the reduction in haptic information.

4.2.2 Effect of compliance on probe force

The analysis of average and peak force indicates that there is no statistically significant difference between different compliances ($P > 0.05$). In other words, compliance of the material being explored does not significantly affect the average or the peak force output of the participants, whether they are probing using their bare fingers or the laparoscopic probe. This holds true for the effect of compliance under different conditions as well. The average and peak force for each compliant specimen explored are shown in Figure 11 and Figure 12, respectively.

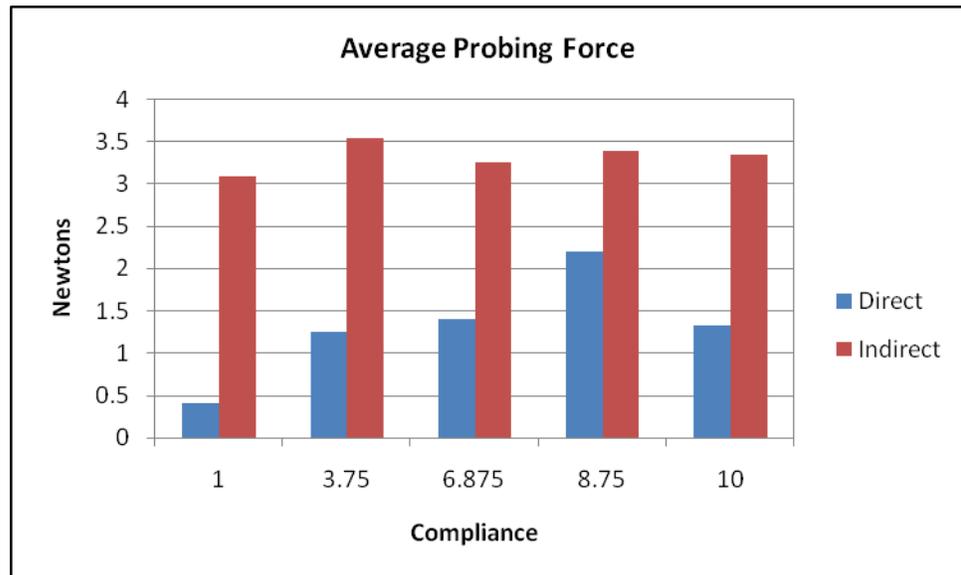


Figure 11: Average probing force and compliance

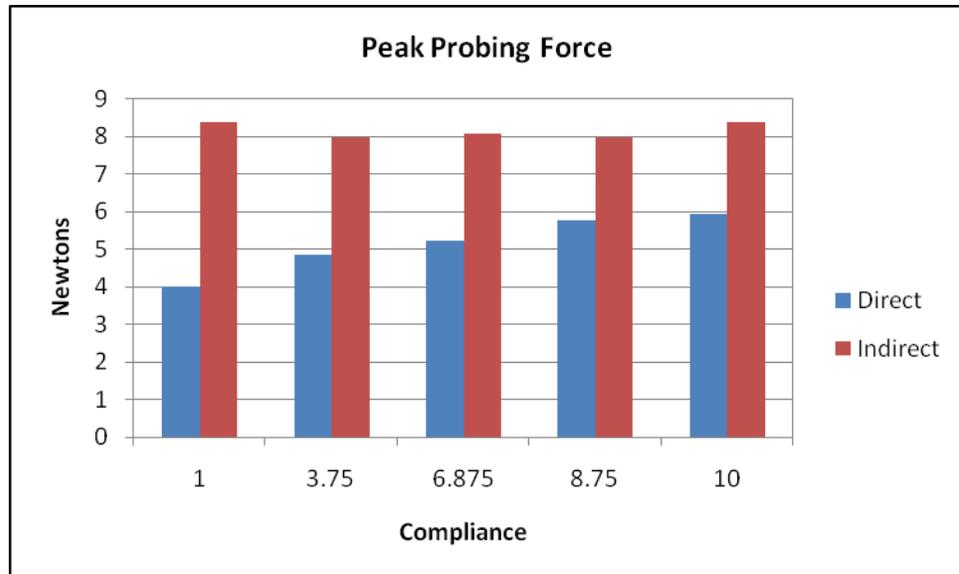


Figure 12: Peak force and compliance

Although indirect probing force is much higher than that used in direct probing, the force across the five materials for each probing condition does not exhibit any trend with the compliance. Analysis of variance (ANOVA) confirms that in both the direct and indirect probing conditions, the compliance of the material is not a significant factor in force output ($P > 0.05$). For the compliance of 8.75, the difference between the average probing forces is insignificant. The difference in peak probing force for the compliance of 6.875 is also insignificant. Compliance 8.75 has the worst discrimination accuracy, while that of 6.875 has the second poorest accuracy. It is possible that the difficulty of discriminating these two particular compliant specimens, due to their close compliance values, leads the participants to exert higher forces in order to obtain more feedback information regarding their respective hardness.

Given the nature of the task, it is natural that the same level of force is used to explore the silicone discs. As force does not vary significantly with compliance, this brings forth the interesting notion that, if the same level of force is used to explore both delicate and more robust tissue during laparoscopy, but the level of force is higher using a laparoscopic instrument in general, then the risk of intra-operative injury is naturally higher in laparoscopy simply because the magnitude of force is higher.

4.2.3 Average and Peak Handle Force

While the average and peak force at the contact point with the rubber discs reveal the magnitude of exploration force, the force at the handle represents the force feedback of the participants during indirect probing. In direct exploration, the probing force and the feedback force are one and the same. In indirect probing, however, the feedback force is measured at the handle. Looking at the handle force could reveal the transformation of force information from the tip to the handle, and how the difference, if any, could contribute to the excessive use of force in laparoscopy. Since the handle force is only measured during indirect probing, the only factor that could affect the force at the handle is the compliance of the rubber discs.

Similar to the force at the probe tip, compliance does not significantly affect the force at the handle ($P > 0.05$). The average and peak handle forces found for each compliance group are illustrated in Figure 13.

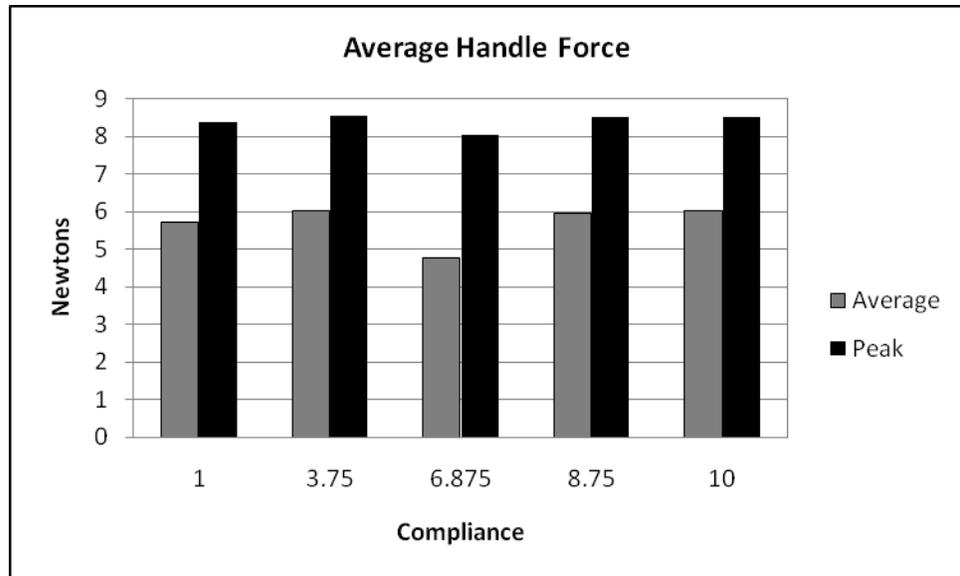


Figure 13: Average and peak forces at the handle

4.3 Comparison Between All Forces

The average force at the handle of the probe is 5.70N, significantly higher than the average direct probing force as well as the average indirect probing force ($P < 0.01$). This is shown in Figure 14

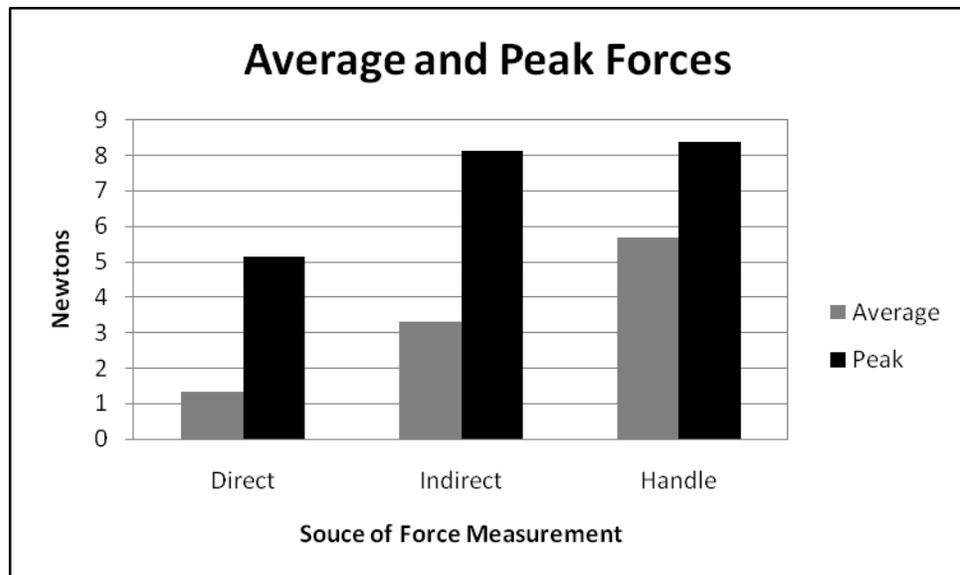


Figure 14: Average and peak forces at each data collection point

Not surprisingly, the peak force at the handle, 8.38N averaged over all participants and trials, is significantly higher than that of the direct probing condition ($P < 0.01$). However, there is no significant difference between the peak force at the tip and at the handle of the probe, as illustrated in Figure 14.

The data from all three collections points show that the magnitude of force involved in indirect probing is higher than that in direct probing. Both the average and the peak forces at each end of the laparoscopic probe are higher than the forces in direct exploration. This in turn means that a) the force exerted on the explored materials is higher using the laparoscopic probe, and that b) the force experienced by the participants is higher using the probe.

The higher force exertion using the probe is not unexpected. The cause for higher force output could be generally acknowledged reduction in haptic feedback as well as the reduction in visual feedback. In the case of compliance discrimination, the indentation of the material under compressive force provides information about the compliance. In indirect probing, the visual cues, especially depth cues, are reduced (Shah et al., 2003) due to the use of the camera and monitor. Participants could be pushing harder in order to see a more noticeable indentation in the material, compared to direct probing. The reduction in haptic feedback could also prompt the participants to probe with higher forces to receive more force feedback. The reduction in force feedback could be seen in the higher force at the handle as well, not through the magnitude of the average and peak force, but through the *variation* in the force at the handle. In all 50 sets of collected data, the variance at the handle is less than that at the tip of the probe (see

Appendix B: Individual Trial Data Variance), while the tip of the probe has the highest variance in force. The higher variance in the average force at the tip is likely due to the fact that the tip is not always in contact with the surface of the rubber discs, while the finger tips are always gripping the handle of the probe. This is illustrated with the full sensor data of a trial from a particular participant (Figure 15).

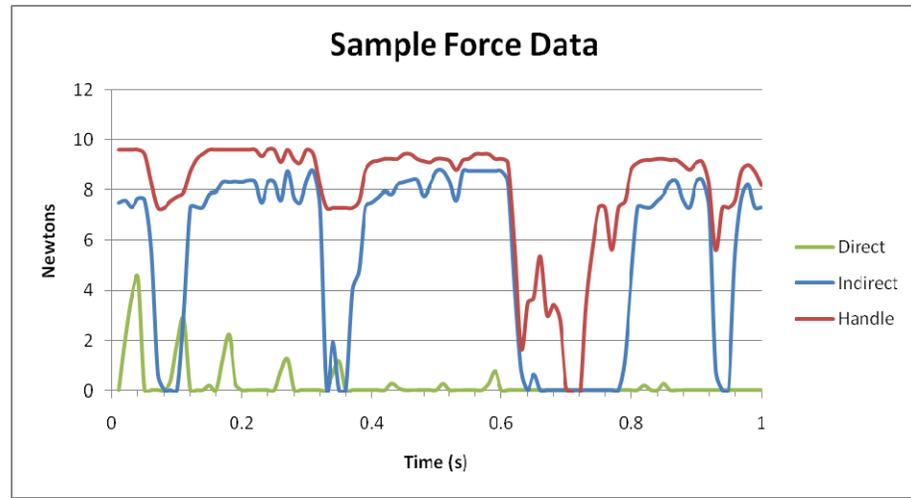


Figure 15: A sample full trial data from participant 9, trial 4

While the tip of the probe leaves the surface of the compliant materials periodically, the index and thumb of the participants are always gripping the probe during the trials. This means that the participants are always receiving force feedback regardless whether they are actively probing the rubber discs. The presence of grip force can be seen as a higher reference force for the participants during the indirect probing trials. Thus, the relative change at the handle force is much smaller compared to those at the tip of the probe or at the finger tip, where the reference force is zero. The higher reference point from the grip force at the handle and the smaller relative change in the magnitude of force is further confirmation of the reduction in force feedback in the indirect probing task.

In addition to increasing the reference force during indirect probing, the grip force on the handle of the probe further reduces a second source of haptic feedback from the participants: the deformation in the finger pad. The Srinivasan and LaMotte study (1994) study has already shown that kinesthetic information alone is sufficient for distinguishing deformable objects, as the indentation of the finger pad against the material is related to its compliance. However, during the indirect probing task, the finger pad of the index finger is already deformed from gripping the rigid laparoscopic probe. Further compression of the finger pad is a result of having to grip the probe harder during downward presses on the rubber discs. Also, with the finger pad already compressed against the probe handle, any change in the deformation of the finger pad will be less noticeable compared to the uncompressed state.

4.4 Self Assessment of Force

All participants filled out a questionnaire at the end of each experimental trial, and provided their subjective assessment of their force exertion on a scale of one to ten. Participants were instructed to anchor their minimum and maximum force as one and 10, respectively, and in the case where no difference exists, to rank all force with the same number.

Analysis of variance on the resultant data shows that the compliance of the material is a significant factor ($P > 0.001$) in the subjective ranking of both the direct and indirect probing force – the higher the compliance, the higher the estimation of force output. The coefficients of correlation between compliance and the subjective assessment of direct probing force and indirect probing force are 0.98 and 0.96, respectively. Probing condition, however, is not a significant factor in the assessment

of force output. Figure 16 shows the difference in subjective ranking in different probing conditions and compliance.

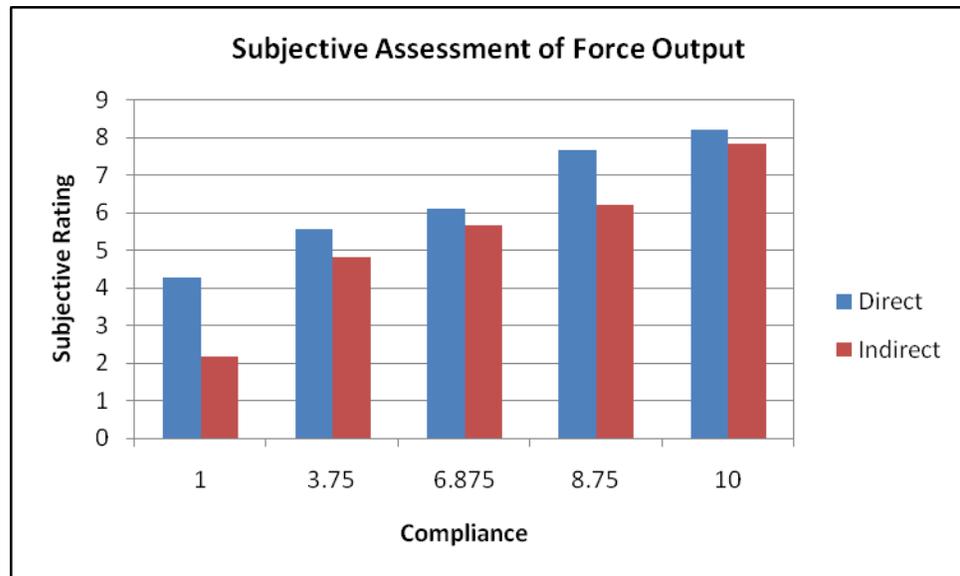


Figure 16: Subjective assessment of force in direct and indirect probing

Although analysis of average and peak probe force showed that there is no significant difference in actual force output between different compliant specimens, the subjective ratings show that the participants' perception of their force output depends on the compliance. This disconnect or discrepancy between the actual and perceived force output means that, during a laparoscopic exploration using a probe, all tissues, regardless of their softness and robustness, receive the same probing force. The softer and more delicate tissues are therefore more likely to be injured, as the surgeons think that their probing force is lower than the actual force output.

5 Conclusions and Future Research

The results of the experiment confirmed two of the three experimental hypotheses: that the accuracy of compliance discrimination will be worse when using indirect probing compared to direct probing, and that the force used in direct probing will be lower than that used in indirect probing. However, the hypothesis that the subjective assessment of force output is more accurate in direct probing compared to indirect probing is disproved. There are many limitations in the design of the experiment, and future works could improve upon the results found at this time.

5.1 Conclusions

The results of the experiment confirmed the hypothesis that the accuracy of compliance discrimination is significantly higher with direct probing using the index finger. The compliance of the material is also a significant factor in the accuracy of discrimination. The accuracy of discrimination is significantly lower for the specimens with closer compliance, similar to earlier results obtained by LaMotte (1995).

The analysis on the average and peak force at the finger tip, the probe tip, and the probe handle shows that the probing force is higher using the laparoscopic probe compared to using the finger tip, confirming the second research hypothesis. Both the average and peak force at the tip of the probe are significantly higher than those found at the finger tip. The higher probing force at the tip of the laparoscopic probe means that the risk of tissue damage or injury is higher with a laparoscopic probe.

The average and peak probing force are not significantly different across different compliant specimens, implying that softer tissues are more likely to be injured or damaged simply because of the higher level of probing force relative to the harder tissues. This is based on the assumption that softer tissues are also more fragile and susceptible to damage and injury.

The average and peak force at the handle of the probe are significantly higher than those at the finger tip, showing that the force experienced by the operator of the probe is higher. Although the force at the handle may not be the same as the applied force, since the force sensor only measures the normal component of the applied force, we can assume that the inclusion of tangential force will likely increase the force at the handle. This does not mean that the force feedback is higher in indirect probing or laparoscopy. Rather, the force feedback is worse in indirect probing because the grip force at the handle increases the reference point from which the operator must perceive changes in the magnitude of force. The higher reference point caused by the grip force effectively reduces the information quality of force feedback from the laparoscopic probe, as seen in the lower variance in the magnitude of force at the probe handle compared to the probe tip and the finger. Additionally, the compression of the finger pad from the gripping action further reduces the force feedback available in indirect probing, as the indentation or deformation of the finger pad is far less noticeable compared to direct probing.

The subjective assessment of the direct and indirect probing force show the participants generally perceive their own force output as higher when the compliance of the material is higher. This disproves the hypothesis that subjective assessment of

force output will be more accurate with direct probing. In fact, the subjective assessment of force output is equally poor for both direct and indirect probing. The correlation between the compliance and the subjective ranking is 0.98 and 0.96 for the direct and indirect probing tasks, respectively. Not only does this show that the operators have a poor understanding of their own force output, but this disconnect between perceived and actual force output puts the softer tissues at further risk for damage and injury – since the indirect probing force is higher compared to direct probing force, and since operators are likely to think that their probing force is lower for the softer tissues.

The results from the analysis of average and peak force support earlier findings that haptic feedback in laparoscopy is reduced compared to conventional open surgery, due to the use of laparoscopic instruments that create higher reference points from the gripping action while simultaneously decrease the deformation/indentation in the finger pads. The results from the subjective assessment of force output reveals a perceptual aspect to force feedback that has not been explored. The disconnection between the actual and the perceived force output means that the participants in general thought that they press the softer materials with a softer force and the harder materials with a stronger force. This again increases the likelihood of damage and injury to softer tissues in laparoscopy.

5.2 Future Research

One of the major limitations of this experiment is the lack of replication with individual participants. Replication of this experiment with more trials for each participant is recommended. Further study into the perceived force output versus

actual force output, and any perceptual disconnect, will be relevant to both laparoscopy and haptic feedback in general. The preliminary results from this study suggest that perhaps we take the accuracy of haptic feedback for granted, that we necessarily know what we are doing when performing physical actions, even ones as simple as probing. Without external feedback such as signs of bruising and bleeding, the awareness of our own force output based solely on the haptic perception warrants further investigation. Future works should investigate subjective force assessment with both novices and experts (participants with training in laparoscopy) to determine if training and experience provides better internal awareness of force output.

Finally, the grip force as a contributing factor in reduced haptic feedback in laparoscopy should be examined in future works. This will have applications in the design of laparoscopic probes and perhaps other instruments. If grip force indeed attenuates haptic feedback by compressing the finger pad and reducing a valuable source of tactile information from the deformation of finger pad, then laparoscopic probes could be designed to reduce grip force at the handle. Experimentation using probes with different surface friction at the handle and/or different weight that will cause different grip forces is one example of possible future works in this respect.

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Appendix A: Documents Submitted to the Office of Research Ethics

The Permission for Recruitment in Undergraduate Classes is a scripted email communication used to contact professors of undergraduate classes to obtain consent to visit a class during lecture hours and recruit participants.

Permission for Recruitment in Undergraduate Classes

Dear Prof. <Name>,

My name is Hao and I'm running an experiment for my Masters's research. I am studying the role of haptic feedback in laparoscopic surgery, a type of minimally invasive surgery performed using small incisions and long and slender instruments. The purpose of this study is to determine the transfer function of force when using a laparoscopic instrument, and to investigate possible factors affecting the transfer of force from the tip of a laparoscopic instrument to the handle.

I would like to recruit the students in your <course code> class to participate in my study. The recruitment will take approximately 5 minutes, during which I will briefly introduce myself and my experiment, distribute an information letter, and demonstrate an instrument that will be used in my experiment. I would greatly appreciate your permission to conduct my recruitment in your class.

This study has been approved by the Office of Research Ethics. If you have any comments or concerns about this study, you may contact the Office of Research Ethics at (519) 888-4567 x36005.

Sincerely,
Hao

The following document is a scripted message used to recruit participants from undergraduate or graduate students during lecture hours, after obtaining permission from the class lecturer or profession using the previous script.

In Class Recruitment Script

Hello, my name is Hao and I am a graduate student in the department of Systems Design Engineering. For my Master's thesis I'm researching the role of haptic feedback in laparoscopic surgery, particularly the force transfer between the tip and the handle of a laparoscopic instrument. I am conducting an experiment to collect quantitative data of force while using a laparoscopic instrument. Here's the instrument I'll be using in my experiment (present laparoscopic grasper).

The focus of my research is to determine how force is changed quantitatively by the instrument. The ultimate goal of my research is to improve surgical performance and reduce the incidences of intra-operative injury in laparoscopy.

If you volunteer as a participant in this experiment, you will be asked to explore a set of rubber and silicone objects, to determine their relative softness, using your index finger in some trials and the laparoscopic instrument in other trials. A pressure sensor will be attached to your finger to measure pressure. As well, there is a short questionnaire concerning perceived softness of the objects. The objects explored will be inanimate and sanitary in nature. There are 2 sessions, schedule a week apart. The sessions should take approximately 30 minutes each, for a total of 1 hour of your time.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics. However, the final decision about participation is yours.

Confidential recruitment card:

Name: _____
Department: _____
Email: _____
Phone #: _____
Best days: _____
Best times: _____

The Information Letter is used to inform potential participants of the details of the experiment and their level of involvement.

Information Letter

University of Waterloo

Date: to be determined

Thesis topic: Force transfer and perception of self-exerted force in laparoscopy

Student investigator: Hao Xin, University of Waterloo, Department of Systems Design Engineering

Graduate supervisor: Dr. John Zelek

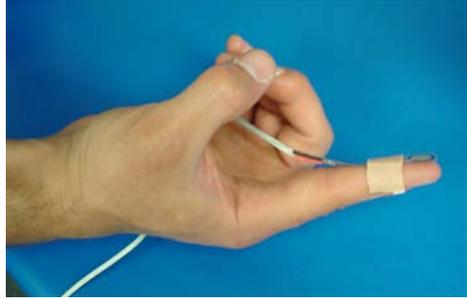
This experiment is the thesis research for Hao Xin, a Master's candidate in Systems Design Engineering. Hao's research focuses on the role of haptic feedback in laparoscopic surgery, a type of minimally invasive surgery performed using small incisions and long and slender instruments. The purpose of this study is to determine the transfer function of force when using a laparoscopic instrument, and to investigate possible factors affecting the transfer of force from the tip of a laparoscopic instrument to the handle.

The experiment involves the use of laparoscopic instruments such as a grasper or a probe. An illustration of the grasper is shown below. The probe looks like the grasper without the handle and the open jaws.



Grasper

The experiment will also employ a pressure sensor that will be attached to your index finger in part of the experiment. The picture below shows the size of the sensor and how it will be attached to the index finger:



The experiment consists of 2 sessions. One session involves probing a set of silicone objects using the index finger and the other involves probing a set of silicone objects using a laparoscopic instrument. The order of probing with the finger or the instrument will be determined randomly. At the end of the sessions there will be a questionnaire concerning the subjective assessment of softness of different objects and your own force output as you were exploring the objects. Each session will take approximately 30 minutes. You may take short breaks during each session if you wish. Refreshments will be provided during both sessions. 40 people maximum will be asked to participate in this experiment.

The ultimate goal of this research is to add to our current understanding of haptic feedback in laparoscopic surgery, and to reduce intra-operative injury in minimally invasive surgeries.

Electronic data collected consists of the force you exert while completing the touching/probing tasks. Your demographic information including age, gender, and previous video game experience will be recorded as well. Your name will not be recorded and consequently the data collected cannot be traced back to you. The electronic data will be stored on a computer in the Intelligent Human-Machine Systems lab indefinitely. The questionnaires will be stored at the same lab indefinitely. All other written records that include your personal information will be destroyed upon the completion of Hao's thesis. Electronic as well as questionnaire data will be presented in my Master's thesis, and might be presented in conferences or academic papers in the future. If an individual participant's data are presented in a figure, names or any identifying information will not be included.

Participation is voluntary and you may decline to answer items on the questionnaire if you wish. You may also withdraw from the study at any time without penalty by verbally indicating this to the researcher. There are no known risks associated with participating in this study.

I would like to assure you that this study has been reviewed and received ethics clearance through the Office of Research Ethics at the University of Waterloo. However, the final decision about participation is yours. If you have any comments or concerns resulting from your participation in this study, you may contact Dr. Susan Sykes, Director ORE, at (519) 888-4567 ext. 36005. If you have additional questions later or want any other information regarding this study, please contact Hao Xin (the

student investigator) at 519-888-4567 ext. 37839 and/or Dr. John Zelek at 519-888-4567 ext. 32567

The Consent Form is presented to participants after they have read the Information Letter.

Consent Form

I have read the information presented in the information letter about an experiment conducted by Hao Xin of the Department of Systems Design Engineering at the University of Waterloo as part of her Master's research. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

I am aware that data collected while I perform the tasks, as well as answers I provide in the beginning of the trail about my age, gender, and video game experience may be included in the publications to come from this research, with the understanding that the information will be anonymous.

I was informed that I may withdraw my consent at any time without penalty by advising the researcher.

This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at the University of Waterloo. I was informed that if I have any comments or concerns resulting from my participation in this study, I may contact the Director of Office of Research Ethics at (519) 888-4567 x36005.

With full knowledge of all foregoing, I agree, of my own free will, to participate in this study.

Yes No

Participant Name: _____

Participant Signature: _____

Date: _____

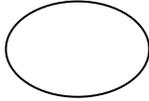
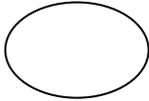
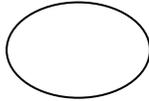
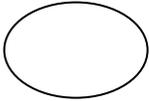
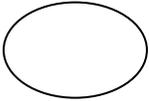
Witness Name: _____

Witness Signature: _____

The Questionnaire is used during the experiment to collect part of the data needed for analysis.

Questionnaire

Please take a moment and answer the following questions based on your interaction with the rubber discs today.

					
1. On a scale of 1 to 10, 1 being the softest and 10 being the hardest of the discs you've encountered in this session, how would you rank the softness of each of the discs? Please provide your answer in the space below.					
1. On a scale of 1 to 10, 1 being the softest and 10 being the hardest of the discs you've pushed on the discs in this session, how would you rank your own force output – i.e. how hard do you think you've pushed on the discs? Please provide your answer in the space below.					

(Note to the Office of Research Ethics reviewer: the rubber pucks used in the study will be arranged in a row. The use of table and puck shapes here is to facilitate identification of pucks and help the participants provide their answers to the correct object in question)

Participant #: _____

The Feedback Letter is presented to the participants upon the completion of their last experimental trial.

Feedback Letter

University of Waterloo

Data

Dear (Insert Name of Participant):

I would like to thank you for your participation in this study. As a reminder, the purpose of this study is to determine the transfer function of force when using a laparoscopic instrument, and to investigate possible factors affecting the transfer of force from the tip of a laparoscopic instrument to the handle. The ultimate goal of this research is to better our understanding of haptic feedback in laparoscopy and improve surgeon performance, reducing the risk of intra-operative injury and improve patient safety.

The data collected during interviews will contribute to a better understanding of our perception and self-assessment of our own force output. This will help with the design of laparoscopic instruments that will be able to enhance or complement the surgeons.

Please remember that any data pertaining to you as an individual will be kept confidential. Once all the data are collected and analyzed for this research, I plan on sharing this information with the research community through the publication of my thesis and conference/journal papers. If you are interested in receiving more information regarding the results of this study, or if you have any questions or concerns, please contact me through the email address listed at the bottom of the page. If you would like a summary of the results, please let me know now by providing me with your email address. When the study is completed, I will send it to you. The approximate completion date of this research is August 30th, 2007.

As with all University of Waterloo studies involving human participants, this study was reviewed by, and received ethics clearance from, the Office of Research Ethics at the University of Waterloo. Should you have any comments or concerns resulting from your participation in this study, please contact the Office of Research Ethics at (519) 888-4567 x36005.

Hao Xin

University of Waterloo
Department of Systems Design Engineering

UW Email Address: h2xin@engmail.uwaterloo.ca

Appendix B: Individual Trial Data Variance

Participant	Trial	Direct	Handle	Indirect
2	1	0.59	0.44	1.30
	2	0.19	0.39	1.96
	3	0.35	0.39	2.74
	4	0.67	0.46	2.79
	5	0.64	0.39	2.68
3	1	1.18	0.41	2.88
	2	1.47	0.95	3.14
	3	2.11	0.19	3.51
	4	2.65	0.72	3.45
	5	2.89	0.24	3.28
4	1	1.80	0.02	3.51
	2	0.88	0.48	3.31
	3	1.89	0.04	2.97
	4	1.55	0.02	2.83
	5	1.91	0.72	2.82
6	1	0.13	0.05	1.75
	2	0.30	0.02	2.22
	3	0.44	0.04	1.49
	4	0.08	0.05	1.05
	5	0.63	0.03	2.17
7	1	1.08	0.44	2.51
	2	1.97	0.81	2.58
	3	0.50	1.50	2.43
	4	2.09	0.50	2.16
	5	1.62	0.67	2.67
8	1	0.07	0.07	2.48
	2	0.21	0.58	2.21
	3	0.03	0.08	2.40
	4	1.29	0.08	2.49
	5	1.36	0.06	2.87
9	1	0.03	1.25	2.45
	2	0.04	0.59	2.49
	3	0.01	1.28	2.59
	4	0.22	1.02	2.93
	5	0.06	0.30	2.38
11	1	1.06	0.04	2.55
	2	1.90	2.20	2.64
	3	2.52	0.33	2.03

	4	3.08	0.20	3.13
	5	1.56	0.52	3.76
12	1	0.10	0.89	1.88
	2	0.17	1.36	2.40
	3	0.05	1.82	1.95
	4	0.11	1.41	2.03
	5	0.15	1.34	2.03
15	1	0.17	0.68	0.97
	2	0.36	0.45	1.57
	3	0.34	1.12	2.02
	4	0.29	0.49	1.13
	5	0.29	1.24	2.60