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FEELING FOR FAILURE: HAPTIC FORCE PERCEPTION OF SOFT TISSUE CONSTRAINTS IN A SIMULATED MINIMALLY INVASIVE SURGERY TASK

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FEELING FOR FAILURE:
HAPTIC FORCE PERCEPTION OF SOFT TISSUE CONSTRAINTS IN A SIMULATED MINIMALLY INVASIVE SURGERY TASK

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ABSTRACT

In minimally invasive surgery (MIS), the ability to accurately interpret haptic information and apply appropriate force magnitudes onto soft tissue is critical for minimizing bodily trauma. Force perception in MIS is a dynamic process in which the surgeon's administration of force onto tissue results in useful perceptual information which guides further haptic interaction and it is hypothesized that the compliant nature of soft tissue during force application provides biomechanical information denoting tissue failure. Specifically, the perceptual relationship between applied force and material deformation rate specifies the distance remaining until structural capacity will fail, or indicates Distance-to-Break (DTB). Two experiments explored the higher-order relationship of DTB in MIS using novice and surgeon observers. Findings revealed that observers could reliably perceive DTB in simulated biological tissues, and that surgeons performed better than novices. Further, through calibration feedback training, sensitivity to DTB can be improved. Implications for optimizing training in MIS are discussed.

DEDICATION

For a lifetime of love and support, this dissertation and the completion of my Ph.D. are dedicated to my incredible family. Without your endless encouragement, I would never have had the strength or confidence to pursue my doctorate. And particularly to my mother, Catherine, whose wisdom and inspiration have been a twinkling light during the brightest and darkest days of this adventure.

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CHAPTER ONE

INTRODUCTION

Haptic Force Perception in Minimally Invasive Surgery

Minimally invasive surgery (MIS) procedures have seen a continual increase over the past few decades as patients demand less invasive surgical options. Traditional open surgery involves manipulating internal body tissues though a large opening revealing bodily structures that can be examined and handled reasonably directly (with gloved hands). This paradigm typically includes a sizeable incision where surgeons are able to examine and then interact with the structures and organs with fingers, clamps, utensils, and other implements. In contrast, MIS entails a few very small incisions or the use of a natural orifice for the insertion of long slender instruments and an unobtrusive endoscopic camera to view the surgical area. Trocars are used as a portal by which instruments are introduced, and in some cases gas is pumped into the cavity inflating the area to better expose the surgical site. Surgeons interact with tissues entirely though the inserted surgical tools while monitoring their activities through video from the inserted camera. These types of procedures are less obtrusive to patients, resulting in reduced bodily trauma, decreased recovery time, less discomfort, and less physical scarring (see Modi, Hassan, Chitwood, 2008; Perigli, Cortesini, Qirici, Boni & Cianchi, 2008).

Due to the nature of MIS, interaction between surgeon and surgical site takes place remotely as the surgeon is physically located outside of the actual surgical environment, resulting in an entirely mediated perceptual experience. Because surgeons access, monitor, and manipulate the surgical site indirectly, they are faced with a host of perceptual problems which have been classified into three main categories: hand-eye coordination issues, decreased visual depth perception, and decreased haptic perception (Westbring-van Der Putten, Goosens, Jakimmowicz, & Dankelman, 2008). Hand-eye coordination issues arise from controlling all instrument behavior by way of camera instead of directly viewing ones hands as well as synchronizing tool behavior viewed on a monitor with that of true manual behavior controlling the tools, as instrument motion is in reverse of hand motion (Breedveld & Wentink, 2001). Issues with visual depth perception occur as the normal three-dimensional visual environment is decomposed into a two-dimensional one, resulting in a class of visual issues collectively referred to as the "remote perception problem" (Gomer, Dash, Moore & Pagano, 2009; Moore, Gomer, Pagano & Moore, 2009; Tittle, Roesler & Woods, 2002). Surgeons must haptically perceive the physical properties of the remote surgical environment through hand-held surgical tools. One or more instruments with different functions are inserted through the skin allowing surgeons to interact with tissue through grasping, prodding, stretching, pushing, sweeping, and squeezing motions. Biomechanical tissue property information is transferred through the instruments to convey information such as texture, compliancy, weight, and viscosity. While perceptual components are critical for proficient surgical performance in MIS, less emphasis has been placed on understanding and improving haptics in MIS, which is also a significant contributor to successful patient outcome.

Surgeons' haptic perception in MIS is a combination of kinesthetic and tactile sensations. Kinesthesis pertains to sensations arising from the muscles, joints and connecting tissues, providing an awareness of the location, position, and movement of bodily limbs in space. Mechanoreceptors within these tissues are stimulated in response to active movement, thus they respond to muscular effort. As a result, this type of articular proprioception also provides property information regarding the manipulation of physical objects, providing an inherent understanding of both hand-held objects (e.g., weight, orientation and extent) and of surfaces probed with hand-held objects (Barac-Cikoja & Turvey, 1993; Burton, 1993, 2004; Carello & Turvey, 2000; Gibson, 1966; Pagano, 2000; Pagano & Turvey, 1998; Peck, Jeffers, Carello & Turvey, 1996; Turvey, 1996). When lifting a beverage can, for example, one relies on a sense of muscular effort to perceive how much fluid is contained in the can. This muscle sense also provides information about the geometric and mechanical properties of both hand-held objects and of surfaces contained with those objects. Thus kinesthesis is responsible for the awareness of positions and movements of arms, hands, surgical tools and manipulated tissues during MIS. “Tactile” mechanoreceptors are located more superficially in the skin and provide the surgeon with sensations arising from physical contact, such as pressure on the skin, surface texture and surface temperature. When operating together, kinesthesis and tactile perception jointly comprise “haptic” perception (Loomis & Lederman, 1986; Pagano, Carello, & Turvey, 1996).

Given that tactile perception primarily serves to inform surgeons about how MIS instruments are held in the hand, they must rely primarily upon kinesthesis to become informed about interactions occurring at the distal ends of the tools and hence, about the properties of tissues being manipulated. The hand and fingers contact only a small portion of the tool, which is wielded about the fulcrum incision port through coordinated gross muscular actions to produce forces at the surgical site. These rotational movements by the surgical instruments in addition to the contact forces with distal surfaces affect the tensile states of the muscles, tendons and ligaments of the hand and arm. Thus, hand-held tools provide the surgeon with 'extended haptic perception' (Burton, 1993), allowing tissues to be detected remotely. Such extended haptic perception allows for the detection of surface abnormalities (Keston, 1956), distortions along surface topography (Choi, Walker, Tan, Crittenden, & Reifenberger, 2005), the distance between separate surfaces (Barac-Cikoja &Turvey, 1991; Chan & Turvey, 1992), and material roughness (Katz, 1925/1989).

Forces experienced in MIS are fundamentally different than those experienced in open surgical procedures and result in degraded haptic information at the tool-tissue interaction site (Deml, Ortmaier, & Seibold, 2005; Nisky, Huang, Milstein, Pugh, Mussa-Ivaldi, & Karniel, 2012; Puangmali, Althoefer, Seneviratne, Murphy, & Dasgupta, 2008; Trejos, Patel, & Naish, 2010; Westebring-Van Der Putten, Goossens, Jakimowicz & Dankelman, 2008; Xin, Zelek, & Carnahan, 2006). Open surgery allows surgeons to handle tissue directly with the fingers, obtaining proficient tissue property information through accurate tactile and kinesthetic feedback, and then to apply controlled forces onto tissue with no interference. In MIS, force perception occurs entirely through the inserted instruments and surgeons are unable to directly feel the structures, textures, stiffnesses, and other properties of tissues and organs. Forces are transmitted through the head of the surgical instrument, through the utensil shaft, and then through the handle until reaching the fingers. The inserted trocar at the port of entry acts as an invariant fulcrum point for the surgical instrument resulting in only four degrees of freedom available inside the body cavity (Van den Dobbelsteen, Schooleman, Dankelman, 2007). Friction from the trocar also acts upon the shaft of the tool, resulting in varying amounts of resistance as the instrument is rotated.

As a result of reduced force perception, MIS procedures requiring high levels of precision are prone to errors, of which a main cause can be attributed to the misapplication of forces within the body cavity (Xin, Zelek, & Carnahan, 2006). An analysis of laparoscopic cholecystectomy procedures found that 75% of the procedures observed resulted in unintentional gallbladder puncture (Joice, Hanna, & Cushieri, 1998). Upon closer inspection of the perforation instances, 73% of them were caused by excessive force and/or instrument displacement, cited as resulting from reduced haptic feedback. In an analysis of errors made in laparoscopic cholecystectomy procedures with trainees, all surgical errors resulting in tissue damage were found to have excessive force application as a common causal factor (Tang, Hanna, & Cushieri, 2005). Further, of those errors cited as being ‘consequential’ (requiring corrective procedures because of bleeding or injury), 55% were the result of too much force being applied at the tissue-tool interface. MIS requires a different motor and perceptual skill set than open surgery, of which significant training and experience are necessary to gain expertise (Xin, Zeleck, & Carnahan, 2006).

Force perception in MIS requires a continuous, dynamic process in which the surgeon’s administration of force onto tissue results in useful information for adapting further interaction. Surgeons act on tissue by applying physical force and through this interaction immediately obtain useful kinesthetic and tactile tissue property information such as surface topography, mass composition, and weight (Bergmann Tiest, 2010). Soft tissues are highly malleable and pressure application also reveals information related to material compliancy, or the extent to which the tissue deforms in response to applied force (Bergmann Tiest & Kappers, 2009; Di Luca, 2011; Srinivasan & LaMotte, 1995; Vincentini & Botturi, 2009). The inverse of compliancy is stiffness, a measure of material resistance to force applied through tension or compression. In effect, compliancy is a ratio between the amount of force applied and material displacement. While vision offers some clues for stiffness discrimination through displacement, a true perceptual understanding of compliancy can only be understood with haptic knowledge of both the force being applied and the displacement extent in response. Because a material physically deforms in response to enough applied force, stiffness and compliancy are used as measures of perceived object fragility (Srinivasan & LaMotte, 1995). Thus, this type of property information may specify motor adjustments that need to be made in order to not damage materials. Stiffness may provide perceptual information regarding the structural capacities of pliable materials such as soft tissues. For MIS surgeons, being able to accurately interpret biomechanical information and apply appropriate force magnitudes onto tissue is critical for successful patient outcomes and for minimizing tissue trauma.

It was hypothesized that the malleable nature of soft tissue during force application provides information that specifies tissue failure, and MIS surgeons could use this biomechanical information to guide continued force applications. Deformable soft tissue will extend and compress to a maximal point at which the structural integrities will fail, resulting in tissue trauma; proficient MIS skill requires the ability to understand the structural limits through haptic interaction and then apply the correct amount of force. Past work has shown that kinesthesis is sensitive to mechanical parameters that are specific to (i.e. lawfully related to) the properties of explored objects and surfaces (e.g., Carello, Silva, Kinsella-Shaw & Turvey, 2008; Carello & Turvey, 2000; Gibson, J. 1966; Pagano & Cabe 2003; Pagano Fitzpatrick & Turvey 1993; Turvey, 1996). In the case of MIS, force interaction through the surgical tools yields information regarding structural properties, even though force perception is degraded. Tissues are perceived as becoming increasingly stiff with increasing amounts of force, providing information that more stress will likely lead to failure. By applying force onto materials such as soft tissue, surgeons may be able to take advantage of some mechanical relationship which denotes changing compliancy and ultimately, information specifying the remaining distance until the tissue structure will fail. Thus, it was hypothesized that via information gained through force application on deformable tissue, one could reliably identify the displacement point at which an additional load would cause breakage. The perceptual relationship between force applied and deformation rate of soft tissue specifies that structural capacity is about to fail, or indicates it is "about to break". This force-based information, available via the muscular sense, is analogous to a relationship in visual perception where observers take advantage of an optically specified invariant that denotes the time remaining until they will reach a surface that they are approaching.

Past work has suggested that haptic and visual perception are guided by similar principles, and thus variables employed during visual perception can be used to inspire the discovery of analogous haptic variables and vice-versa (Cabe, 2011; Cabe & Pittenger, 1992; Garret, Barac-Cikoja, Carello & Turvey, 1996). Lawful relationships within one perceptual modality have been demonstrated to share parallel underpinnings in another, in effect establishing that perceptual systems may share similar dependencies on property information when making observations, whether they are visual or haptic. Using visual perception to uncover analogous variables used in haptic perception is particularly useful for understanding the mechanical properties of distal objects and material information of surfaces via a mediating tool or probe, when touch is used as a "distal" sense (Cabe, 2011; Garret et al., 1996). In the following section we used an optical variable specifying "time-to-contact" to inspire an analogous kinesthetic variable which informs an actor as to when a manipulated tissue is about to break. Specifically, we suggested that in both cases, the optic and haptic information is governed by a similar higher-order invariant relationship. We then proposed two experiments to investigate the possibility that this variable could be employed within a haptic MIS simulation to provide sufficient information for perceiving penetration distance remaining until tissue failure.

Time-to-Contact and Distance-to-Break

In visual perception, there is information in the optical array that a moving observer takes advantage of to determine their time-to-contact with a surface they are approaching (Gibson 1947/1982; Hoyle, 1957; Lee 1976; Lee & Reddish, 1981). Objects in the visual field occupy a given amount of area on the retina, and this amount of area fluctuates continuously and dynamically as an observer moves within their environment. As an observer approaches an object the rate of expansion of the object's projection gives the time remaining until the observer will contact the object (assuming that their velocity remains constant). The optical information is referred to as "time-to-contact" (TTC) and since its discovery TTC "has become one of the best researched topics in perceptual psychology" (Hecht & Savelsbergh, 2004, p1).

As an example of TTC consider an individual approaching a stop sign. As the observer approaches the sign it subtends a larger and larger amount of space in the visual field. As the sign occupies more area on the retina, as the sign "looms" on the retina, the distance between the observer and the sign is perceived to decrease (see Figure 1). The area in the visual field occupied by the sign increases at a rate that is determined by both the speed of approach and the distance remaining until contact. This rate of expansion relative to the area in the visual field occupied by the sign is:

$$\textit{Relative Rate of Expansion} = \frac{\Delta\, Area / \Delta\, Time}{Area}.$$

The inverse of this relative rate of expansion specifies TTC, and is expressed as:

$$TTC = \frac{Area}{\Delta\, Area / \Delta\, Time}.$$

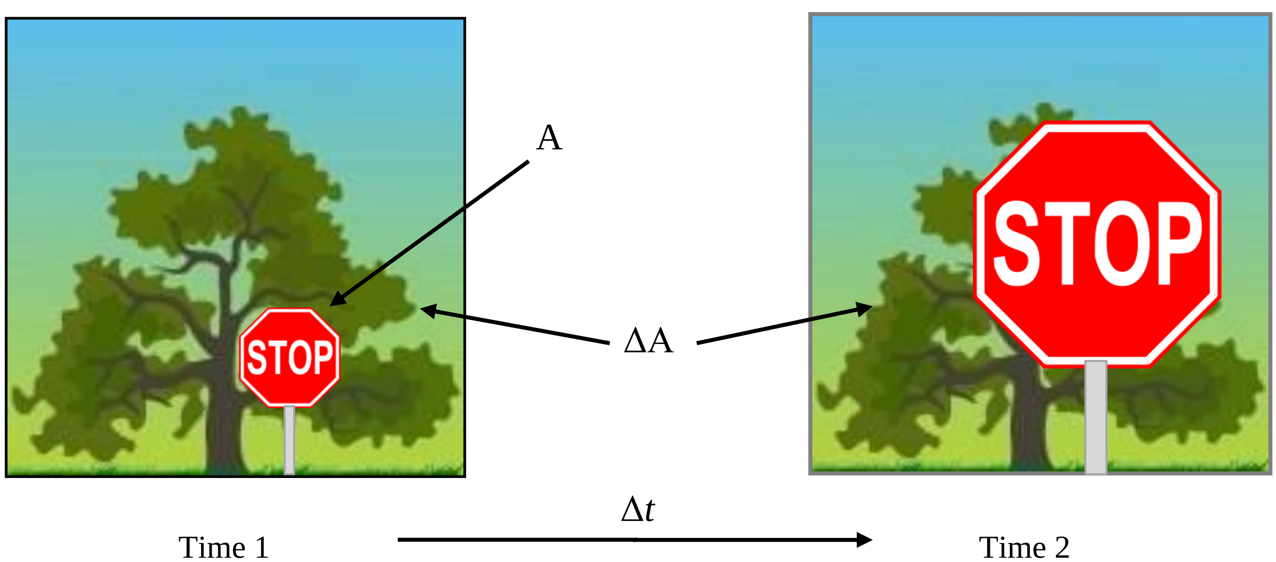


Figure 1. Example demonstrating TTC.

TTC is an optically specified higher-order variable denoting the time remaining until the distance between the observer and object reaches zero assuming that velocity remains constant. If subjects are sensitive to TTC then the time remaining before contact can be perceived without knowledge of lower-level variables such as object distance, approach velocity or object size.

The relationship between an object's distance and the size of its projection on the retina is expressed in Figure 2. As the distance between the object and observer decreases the area of the object subtended onto the visual field increases exponentially. This continues until distance = 0, whereby the area of the visual angle is completely filled (i.e. the object fills the visual field). If the approach velocity of a moving observer is held constant then the relationship between time to contact and optical area is identical to the relationship between object distance and area depicted in Figure 2.

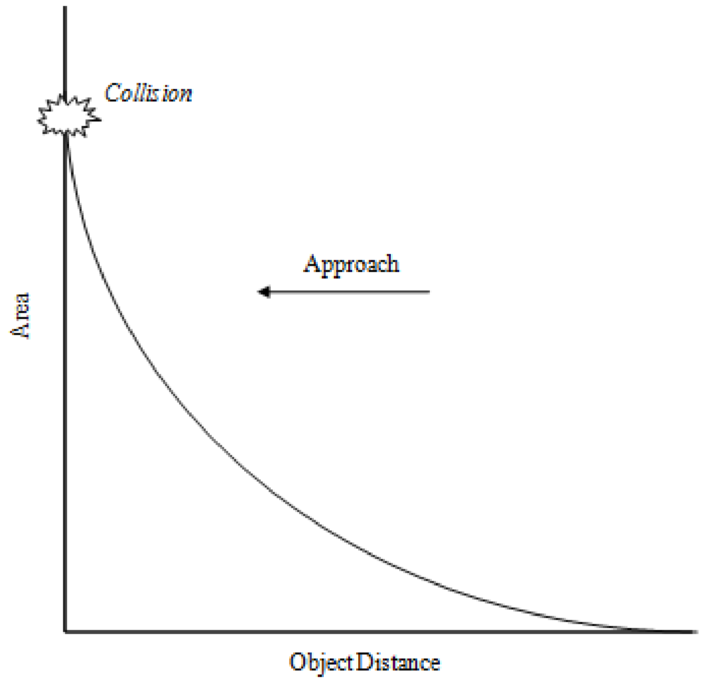


Figure 2. Relationship between an objects distance and the size of its projection on the retina.

Just as TTC judgments are directly specified in the optic array, judgments regarding material breaking point are specified in the haptic array. Compliancy is perceived through surface deformation and through the ratio of contact force to material displacement (Bergmann Tiest & Kappers, 2009), both of which provide information for the perception of material fragility (Srinivasan & LaMotte, 1995). Determined by material stiffness, the extent of tissue displacement in response to applied force may offer information specifying the remaining distance until the material fails, which surgeons may be perceiving in soft tissue in order to apply the appropriate amounts of force. In response to compressive or tensile force, many soft tissues follow an exponential stress-strain pattern (Brouwer, Ustin, Bentley, Sherman, Dhruv & Tendick, 2001; Carter, Frank, Davies, McLean, & Cuschieri, 2001; Fung, 1993; Rosen, Brown, De, Sinanan & Hannaford, 2008; Tamura, Omari, Miki, Lee, Yang, & King, 2002). As the distance into soft tissue progresses towards the point of breakage, the reactionary forces generated by the tissue increase in a nonlinear fashion until the structure can bear no more strain. At this point, the structural limit of the tissue is breached and the tissue breaks (Rosen et al., 2008; Yamada, 1970). The relationship between applied force and tissue displacement is expressed schematically in Figure 3, with the point of breakage being denoted as a displacement, or distance, of zero. Note the similarity between this relationship and the optical relationship depicted in Figure 2.

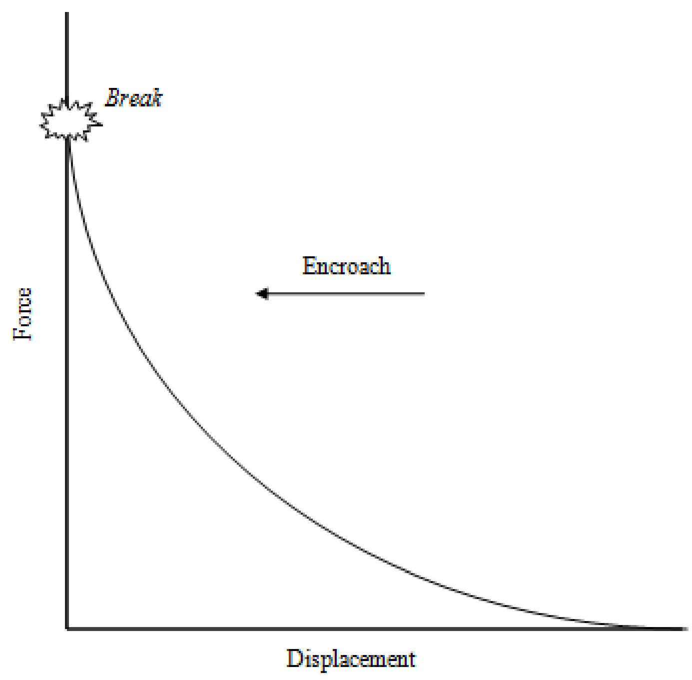


Figure 3. Relationship between material displacement and mechanical force required for that displacement.

It is possible that this relationship provides the haptic information necessary to perceive the penetration distance remaining until tissue failure, or Distance-to-Break (DTB). The change in unit of applied force per change in unit of tissue displacement may convey the physical constraints of nonlinear tissue, providing adequate information indicating the maximal force load the material can withstand. This relationship may denote the particular point of discontinuity that specifies DTB. The inverse of this relationship can be expressed as:

$$DTB = \frac{Force}{\Delta\, Force/\, \Delta\, Displacement}.$$

DTB is a ratio of amount of force applied to the change in reactionary force over amount of displacement. As force is continually applied onto a compliant material, deformation behavior in response provides information denoting the degree of additional displacement which can be tolerated before failure. This haptically specified information is an invariant relationship available in the material and obtained through physically acting on the compliant mass. Like TTC, DTB requires no knowledge or mental calculations of lower-order physical variables such as the reactionary force of the material or distance traveled into the material.

Perception of haptic invariants, such as DTB, is dynamic and movement-based, such that observers must expend energy and act upon the physical space for the information to become available. In effect, active exploration reveals invariants specifying the consequence of those actions (e.g., Barac-Cikoja & Turvey, 1993; Gibson, 1966; Pagano et al., 1993, 1996; Turvey, 1996). For instance, when assessing virtual surfaces, users tend to maintain a constant penetration force in their haptic exploration patterns. Known as the *force-constancy hypothesis* (Choi et al., 2005), observers use kinesthetic perception through lateral motions to perceive landscape distortions. By applying force during exploration, observers can identify and attune to the important mechanical invariant properties within the haptic array. In the case of TTC, the area of the optical object subtended onto the visual field only changes in response to movements. Thus, the information specifying TTC at any particular temporal instant is only available as the distance between optical object and observer is changing. This relationship is unavailable when behavior is stationary and is only perceptible as the observer is actively moving within their environment. Similarly, information denoting DTB becomes available only as the perceiver operates on their environment by acting on a material causing surface deformation. This type of active haptic exploration, referred to as "dynamic touch", is reliant upon biomechanical effort to extract available information within the haptic array (Gibson 1966, Pagano 2000; Pagano & Cabe, 2003; Pagano et al., 1993; Pagano & Turvey, 1998; Turvey 1996). Muscular energy is exerted for force application, thereby stimulating kinesthetic receptors in muscles, joints and connective tissues, which is proposed to denote the distance remaining before mechanical failure of the material.

Kinesthetic perception of the resulting changes in perceived tissue reactionary force per rate of change of tissue displacement may yield haptic information specifying DTB, which we predicted would be used by observers to estimate the deformation distance compliant materials could withstand before failure. Active contact with the material and the resulting rate of deformation per unit of force applied provides information to the observer regarding tissue pliability and stiffness. The relationship between the force applied by the observer and the nonlinear reactionary behavior of the material specifies DTB, which informs the user about material strength, which is used to modify further contact forces. In the case of MIS, DTB offers information of tissue constraints which surgeons need to be particularly adept at perceiving through haptic exploration with surgical tools. Surgical environments include a wide range of soft tissues, all with differing levels of stiffness and deformation rates. Surgeons must be particularly skilled at attaining DTB in order to correctly identify differing tissues, apply the precise amounts of force, and minimize tissue trauma.

Purpose and Overview

The proposed experiments were designed to investigate whether observers were able to perceive DTB in nonlinear compliant materials through haptic force application and then use this information to identify the distance remaining until mechanical failure. First, we hypothesized that observers would be sensitive to DTB and thus be able to estimate the location of mechanical failure. Even as stiffness varied between materials and material profiles differed, the necessary mechanical information would be available and detectable through force application. Second, it was hypothesized that the ability to locate DTB was a perceptual skill that could be improved through training. With feedback, observers could be trained to attend to specific mechanical property information in a haptic array (e.g., J. Gibson, 1966; E. Gibson, 1969), which we hypothesized would improve sensitivity to the useful DTB information available. Finally, it was hypothesized that identifying the haptic invariant of DTB was a perceptual skill affected by experience. Observers with more experience interacting with compliant materials through force application would be better than less experienced observers at identifying and using DTB. These three hypotheses were explored through two experiments.

While DTB is hypothesized to be perceptible in any nonlinear physical material that can be haptically explored through force application, the present research focused on the haptic forces similar to those experienced in MIS. Because proficient performance in MIS is so dependent upon force perception, surgeons must be particularly skilled in using haptic information to make decisions and guide further interactions. Surgeons interact with a range of nonlinear soft tissues with differing mechanical profiles and then must be able to use this haptic information to apply precise amounts of force without damaging tissue. Previous research has identified and validated a set of core haptic skills used in MIS where precise knowledge of tissue strengths and application of forces is imperative for proficient performance (Singapogu, DuBose, Long, Smith, Burg, Pagano, et al., 2013; Singapogu, Smith, Long, Burg, Pagano, & Burg, 2012b). The three skills identified were grasping, probing, and sweeping. Grasping is gripping and squeezing the surgical tool handles as tissue is handled and compressed in the tool jaws; probing is using the tool to push into and penetrate tissues; and sweeping is applying force to brush and move aside tissues and materials as tissue is repositioned.

Previous work and research within our lab has led to the development of a simulator able to emulate the three core haptic skills tasks used in MIS (Singapogu et al., 2012a; 2012b; 2013). Using standard instruments in MIS, observers apply forces onto simulated tissues through one of the core haptic actions. Haptically, they feel contact with and increasing resistance from a simulated compliant mass as they apply more force through the surgical tool. Biomechanical factors such as material stiffness and failure location can be independently altered to model real soft tissue parameters. Using a simulator and virtual materials for the current research, as opposed to live tissue, permitted precise control over tissue compliancy and location of breaking points, as well as ensured material profiles would be the same across observers.

Perception of DTB was explored through tensile force loading and specifically addressed in MIS through the simulated probing task. In most MIS interactions surgeons explore tissues with a high degree of pushing, prodding and palpations, whereas too much force can stretch tissue beyond capacity. Just like any compliant material, applying too much uniaxial force to tissue through stretching will sever the structural integrity and result in failure (Fung, 1993; Rosen, Brown, De, Sinanan, & Hannaford, 2008; Yamada, 1970).

Two experiments using the core haptic skills simulator examined the proposed perceptual theory of DTB in MIS. The purpose of the first experiment was to investigate whether observers were able to reliably perceive DTB in nonlinear tissues rendered by the core haptic skills simulator. Experiment 1was also conducted to assess the effects of training on the perception of DTB. Using a feedback-calibration training model, it was investigated whether sensitivity to the haptic information specifying DTB would be improved. Experiment 2 explored whether the perception of DTB was improved by experience by investigating skilled surgeons and assessing whether they were significantly better than the novices from Experiment 1 at identifying DTB.

CHAPTER TWO

EXPERIMENT ONE

If useful mechanical DTB information becomes available as observers haptically explore a compliant material through force application, then this information should be sufficient regardless of the specific nonlinear profile for a particular type of tissue. As stiffness varies between different soft tissues, observers should be able to haptically perceive *the point at which the tissue will fail* by attending to DTB. The higher-order mechanical relationship between applied force and material displacement contained in the nonlinear profiles would be sufficient for specifying DTB, even as the nonlinear material profiles were randomly presented without visual feedback. The first purpose of Experiment 1 was to discern whether DTB is perceptible even as lower-order variables were varied from trial to trial by simulating various tissues that break at different values of force and displacement.

With practice, it is possible to increase the observers' reliance on perceptual invariants and train them to become more sensitive to specific information in the haptic array (E. Gibson, 1969; J. Gibson, 1966). Haptic information available in the environment for tactile and kinesthetic perception is limitlessly rich, and sensory systems are continually exposed to sensations that may or may not convey useful perceptual information about object properties. Through experience and feedback within these stimulus-rich environments, haptic perception over time becomes "tuned" to those mechanical properties that are lawfully related to perceptual variables, known as specifying variables. These useful mechanical features become differentiated from the vast collection of available and ambiguously-related stimuli within the haptic array as perceptual systems identify those features as being lawfully related to useful object properties. Referred to as the "education of attention" (E. Gibson, 1969), perceivers learn to isolate and attend to, or *attune* to, those salient invariants that specify information. Through the same feedback process, the specifying information is also correctly scaled for accurate perceptual judgments. With experience, the magnitude of the perceptual system's output is adjusted, or metrically scaled to, the mechanical properties. That is, haptic perceptual systems are *calibrated* such that the use of the specifying information results in accurate perceptual judgments. Perceptual training through attunement and calibration has been used in training observers to perceive specific kinesthetic properties of physical objects (Long, Singapogu, DuBose, Arcese, Altenhoff, Burg, et al., 2012; Singapogu, et al., 2013; Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2005). Through a feedback and calibration perceptual training model, sensitivity to mechanical qualities specifying material properties can increase and observers can be trained to differentiate and attune to specific invariant properties over a host of mechanical qualities. With regard to DTB, attunement and calibration training may improve the ability of observers to perceive the mechanical information specifying the location of material failure points. The second goal of Experiment 1 was to improve the accuracy of kinesthetic perceptual judgments of DTB by increasing the sensitivity to the mechanical features specifying DTB and improving the scaling of those specifying variables.

The simulated haptic skill of probing was evaluated over two tasks in Experiment 1. Task 1 was an exploratory break detection phase where participants were allowed to freely explore various simulated materials through force application, and then indicate the location at which they believe the material feels as if it should break. This task encouraged participants to haptically survey each material by applying force both below and beyond the theoretical mechanical yield point of the simulated material. With the same purpose of some flight simulators, the haptic skills simulator permitted learning how to behave with the virtual material through imperfect force application in a manner with no real consequences. Thus they can break and re-break the same materials a number of times in order to learn how the material feels as the break point is approached. Task 2 used virtual nonlinear materials containing true breaking points and determined whether participants were able to detect DTB while applying force *without* breaking the simulated material. For this task, participants were instructed to stop applying force to the simulated materials before reaching the mechanical failure point; their goal was to move as close as possible to the break point without actually breaking the tissue, or in a sense, perceive the breaking point location *before* actually perforating the material. Instructions explained the task as being similar to “stretching a rubber band as far as you can without breaking it” or “moving as close as you can to the edge of a cliff without falling off the edge”. The purpose of the new task was to determine if training from the original task would transfer to more realistic simulated materials that actually broke.

A pre-feedback, feedback-training, post-feedback, transfer-of-training paradigm was employed in Experiment 1. Data collected from the pre-feedback phase was used to address the first hypothesis. To evaluate effects of the calibration training model and address the second hypothesis, accuracy of haptic judgments were compared between pre- and post-feedback phases. Finally, the transfer of training phase evaluated the degree to which to feedback calibration training affected DTB attunement in a task more representative of real-world MIS, and further validated the training capability of the Core Haptic Skills Trainer.

Methods

The Institutional Review Board of Clemson University approved the described protocols and materials of Experiment 1.

Participants.

A total of 29 Clemson undergraduate students participated in Experiment 1 (16 females, 13 males; mean age = 19.3, SD = 0.95).

Undergraduate students were recruited using an online Clemson University participant pool system and received course credit for participation. None of the participants had any experience practicing MIS, and all participants used their preferred, or verbally indicated dominant, hand throughout the entire experiment.

Materials & Apparatus.

Simulator. Nonlinear soft tissues were rendered using the Core Haptic Skills Trainer, a simulator developed at Clemson University for the purpose of training force-based skills in laparoscopic surgery. Earlier prototypes led to the development of the current simulator, which emulates three different force-based skills identified as particularly salient in minimally invasive surgery; grasping, probing, and sweeping (see Singapogu et al., 2011, 2012a, 2012b, 2013). Probing was used in the present study.

The force-based skills were integrated into a comprehensive simulator containing a single input device permitting the user to make discrete probing, grasping, and sweeping motions (see Figure 4). The input device was a laparoscopic surgical forceps tool with a scissor grip handle whose pinchers were removed (a Covidien Autosuture™ Endo® device, Dublin, Ireland). A robotic motion system delivered force feedback to the input device through two direct-drive DC motors (Tohoku Ricoh™, Miyagi 987-0511, Japan) located at the center and the end of the forceps shaft. Through a series of computer algorithms, the system renders force feedback by generating a torque in response to user motion.

Haptic feedback rendered by the simulator emulates the tool coming into contact with and encroaching into an amenable mass, such as soft tissue. For probing, the user applies force through the input device by gripping the handles of the input device and pushing the tool forward. Advancing the tool produced feedback imitating coming into contact with and then pushing onto soft tissue, effectively simulating the tensile forces experienced as one stretches soft tissue.

Task 2 was designed to present haptic feedback in which the simulated material would truly ‘break’, or fail, when excessive force was applied. As the user applied more force through the input tool, resistive force feedback increased in an exponential rate. Once the applied force became great enough, resistive feedback rendered by the simulator immediately ceased, emulating a soft tissue perforation.

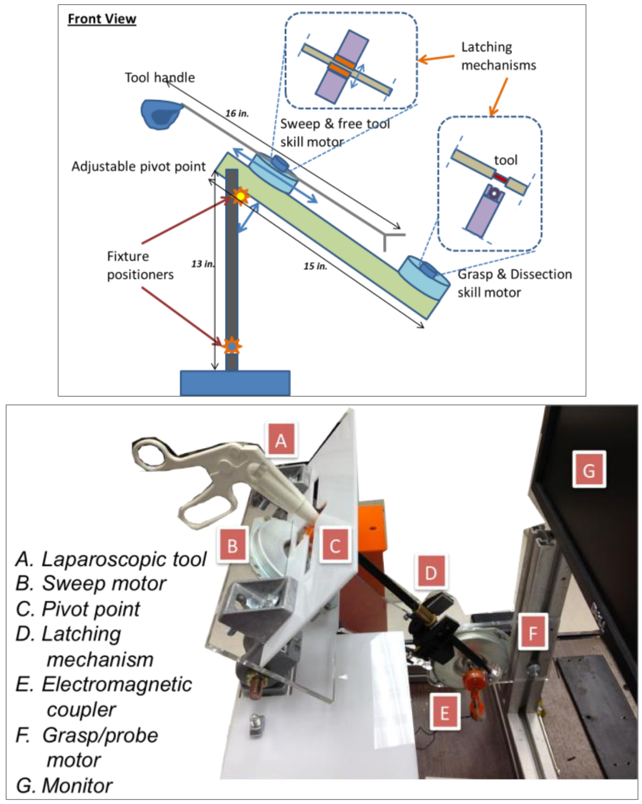


Figure 4. Schematic and photographic representation of the Core Haptic Skills Training Simulator (reprinted from Singapogu, et al., 2013).

Visual Feedback. Visual feedback was incorporated into a feedback training phase allowing participants to view errors and then adjust, or calibrate, their force application after each trial. The feedback was in the form of a custom visual graphic displayed on a computer monitor that denoted penetration distance of the tool into the current simulated material (see Figure 5). The graphic included a black horizontal bar indicating probe distance with a vertical bar indicating break point. A dynamic indicator marker, proportional to the placement of the tool, moved along the bar in response to increasing and decreasing applied force. As the observer applied more or less force through the surgical input tool, the marker dynamically repositioned across the length of the bar in response. At the starting position, the marker was located at the far left; as force was applied, the marker moved from left to right. Because the breaking point for each simulated material was relative to the material profile itself (described in detail below), the indication for break point in the graphic was static and only the application force required to move the indicating marker varied. Thus, the location of the break point in the graphic did not change; only the application force required to move the indicating marker varied. Using this graphic, participants were able to visually view their haptic force estimates as they located the designated breaking point, but also view their performance as they produced excessive force.

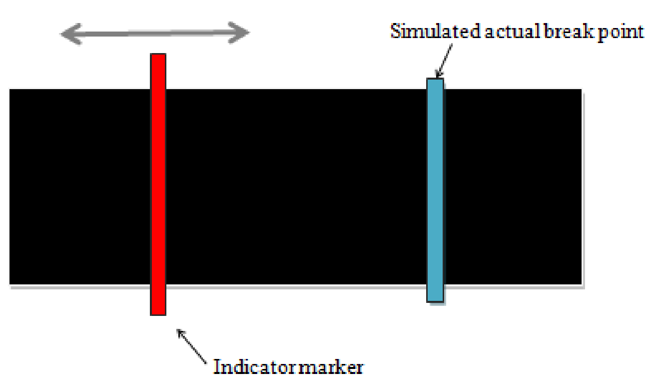


Figure 5. Visual graphic used in calibration feedback phase.

Simulated Material Profiles. Nine different nonlinear materials were simulated on the basis that many soft tissues exhibit exponential stress-strain relationships in response to compressive and tensile force loadings (Brouwer, et al., 2001; Fung, 1993;

Rosen, et al., 2008; Tamura, et al., 2002). The nine compliance profiles and breaking points were designed to be the product of three different material strengths (*F*) at three different displacement locations (*d*) (see Figure 6). Thus each material contained a different point of failure, or location at which it would 'break'. Constructing the simulated tissue profiles in this way permitted the profiles to vary along one dimension while remaining constant along the other, as the breaking point for each material was manipulated by modifying the relationship between force and displacement. It was hypothesized that observers would not rely solely upon one varying dimension or the other when determining DTB, but would rely on the invariant relationship between the two of them. Therefore, as one dimension was modified and the true breaking point changed, the relationship was still maintained, which would be sufficient for specifying DTB.

Numbers were assigned to the nine different material profiles for nomenclature and analysis purposes. Figure 6 displays the numbers used to refer to each material profile. The nine materials were grouped into the three displacement (*d*) categories of low, medium, and high (1, 2, & 3; 4, 5, & 6; and 7, 8, & 9; respectively) and the three material reactionary strength (*F*) categories of low, medium, and high (1, 4, & 7; 2, 5, & 8; and 3, 6, & 9; respectively).

Actual construction of the simulated material profiles resulted in one of the profiles having a distinctly different break point distance (profile #9; explained in more detail below). Therefore, in actuality, nine different simulated profile break points were based on three reactionary force locations and four different displacement locations (see Figure 7). The nine profiles were used in pre-feedback, post-feedback, and transfer phases while only five were used during the feedback phase (see Figure 9). Table 1 displays all of the parameters defining the nonlinear characteristics for each material profile, including break point distance and reactionary force.

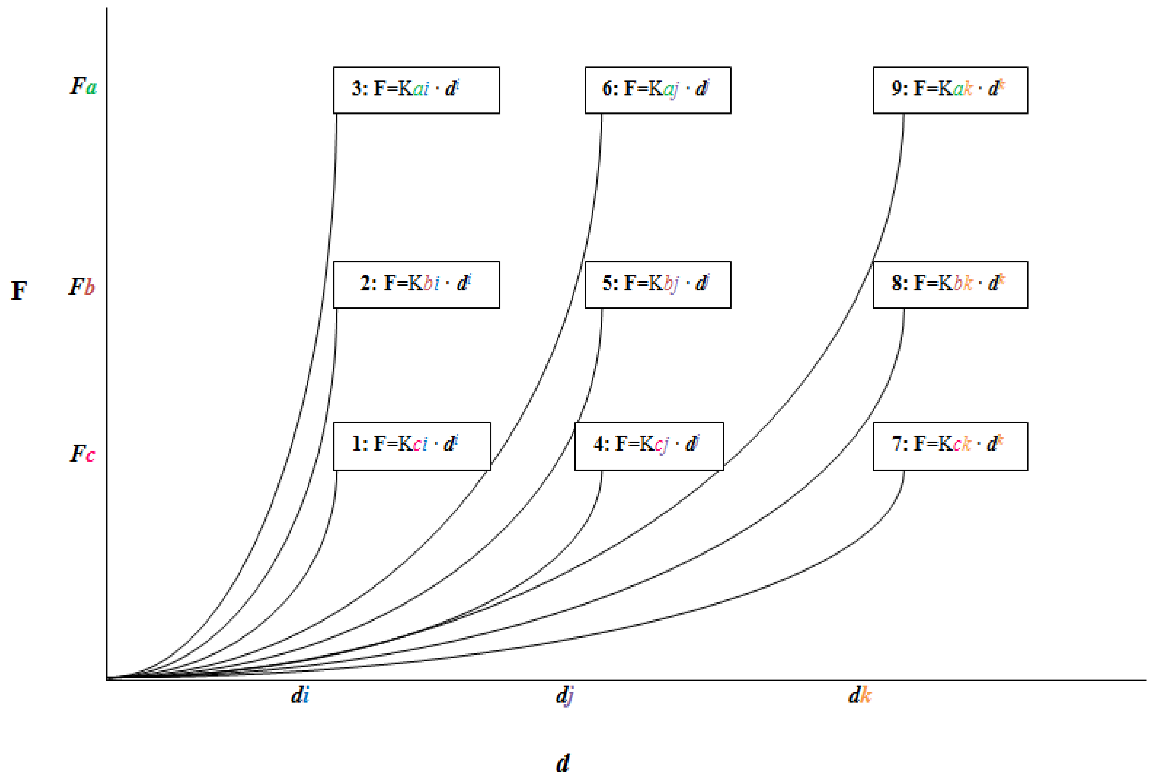


Figure 6. The nine simulated material profiles and their designated breaking point location, as they were originally conceptualized.

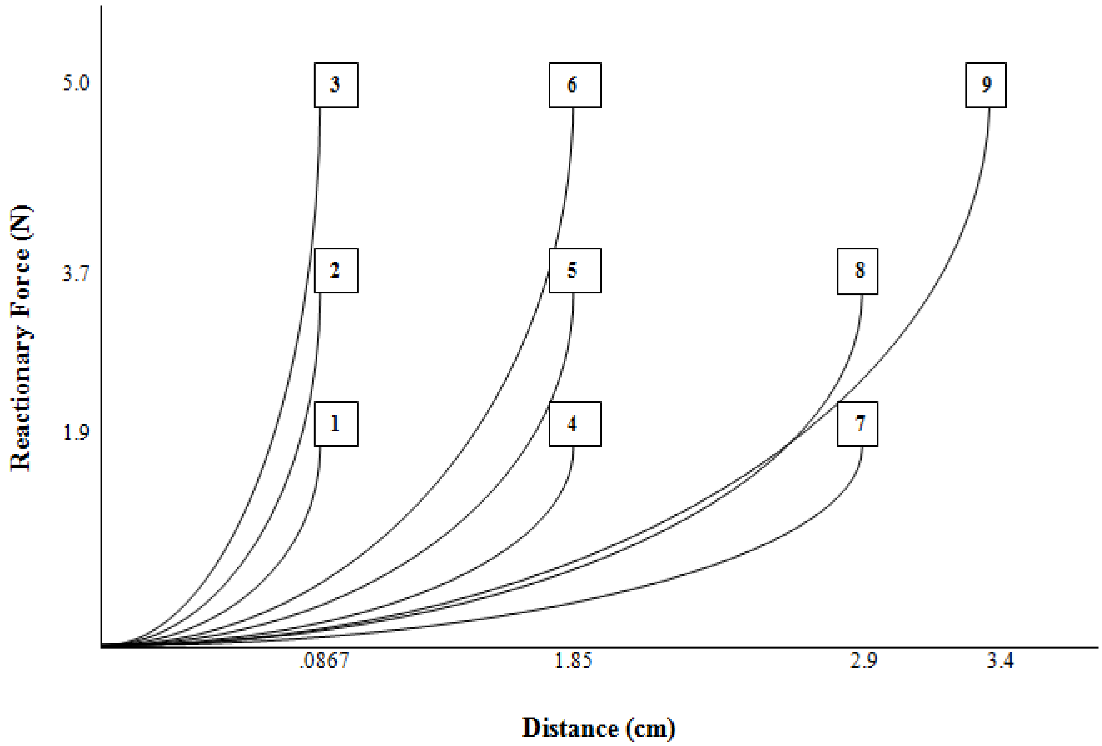


Figure 7. The nine simulated material profiles and their respective break point locations as they were actually displayed in Experiments 1 and 2.

Procedure.

This experiment utilized a pre-feedback, feedback-training, post-feedback, transfer-of-training model. The pre-feedback phase was used as a pre-training baseline. Calibration feedback training was evaluated through comparisons between the pre- and post- phases. An additional transfer task evaluated the degree to which DTB perceptual skill would carry over to a novel simulated task. During an initial day of testing, participants completed study-related paperwork, became introduced to the experiment, completed an introductory training phase, and completed the pre-feedback phase. Within seven days following the initial testing, participants returned for the second day of testing, where they completed the feedback-training, post-feedback, and transfer phases.

On the first day of testing, after completing informed consent and a series of demographics questions (see Appendix B for the demographics questionnaire use in Experiment 1), participants viewed a brief PowerPoint presentation providing an overview of the experiment and the tasks they were to complete. Before experimental phases, an introductory training phase presented two versions of a single nonlinear material which participants were allowed to survey. The purpose of this phase was to allow participants to understand the basic nonlinear properties of the virtual materials as well as become comfortable with the laparoscopic tool. First participants explored the version of the nonlinear material containing a true breaking point. The material increased in stiffness as applied force increased, before excessive force caused the material to truly break, emulating puncture. The second version presented to participants was the same simulated material profile, though did not contain a true breaking point. The participants used their verbally-indicated dominant hand in all trials.

1. Pre-feedback phase. For the first task, participants freely explored simulated materials by applying forces up to and beyond a hypothetical break point with the goal of identifying the location along the profile where the material felt as if it should rupture (see Figure 8).   With no visual feedback and using the laparoscopic input tool, participants were presented with a virtual tissue and applied force onto the material to identify the location of the breaking point as if the material were real. Participants made estimates of the location within the material by suspending their force application and verbally designating their estimate to the experimenter. As soon as participants indicated their judgment, the experimenter immediately pressed a key on a keyboard to capture their performance estimate through distance (in simulator-based encoder units, explained in more detail below). In addition, an experimenter recorded distance values by hand, which were displayed on a nearby computer monitor attached to the simulator and not visible to participants. Once data had been recorded, the trial ended and participants returned the surgical tool to the starting position.

Nine different nonlinear materials were presented to participants three times each in a random order. As described earlier, the nonlinear virtual materials were presented with stiffnesses and breaking points that varied (see Figure 7). Participants completed a total of 27 trials (9 total materials x 3 presentations), and performance was evaluated by the accuracy of break point position estimates.

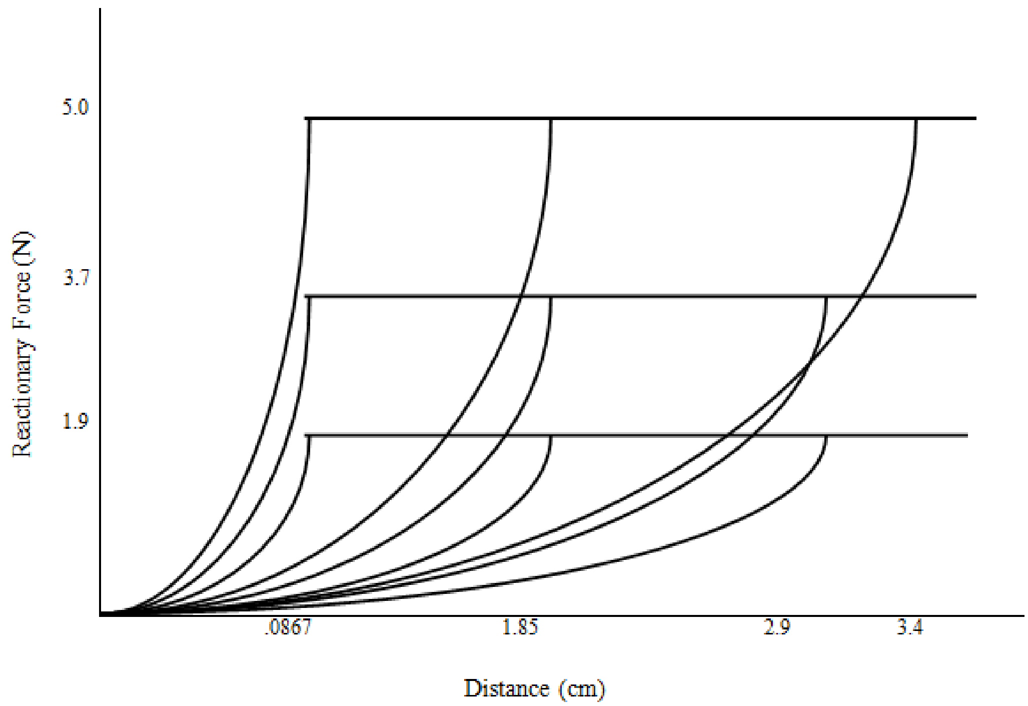


Figure 8. Nine simulated material profiles and their hypothetical break point locations used in the pre-feedback and post-feedback phases of Experiment 1.

2. Feedback training phase. The training phase used the same procedures as the pre-feedback phase, but incorporated a visual feedback graphic to allow participants to calibrate their haptic estimate, and utilized only five of the nine experimental tissue profiles. The feedback training phase was completed approximately 5 days after the pre-feedback phase (M = 5.17, SD = 1.88).

Explicit instructions informed participants that the goal of training was to learn to apply sufficient force onto each simulated profile without ‘breaking’ the material. They were informed that later phases would be scoring excessive force application as an error and that identifying the failure point should be occurring *before* reaching the breaking point.

Similar to the pre-feedback phase, participants indicated the location of the hypothetical breaking point, though also viewed a visual graphic providing real-time feedback of their performance allowing them to calibrate and make adjustments to their haptic estimate (see Figure 5). The task was to locate the designated breaking point along the five nonlinear materials depicted in Figure 9, again applying the amount of force they believed was required to puncture, or break, the material. There was no actual breaking point present and participants were encouraged to freely explore the material by applying force while honing in on their estimate. With each trial, participants viewed their real-time performance in the form of a visual graphic (see Figure 5) displayed on a monitor directly in front of them. This information allowed participants to view and make corrections to their haptic judgment by adjusting the amount of force applied onto the tool. Once participants felt comfortable that they could locate the break point, they indicated their haptic estimate by again pausing their force application and verbally signifying their judgment. An experimenter captured their performance by pressing the space bar and recorded the performance metrics by hand. The visual graphic was then removed, the tool was returned to its starting location, and the next trial began. Participants completed 30 trials (5 profiles x 6 presentations) presented randomly.

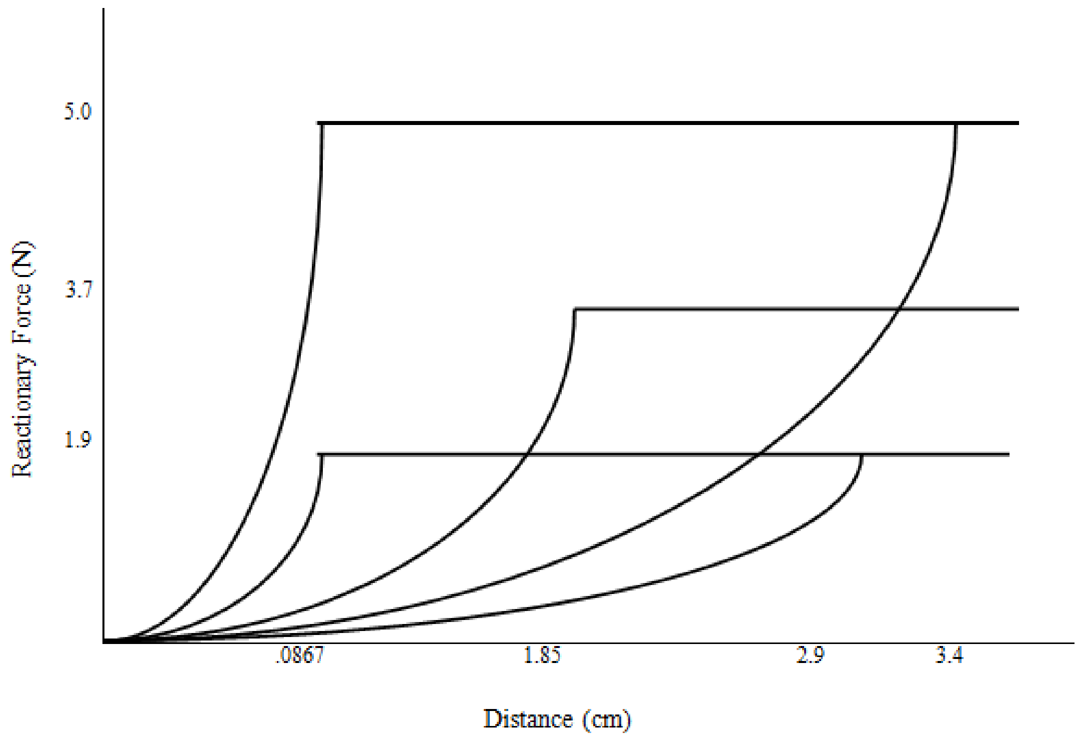


Figure 9. The five material profiles and their hypothetical break point locations used in the feedback phase of Experiment 1.

3. Post-feedback phase. Participants were required to take a five-minute break between concluding the feedback-training phase and beginning the post-feedback phase. The post-feedback phase implemented the same protocol used in the pre-feedback phase and used the same nine simulated profiles (see Figure 8). Observers completed a total of 27 trials (9 materials x 3 presentations) in the absence of any visual feedback.

4. Transfer-of-Training Task. Participants were required to take a five-minute break between concluding the post-feedback phase and beginning the transfer-of-training phase. The transfer task was similar to the tasks in the three prior phases except the designated break location within the simulated profiles was rendered to truly emulate breakage. As participants applied force onto the material, the reactionary force of the material increased until a certain point at which the material was programmed to fail (see Figure 10), haptically emulating puncture. Participants were instructed to apply as much force as they could onto different materials *without* breaking the material. A comparison was also given to participants during instructions: like being near the edge of a cliff, their goal was to inch as close to the edge as possible without going over. Any breaks were marked as an error and terminated the trial. The same nine nonlinear tissue profiles used in the pre- and post-training phases were used for this additional task, and the breaking points occurred at the displacement location where the material function approached an asymptotic direction (see Figure 7). Trials in which participants applied excessive force and caused the tissue to break were moved to the end of the list of profiles presented and were repeated. The participants repeated trials where they broke the simulated tissue until they successfully completed the 27 trials (9 materials x 3 presentations). Performance was assessed by the proximity of force application to the breaking point and the number of tissue breaks. The transfer-of-training task was completed immediately after the feedback training phase.

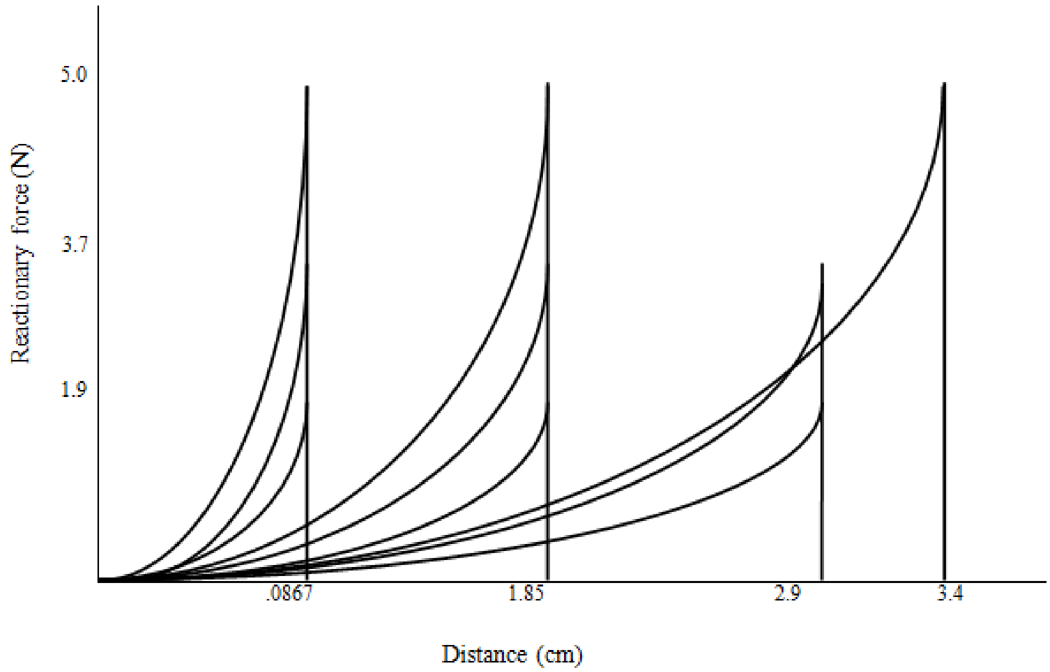


Figure 10. The nine virtual material profiles and their respective actual break point locations used in the transfer task of Experiment 1.

Metrics for Analysis.

Distance. Displacement traveled by the input device into the simulated materials was presented by the simulator in terms of encoder units. Encoder units ranged from 0 – 148.1, and the three encoder unit values designated as breaking points were 33, 66, and 99.

Encoder units were transformed into centimeters by first physically measuring the absolute distance traveled by the input tool until the breaking point for each of the nine material profiles. While the break point locations in encoder units were located at 33, 66, and 99, measuring the absolute distance traveled by the input tool revealed four distinct break point locations that reliably corresponded to the nine materials. The materials were designed to break at three distinct distance intervals (.0867, 1.85, and 2.90 cm), though profile #9 broke at an absolute distance of 3.40 cm (though still corresponding to 99 encoder units). This material was extreme in design because it required the farthest distance and largest applied force before the break point was breached (see Figure 7), and it was hypothesized that the excessive parameters of this particular profile caused a slight inaccuracy in the haptic rendering algorithm of torque generation from the motors.

To accommodate for the discrepancy with profile #9, the absolute distance traveled by the input tool was used to scale up the respective encoder units for analysis. Essentially, for profile #9 the break point of 99 EU was transformed into a value that was appropriately scaled to break at a centimeter distance of 3.40. A simple mathematical transformation was conducted and is demonstrated below:

$$\frac{\boldsymbol{Distance(cm)}}{\boldsymbol{Distance\ (EU)}} = \frac{\mathbf{2.9}}{\mathbf{99}} = \frac{\mathbf{3.4}}{\boldsymbol{x}}.$$

Where $\frac{\mathbf{3.4}}{\mathbf{.0292}} = \boldsymbol{x}$, and $\boldsymbol{x} \cong \mathbf{116}$.

Thus, the EU breaking point for material #9 was changed from 99 to 116. The encoder units recorded for each individual’s performance with that single profile were correspondingly transformed by a scaling factor of 1.16 EU to accommodate for the modified breakpoint.

Both EU and cm distance metrics are displayed in Table 1. Linear regression analysis predicting the four cm distance values (0.867, 1.85, 2.90, and 3.40 cm) from the four encoder units (33, 66, 99, and 116) provided a model with which encoder units could be transformed into centimeters. Appendix A includes the linear regression model by which distance in centimeters were calculated.

Force. Reactionary force rendered by the simulator was presented in terms of rendered voltage and transformed into Newtons. Rendered voltage was used in the profile design of the simulated materials. The parameters for material breaking point were in part defined by the maximum voltage to be rendered by the simulator; thus, three set voltages defined the reactionary behavior by the simulator: 3.8, 7.4, and 10 V. Voltages were directly recorded as output from the simulator, and then transformed into Newtons via the following equation:

$$\boldsymbol{Force}\ (\boldsymbol{N}) = \frac{\boldsymbol{Torque}}{\boldsymbol{radius}} = \frac{\boldsymbol{K}\,\tau \bullet i}{\boldsymbol{radius}} = \left[\frac{\boldsymbol{K}\,\tau}{\boldsymbol{radius} \bullet \boldsymbol{R}}\right]\boldsymbol{V},$$

where $\tau = \frac{(0.0571+0.044)}{2} = 0.051\,\frac{\mathrm{Nm}}{\mathrm{A}}$, and $R = 2.4395$. From this, force was indirectly estimated via:

$$\boldsymbol{Force}\ (\boldsymbol{N}) = \mathbf{0.5}\boldsymbol{V}.$$

Reactionary force in terms of both voltage and Newtons are displayed in Table 1.

Table 1. Metric qualities defining each simulated profile.

Material Profile	**K**	**Power**	**Distance at break point**		**Reactionary force at break point**	
			Encoder units	*Centimeters*	*Voltage*	*Newtons*
1	2.133	8	33	.0867	3.8	1.9
2	4.646	6	33	.0867	7.4	3.7
3	7.589	4	33	.0867	10.0	5.0
4	1.913	10	66	1.85	3.8	1.9
5	1.666	8	66	1.85	7.4	3.7
6	1.089	6	66	1.85	10.0	5.0
7	3.384	12	99	2.9	3.8	1.9
8	6.634	10	99	2.9	7.4	3.7
9	9.754	8	116	3.4	10.0	5.0
Sample	1.000	8	66	1.85	7.4	3.7

Accuracy. Accuracy was defined as the difference between the perceived, or participant indicated, breaking point location and the actual breaking point location of the simulated material profiles (estimated location – actual location). For Task 1 containing profiles that only contain hypothetical breaking points and do not truly fail, the difference could be positive, indicating that observers applied more force than necessary to break the material (excessive force application causing excessive displacement), or negative, indicating that participants did not apply enough force to break the material (conservative force application). For Task 2, in which profiles truly do fail with excessive force application, accuracy would only be negative among trials considered for analysis, since estimates must be short of the true break location.

Absolute error was also a measure of accuracy and was defined as |estimated location –actual location|.

Results.

Three participants either did not return to complete the second part of the study or experienced technical difficulties during data collection. Thus, a total of 26 participants completed all phases of Experiment 1.

Data Exclusions. Four trials were removed due to erroneous or incomplete simulator readings, or an indication that the participants applied zero force. Exclusions are displayed in Table 2.

Table 2. Trial exclusions in Experiment 1.

Participant	Phase	Trial	Material	Encoder units
110	Pre	2	3	-9.411
110	Pre	25	3	1.486
102	Feedback	19	9	0.9916
126	Feedback	13	5	0.495

Outlier analysis. Before conducting analyses, the standardized residuals of haptic distance estimates were analyzed and used to identify outlying data for the pre-feedback, feedback, post-feedback, and transfer task phases. Linear regression models predicting haptic distance estimates from actual distance were conducted for each phase to obtain standardized residuals. Because the tasks were inherently perceptual, a more conservative approach to trial removal was preferred. Using ±4 as a limit was more inclusive and resulted in a total of 19 trials being removed from the pre-feedback, feedback, and post-feedback phases of Experiment 1 (0.64%). Had ±3been set as a cutoff for standardized residuals of distance estimates, trial exclusion would have increased to 9,23,11, and 5 for the pre-feedback, feedback, post-feedback, and transfer phases, respectively (48 total;1.63% of total trials). Table 3 shows the individual trials that were removed from Experiment 1as a result of standardized residuals being greater than ±4.0.

Table 3. Outlying distance estimate trials removed from Experiment 1 analyses.

Phase		**ID**	**Trial**	**Profile**	**Actual Distance (cm)**	**Distance estimate (cm)**	**Standardized residual**
Pre	1	113	10	1	.0867	6.82	4.77
	2	113	11	1	.0867	6.71	4.66
	3	113	15	4	1.85	6.83	4.04
Feedback	1	101	13	5	1.85	2.32	5.71
	2	101	25	9	3.4	3.76	4.88
	3	101	28	1	0.867	1.61	8.42
	4	108	16	1	0.867	1.23	4.20
	5	108	17	7	2.9	3.28	4.97
	6	117	3	1	0.867	1.38	5.89
	7	119	6	1	0.867	0.49	-4.09
	8	121	6	7	2.9	3.29	5.14
	9	121	7	3	0.867	1.23	4.20
Post	1	106	6	6	1.85	5.06	4.31
	2	106	11	1	.0867	5.47	6.17
	3	128	3	9	3.4	0.74	-4.23
Transfer	1	107	5	9	3.4	2.35	-4.05
	2	107	24	9	3.4	1.88	-6.89
	3	109	1	9	3.4	1.31	-10.27
	4	110	2	9	3.4	2.31	-4.26
Total	19						

Performance. Following outlier removal, performance was assessed by analyzing displacement into the simulated material via distance in centimeters. Means and standard deviations of distance estimates are displayed by material type and experimental phase in Table 4.

Table 4. Experiment 1 break point distance estimate means and standard deviations by profile type and experimental phase.

Metric	Profile	Actual Distance	Pre		Feedback		Post		Transfer	
			M	±SD	M	±SD	M	±SD	M	±SD
Distance (cm)	1	.0867	2.24	±1.11	0.85	±0.08	1.45	±0.72	0.82	±0.03
	2	.0867	2.17	±1.17			1.41	±0.80	0.76	±0.05
	3	.0867	1.95	±1.00	0.83	±0.07	1.30	±0.70	0.65	±0.08
	4	1.85	2.95	±0.90			2.33	±0.57	1.80	±0.06
	5	1.85	2.94	±0.94	1.83	±0.06	2.30	±0.61	1.69	±0.09
	6	1.85	2.66	±0.94			2.06	±0.57	1.55	±0.11
	7	2.9	3.84	±0.83	2.84	±0.08	3.23	±0.46	2.75	±0.09
	8	2.9	3.64	±0.71			3.08	±0.48	2.62	±0.13
	9	3.4	3.93	±0.74	3.30	±0.07	3.43	±0.57	2.87	±0.14
	Overall		2.93	±1.17	1.93	±1.01	2.29	±0.99	1.72	±0.83
n trials			**778**		**777**		**699**			**691**

Perception of DTB. To evaluate the contributors to perceptual estimates of distance, simple regression models were used to determine the slopes and intercepts of the functions predicting indicated distance for each participant and for each experimental phase, and then comparing the contributions of actual target distance and actual force. The slopes, intercepts, and r^2 values for both metrics for each participant across the pre-feedback, feedback, post-feedback, and transfer phases of Experiment 1 are displayed in Tables 5a, 5b, 5c, and 5d, respectively. Perfect performance estimating target distance would result in a r^2=1, slope = 1, and intercept =0 for actual distance and r^2=0 for force.

Table 5a. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant during the pre-feedback phase in Experiment 1.

	Pre					
	Distance			*Force*		
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept
101	.354**	.543	2.406	.077	-.181	4.093
102	.396**	.554	2.317	.001	.022	3.329
103	.849**	.970	.873	.032	-.134	3.217
104	.737**	.789	1.38	.025	-.104	3.527
105	.802**	.856	.901	.070	-.048	2.721
106	.602**	.843	2.321	.181*	.331	2.777
107	.804**	.963	.591	.023	.118	2.031
108	.757**	.785	1.633	.022	.094	2.749
109	.990**	.972	.056	.001	.016	1.872
110	.963**	.94	.023	.008	.063	1.701
111	.481**	.653	2.572	.123	-.236	4.667
112	.989**	.962	.028	.000	.010	1.848
113	.189*	.445	4.44	.428**	-.509	7.237
114	.064	.266	3.598	.076	-.207	4.842
115	.854**	.950	.108	.031	-.129	2.396
116	.718**	.635	1.825	.039	-.106	3.426
117	.596**	.842	.998	.018	-.105	2.991
118	.547**	.703	1.184	.087	-.201	3.248
119	.655**	.674	1.649	.001	.019	2.880
120	.405**	.758	1.852	.178*	-.359	4.584
121	.687**	.992	.863	.012	.092	2.451
122	.362**	.557	1.819	.056	-.157	3.446
123	.901**	.840	.844	.004	-.041	2.610
124	.580**	.763	1.462	.008	-.065	3.161
125	.947**	.932	.043	.011	-.070	2.088
126	.372**	.496	2.481	.000	-.010	3.473
127	.827**	.670	1.615	.001	.012	2.863
128	.710**	.666	2.395	.007	.048	3.508
129	.841**	.834	.316	.052	-.149	2.451
Mean	**0.65**	**0.75**	**1.47**	**0.05**	**-0.07**	**3.18**
SD	**0.25**	**0.18**	**1.09**	**0.09**	**0.16**	**1.13**

**p*<.05; ***p*<.01

Table 5b. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant during the calibration feedback phase in Experiment 1.

	Calibration					
		Distance			*Force*	
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept
101	.996**	.952	.143	.003	.040	1.880
102	.988**	.961	.074	.000	.008	1.90
103						
104	.999**	.968	-.010	.008	.066	1.673
105						
106	.994**	.981	.005	.007	.062	1.726
107	1.0**	.983	-.043	.009	.070	1.655
108	.997**	1.0	.050	.003	.044	1.873
109	1.0**	.971	-.031	.010	.072	1.636
110	1.0**	.973	-.041	.011	.077	1.613
111	.996**	.970	-.042	.009	.069	1.633
112	1.0**	.988	-.017	.010	.073	1.681
113	.999**	.981	-.005	.008	.067	1.70
114	.999**	.975	-.035	.009	.068	1.654
115	1.0**	.978	-.027	.010	.074	1.647
116	.999**	.974	-.026	.010	.072	1.648
117	.996**	.961	.047	.002	.034	1.864
118	.999**	.9799	-.026	.011	.077	1.641
119	.999**	.972	-.008	.003	.038	1.815
120	.999**	.969	-.022	.011	.075	1.626
121	.999**	.976	-.013	.032	.131	1.462
122	.988**	.978	.153	.003	.037	1.958
123	1.0**	.983	-.045	.010	.073	1.642
124	.997**	.983	-.031	.008	.064	1.688
125	.999**	.963	-.006	.008	.064	1.674
126	.996**	.985	.033	.006	.057	1.788
127						
128	.999**	.975	-.019	.011	.077	1.638
129	.999**	.969	.000	.009	.069	1.674
Mean	**1.00**	**0.97**	**0.00**	**0.01**	**0.06**	**1.71**
SD	**0.00**	**0.01**	**0.05**	**0.01**	**0.02**	**0.11**

*p<.05; **p<.01

Table 5c. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant during the post-feedback phase in Experiment 1.

	Post-feedback					
	Distance			*Force*		
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept
101	.588**	.738	1.411	.024	.107	2.455
102	.746**	.907	1.627	.000	-.002	3.381
103						
104	.723**	.845	1.134	.035	-.134	3.237
105						
106	.625**	1.025	1.062	.001	.030	2.980
107	.993**	.914	.060	.002	.029	1.719
108	.949**	.927	.035	.017	-.090	2.140
109	.987**	.924	.026	.002	.028	1.709
110	.966**	.939	-.008	.005	-.047	1.968
111	.576**	.564	1.717	.000	-.011	2.845
112	.968**	.897	.065	.007	-.053	1.981
113	.285**	.386	1.685	.039	-.103	2.793
114	.310**	.319	2.751	.036	-.078	3.640
115	.963**	.917	.159	.009	-.064	2.153
116	.729**	.722	1.165	.050	-.136	3.037
117	.984**	1.005	.008	.000	-.006	1.967
118	.855**	.821	.693	.013	-.072	2.530
119	.877**	.964	.506	.005	-.050	2.543
120	.957**	.930	.088	.005	-.048	2.050
121	.854**	.724	.702	.000	-.009	2.131
122	.974**	.937	.192	.000	-.001	2.004
123	.923**	.880	.388	.019	-.089	2.401
124	.960**	.968	.284	.003	-.037	2.282
125	.991**	.945	-.029	.000	.010	1.757
126	.803**	.844	.633	.007	-.057	2.463
127						
128	.527**	.857	.985	.042	.169	2.001
129	.968**	.940	.112	.002	.029	1.823
Mean	**0.81**	**0.84**	**0.67**	**0.01**	**-0.03**	**2.38**
SD	**0.21**	**0.18**	**0.72**	**0.02**	**0.07**	**0.54**

*p<.05; **p<.01

Table 5d. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant during the transfer task phase in Experiment 1.

Transfer							
	Distance			*Force*			Count of breaks
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept	
101	.981**	.861	-.009	.011	-.065	1.879	1
102	.956**	.872	-.033	.003	-.036	1.810	6
103							
104	.958**	.892	-.041	.011	-.068	1.863	6
105							
106	.982**	-.050	.935	.001	-.023	1.835	6
107	.963**	.827	.065	.012	-.064	1.835	5
108	.963**	.858	.006	.011	-.066	1.894	2
109	.989**	.929	-.045	.012	-.073	1.947	4
110	.980**	.930	-.063	.015	-.079	1.952	5
111	.981**	.964	-.069	.001	-.022	1.867	5
112	.965**	.900	-.046	.011	-.070	1.935	0
113	.965**	.860	.008	.007	-.054	1.856	3
114	.978**	.889	.012	.011	-.069	1.987	5
115	.973**	.895	-.008	.020	-.096	2.112	9
116	.977**	.917	-.043	.004	-.045	1.890	9
117	.964**	.874	.022	.005	-.047	1.874	6
118	.983**	.886	.062	.009	-.064	2.045	13
119	.981**	.903	-.047	.001	-.022	1.773	7
120	.982**	.902	.013	.001	-.021	1.827	9
121	.985**	.914	.021	.000	-.009	1.816	6
122	.984**	.934	-.022	.001	-.016	1.836	7
123	.982**	.919	.014	.009	-.064	2.052	10
124	.974**	.881	.034	.000	.006	1.676	9
125	.985**	.923	.015	.018	-.012	1.835	21
126	.975**	.917	-.027	.005	-.049	1.913	5
127							
128	.971**	.916	-.031	.006	-.051	1.954	15
129	.973**	.881	.011	.002	-.029	1.813	5
Mean	**0.98**	**0.86**	**0.03**	**0.01**	**-0.05**	**1.89**	**6.88**
SD	**0.01**	**0.19**	**0.19**	**0.01**	**0.03**	**0.09**	**4.40**

Note. For transfer phase, trials resulting in a material break were not included in analyses. *p<.05; **p<.01

To assess the contributors to the perceptual estimates of distance during the pre-calibration phase, multiple linear regression analyses were conducted using the independent variables of actual distance (.0867, 1.85, 2.9, and 3.4 cm) , actual force (1.9, 3.7, and 5 N), and the interaction between the two to predict the produced haptic distances of observers. The overall model was significant, $F(3,774) = 145.13$, $p < .001$, yielding an $r^2 = .36$. Coefficients for actual distance, actual force, the interaction term, and intercept are displayed in Model 1 of Table 5. There was a main effect of actual break point distance, though not for actual force or the interaction. As a result, the interaction term was dropped and the analysis was repeated. The resulting model was also significant, $F(2,775)=217.97$, $p<.001$, and produced an $r^2=.36$. With no interaction term, both actual distance and actual force were significant predictors of haptic distance estimates, and coefficients are displayed in Model 2 of Table 6. Actual break point distance explained the majority of variance in distance estimates, 35%, while actual force accounted for only 1%. A visual depiction of the predictive relationship of both actual distance and actual force is displayed in Figure 11

Table 6. Multiple regression models of actual break distance, actual force, and the interaction on estimated distance for the pre-feedback phase in Experiment 1.

Model	**Variable**	***b***	**se *b***	***t***	**r^2 contribution**
1	Actual distance	.775	.115	6.74**	.35
	Actual force	-.088	.062	-1.42	.01
	Interaction	-.002	.029	-.072	
	Intercept	1.76	.240	7.29**	
	Note: r^2 = .36, adj. r^2 = .358, *F* = 145.123**, df = 3,774; *n* = 778				
		b	**se *b***	***t***	**r^2 contribution**
2	Actual distance	.767	.037	20.78**	.35
	Actual force	-.092	.026	-3.48**	.01
	Intercept	1.770	.119	14.92**	
	Note: r^2 = .36, adj. r^2 = .358, *F* = 217.97**, df =2,775; *n* = 778				

*p < .05, **p<.01.

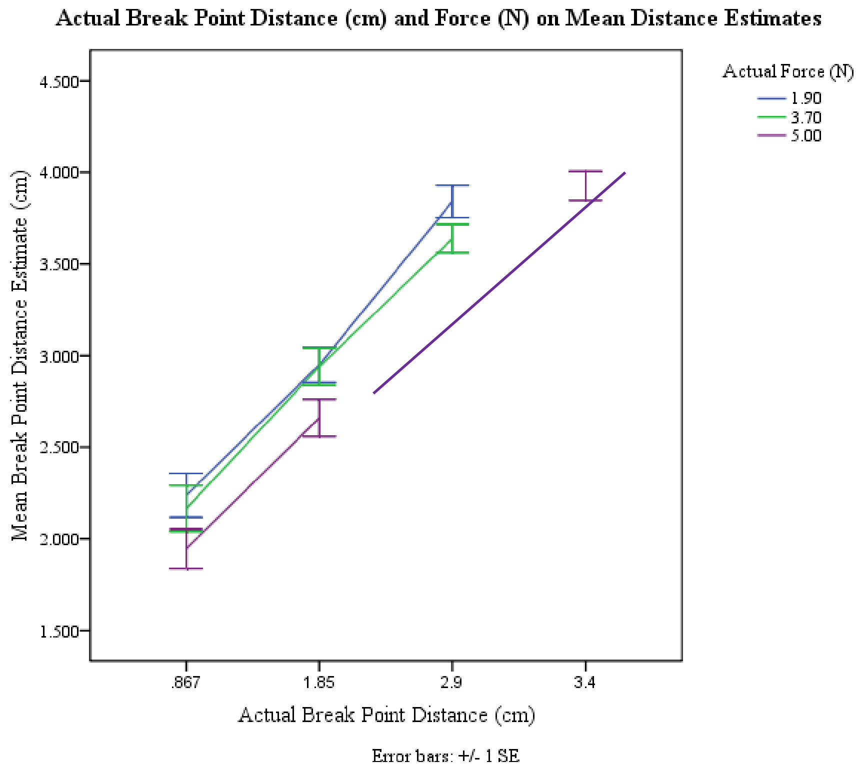


Figure 11. Actual break point distance and actual break point force on distance estimations during the pre-feedback phase of Experiment 1.

In the transfer phase using Task 2, where profiles truly did break with excessive force application, participants were required to undershoot their haptic estimates as they applied force onto materials. It was of interest to assess the relative distance 'remaining' before breakage following each estimate and whether participants were attuning to a mechanical relationship relative to each profile. The percentage of residual distance was calculated for each profile by dividing the absolute error of each estimate by the actual length of each respective profile. Average residual percentages are listed in Table 7 and the average residual distance position is approximately displayed in Figure 12.

Table 7. Mean relative residual distance remaining before breakage in the transfer task (Task 2) of Experiment 1.

Profile	Actual Break Location		Residual Distance (cm)	
	Distance (cm)	Reactionary Force (N)	M	SD
1	.0867	1.9	5.85%	±3.28%
2	.0867	3.7	11.91%	±5.94%
3	.0867	5.0	25.15%	±9.27%
4	1.85	1.9	3.06%	±2.87%
5	1.85	3.7	8.58%	±5.06%
6	1.85	5.0	16.17%	±5.84%
7	2.9	1.9	5.11%	±3.02%
8	2.9	3.7	9.77%	±4.59%
9	3.4	5.0	15.55%	±4.18%
n trials			688	

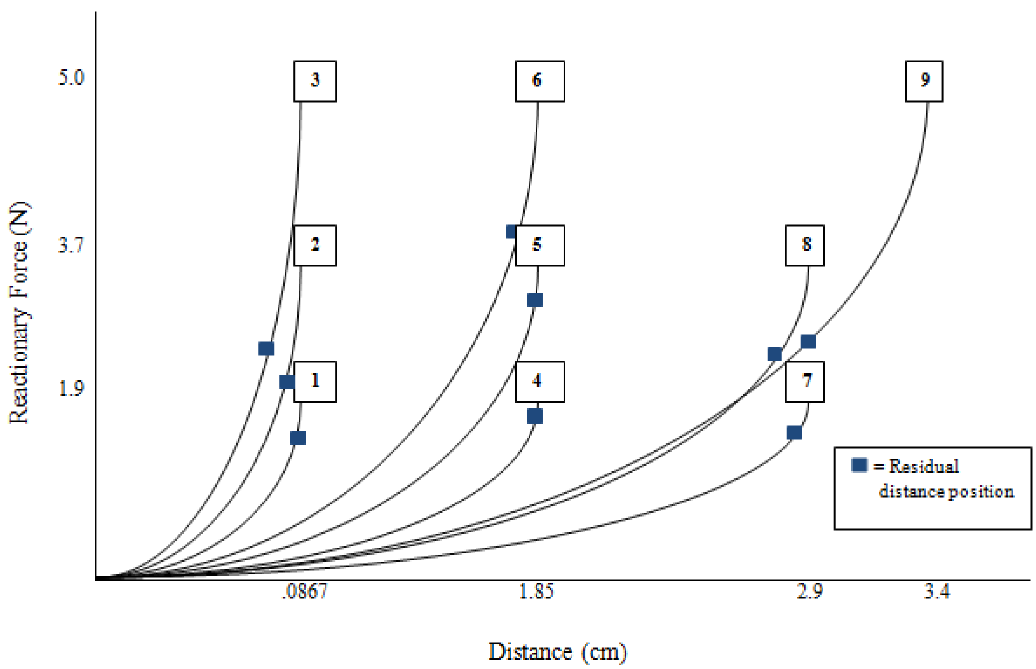


Figure 12. Approximate average relative residual distance remaining before breakage during Task 2 of Experiment 1.

Effects of Calibration and Attunement. Multiple linear regression was conducted for the post-feedback phase performance data to asses any improvements in the perception of DTB following the calibration training. The independent variables of actual distance (.0867, 1.85, 2.9, and 3.4 cm), actual force (1.9, 3.7, and 5 N), and the interaction between the two were used to predict the indicated haptic distances of observers. The overall model was significant, $F(3,695)=362.35$, $p<.001$, yielding an $r^2=.61$. Coefficients for actual distance, actual force, the interaction term, and intercept are displayed in Table 8 (Model 1). Again, actual break point distance significantly predicted haptic estimates of distance and explained the large majority of variance in observer distance judgments (53%). There was no significant effect of actual force, which accounted for under 1% of the variance in estimations. Lastly, there was no significant interaction between the two nor did the interaction term contribute any percentage of explained variance to the overall model. Consequently, the interaction term was dropped and the analysis was repeated with only the independent variables of actual distance and actual force (Model 2 in Table 8). The resulting model was again significant, $F(2,696)=544.05$, $p<.001$ with a $r^2=.61$, demonstrating an increase of 25% for the overall model r^2 following the feedback calibration phase. Actual break point distance was again a significant predictor of haptic distance estimates. With no interaction term actual force became a significant predictor of break point distance estimates, though still only accounted for less than 1% of the total explained variance. A visual depiction of the predictive relationship of both actual distance and actual force is displayed in Figure 13.

Table 8. Multiple regression models of actual distance, actual force, and the interaction on estimated distance for the post-feedback phase.

Model	Variable	*b*	se *b*	*t*	r^2 contribution
1	Actual distance	.881	.08	11.03**	.602
	Actual force	-.050	.043	-1.16	.008
	Interaction	-.009	.02	-.455	
	Intercept	.829	.167	4.97**	
	Note: r^2 = .610, adj. r^2 = .608, *F* = 362.35**, df = 3,695; *n* = 699				
		b	**se *b***	***t***	**r^2 contribution**
2	Actual distance	.846	.026	32.95**	.602
	Actual force	-.067	.018	-3.66**	.008
	Intercept	.894	.082	10.86**	
	Note: r^2 = .610, adj. r^2 = .608, *F* = 544.05**, df =2,696; *n* = 699				

**$p<.001$

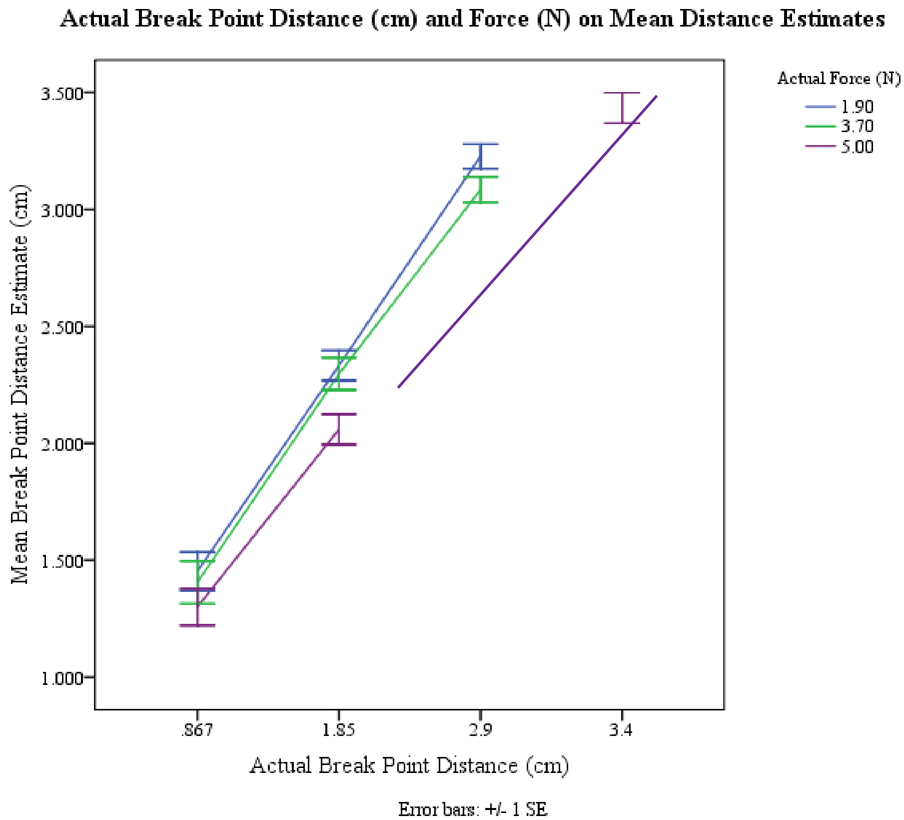


Figure 13. Actual break point distance and actual break point force on distance estimations during the post-feedback phase of Experiment 1.

The individual influence of distance in the perceptual estimates of observers also increased following calibration and attunement as the partial variance due to actual distance increased by 25.2%. This difference between pre- and post-feedback phases is visually demonstrated in Figure 14, which displays both models regressing produced distance on actual distance for both phases of Experiment 1.

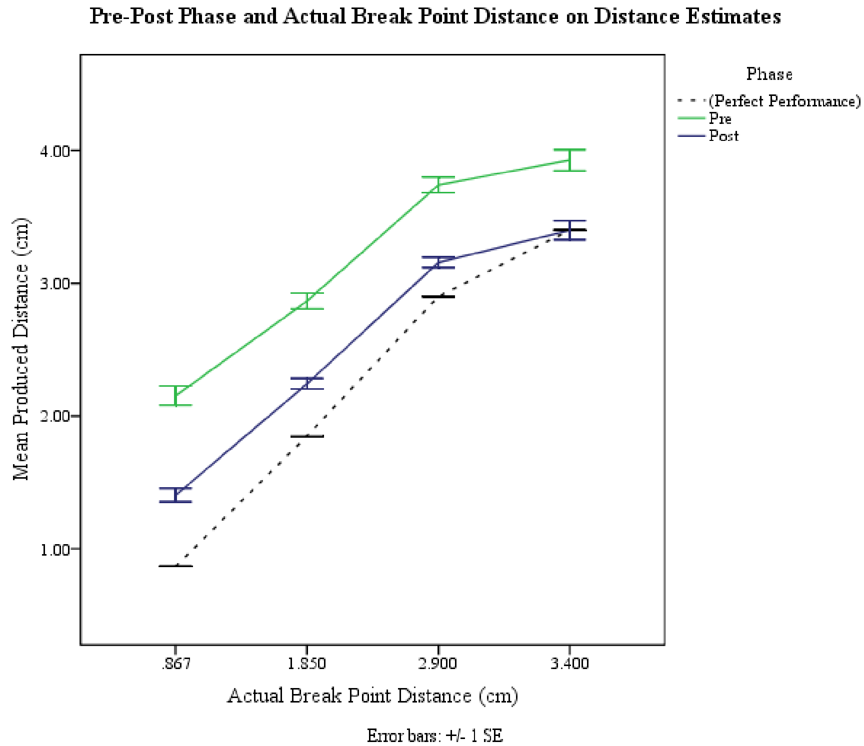


Figure 14. Influence of actual break point distance between pre- and post-feedback phases.

To assess improvements in perception of actual distance within individuals following the calibration feedback phase paired samples t-tests were conducted on the pre- and post-calibration regression coefficients of distance depicted in Tables 5a and 5c, respectively. There was a significant improvement in mean estimate accuracy following calibration for regression coefficients, indicating that estimates became more precise and were less excessive. The means for regression coefficients for both pre- and post-feedback phases are depicted in Table 9.

Table 9. Paired samples t-test comparing performance metrics between pre- and post-calibration phases of Experiment 1.

	Pre-		Post					
	M	(SD)	M	(SD)	n	r	t	df
Distance								
r^2	.63	(.25)	.81	(.21)	26	.69**	-4.69**	25
Slope	.75	(.19)	.84	(.18)	26	.64**	-3.15**	25
Intercept	1.51	(1.14)	.67	(.72)	26	.80**	6.01**	25

**p<.01

CHAPTER THREE

EXPERIMENT TWO

The forces experienced in minimally invasive surgery are fundamentally different from those experienced in open surgery. Both haptic and visual perception are mediated in MIS, and surgeons must rely on indirect perceptual information to determine mechanical properties. As a result, proficiency in MIS demands that surgeons accurately perceive mechanical properties through force application when interacting with soft tissue. Previous research has shown that experienced surgeons differ from novices in force application (Heijnsdijk, Pasdeloup, van der Pijl, Dankelman, & Gouma, 2004; Richards, Rosen, Hannaford, Pelligrini, & Sinanan, 2000; Singapogu, Smith, Long, et al., 2012; Zhou, Perreault, & Schwaitzberg, & Cao, 2008) and haptic perception of some mechanical qualities in soft tissue (Forrest, Ballie, Kalita, & Tan, 2010). Because of the reliance upon haptic perception to estimate tissue fragility, MIS surgeons must become expert at attuning to properties of compliant soft tissue that delineate failure points.

The goal of Experiment 2was to ascertain whether surgeons, who have experience with indirect haptic perception during MIS, were more sensitive to the information specifying DTB than novices. It was hypothesized that because of experience manipulating compliant soft tissue through force application, surgeons would perceive the tissue breaking point more accurately then novices. In the absence of visual feedback, they would be able to indicate the location of tissue failure with more precision than novices.

Methods

Data from Experiment 2 were collected at a large Southeastern University Medical Hospital. All described procedures and paperwork were approved by the Institutional Review Board of the hospital in conjunction with Clemson University.

Participants. Fourteen surgeon participated in Experiment 2, and were a combination of 9 residents and 5 attendings. Participation required some degree of minimally invasive surgical experience. Table 10 displays demographic information for the fourteen participants used for Experiment 2.

Surgeons were recruited via word-of-mouth, flyers, and email announcements at the hospital. Participation was entirely voluntary and no compensation was offered. All surgeons used their preferred hand during all trials.

Table 10. Demographic information for participating surgeons in Experiment 2.

	n	Mean age		Gender	Mean years practicing general surgery		Mean years practicing MIS procedures	
Resident	9	31.14	±4.10	7 males, 2 females	2.78	±2.16	1.78	±1.30
Attending	5	40.60	±5.90	4 males, 1 female	11.0	±6.20	10.20	±5.97
Overall	14	35.08	±6.73	11 males, 3 females	5.71	±5.61	4.79	±5.43

Note. ± SD

Materials & Apparatus.

Simulator. The Core Haptic Skills Trainer used in Experiment 1 was also used in Experiment 2. Using the probing haptic skills task, all participants completed two phases of trials applying force onto simulated materials.

Simulated material profiles. The same nine nonlinear materials described and used in Experiment 1 were also used in the current study (see Figure 7). For the first task participants applied force onto the version of materials used in the pre-feedback phase of Experiment 1, which contained a hypothetical, designed breaking point but did not truly break (Figure 8). The second task used the version of the materials used in the transfer task of Experiment 1, which truly emulated puncture at the break point (Figure 10).

Procedure.

Participants signed an informed consent form and completed a series of demographics questions before being briefed on the overview of the study and the two tasks they would complete (see AppendixC for Experiment 2 demographics questionnaire). Like Experiment 1, before beginning experimental trials participants were allowed to haptically explore two versions of a sample nonlinear material profile to familiarize themselves with the simulator and virtual materials. The mechanical profile between the two versions was the same, though the first truly emulated a perforation and the second did not. Participants used their dominant hand in all trials.

All participants completed two tasks on the probing haptic skills task. The first task followed the pre-feedback phase protocol described in Experiment 1. Participants freely applied force up to and beyond a hypothetical break point to identify the location along the profile where the material felt as if it should break. In the absence of visual feedback, participants used the laparoscopic input tool to haptically estimate the location along the profile where it felt as if it should rupture. Each of the nine nonlinear profiles displayed in Figure 8 were randomly presented to participants across three presentations. Thus, participants completed a total of 27 trials (9 profiles x 3 presentations).

The second task followed the same protocol for the transfer-of-training task used in Experiment 1. The nine nonlinear materials used were the same as the first task, except they were rendered to truly emulate a perforation (see Figure 10). As participants applied force onto the material, the reactionary force of the material increased until a certain point at which the material was programmed to fail, haptically emulating puncture. Participants were randomly presented with one of the nine nonlinear materials and instructed to apply as much force as possible without breaking the material. They were told to consider the task similar to one inching as close as they could toward the edge of a cliff without going over. Any breaks were recorded and marked as an error, though terminated the trial. However, those trials were moved to the end of the phase and repeated. The nine material profiles were randomly presented three times for an original, starting total of 27 trials (9 materials x 3 presentations). Performance was assessed by the proximity of force application to the breaking point and the number of tissue breaks.

Metrics for Analysis. The same metrics described in Experiment 1 were recorded and used to evaluate performance. Tool displacement was measured in encoder units and transformed into distance units (cm) using the procedure outlined in Experiment 1 and the linear model described in Appendix A. Break point force was estimated using voltage rendered and transformed into Newtons. Accuracy was also used to asses performance and was defined in the same manner as described in Experiment 1.

Results.

Two of the fourteen surgeons were unable to complete Task 2 due to time constraints.

Data Exclusions. Performance data for two trials were absent from simulator output readings and are listed in Table 11.

Table 11. Trial exclusions in Experiment 2.

Participant	Task	Trial	Material
203	1	12	5
201	2	20	3

Outlier analysis. Outliers were identified before conducting further analyses. Like Experiment 1, the standardized residuals of haptic distance estimates were analyzed and used to identify outlying data for both tasks. Linear regression models predicting haptic distance estimates from actual distance were conducted for Tasks 1 and 2 to obtain standardized residuals. Again, standard residuals ±4.0 were used as a threshold for trial exclusion and resulted in a total of 6 trials being removed from both tasks of Experiment 2 (0.86%). If ±3.0 was used as a less conservative cutoff instead, the number of outliers would have increased to 5 and 6 for Tasks 1 and 2, respectively (11 total, 1.59%). Table 12 displays the individual trials that were removed from Experiment 1 because of standardized residuals being greater than ±4.0.

Table 12. Outlying trials removed from Experiment 2 analyses.

Task		ID	Trial	Profile	Actual distance (cm)	Distance estimate (cm)	Standardized residual
1	1	206	17	1	.0867	5.19	4.21
2	1	202	4	9	3.4	166	-5.99
	2	202	8	8	2.9	1.56	-4.46
	3	202	20	9	3.4	1.57	-6.40
	4	206	20	1	.567	1.77	4.59
	5	210	23	7	2.9	3.64	5.03
Total	6						

Performance. Performance was assessed via the same metrics and methods described in Experiment 1. Observer displacement into the simulated profiles was evaluated via distance (cm). Means and standard deviations of displacement for Tasks 1 and 2 are displayed in Table 13a and 13b, respectively.

Table 13a. Experiment 2 break point distance estimate means and standard deviations by profile type for Task 1.

Task 1			
Metric	**Profile**	**Actual Break Point Distance (cm)**	**Estimated Break Point Distance (cm)**
Distance (cm)	1	.0867	1.93 ±0.99
	2	.0867	1.53 ±0.93
	3	.0867	1.24 ±0.79
	4	1.85	2.70 ±0.81
	5	1.85	2.44 ±0.87
	6	1.85	2.16 ±0.71
	7	2.9	3.42 ±0.66
	8	2.9	3.23 ±0.67
	9	3.4	3.41 ±0.67
	Overall		**2.45** ±**1.10**
n trials			**376**

Note. Performance data for this task includes trials of a participant later identified as an outlier.

Table 13b. Experiment 2 break point distance estimate means and standard deviations by profile type for Task 2.

Task 2			
Metric	**Profile**	**Actual Break Point Distance (cm)**	**Estimated Break Point Distance (cm)**
Distance (cm)	1	.0867	0.80 ±0.04
	2	.0867	0.73 ±0.06
	3	.0867	0.67 ±0.08
	4	1.85	1.80 ±0.08
	5	1.85	1.66 ±0.07
	6	1.85	1.46 ±0.16
	7	2.9	2.75 ±0.11
	8	2.9	2.61 ±0.13
	9	3.4	2.82 ±0.15
	Overall		**1.69 ±0.82**
n trials			**318**

Perception of DTB. To assess the contributors to the perceptual distance estimates of surgeons, simple and multiple regression analyses were conducted. Individual performance was assessed for Task 1 and 2 via simple linear regression analyses using both actual distance (.0867, 1.85, 2.9, and 3.4 cm) and actual force (1.9, 3.7, and 5 N), and then comparing the regression coefficients between the two independent variables. These analyses provided slopes, intercepts, and r^2 values for each surgeon in both Tasks 1 and 2, and are displayed in Tables 14a and14b, respectively. Perfect performance estimating target distance would result in a r^2=1, slope = 1, and intercept =0 for actual break point distance and r^2=0 for force.

Table 14a. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant for Task 1 in Experiment 2.

	Task 1					
	Distance			*Force*		
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept
201	.490**	.643	.204	.133	-.240	4.127
202	.922**	.790	.126	.024	-.091	1.971
203	.975**	.889	.058	.003	-.034	1.897
204	.950**	.933	.309	.006	-.053	2.296
205	.835**	.878	.606	.010	-.069	2.545
206	.396**	.585	2.969	.006	-.053	4.31
207	.323**	.687	1.447	.270*	-.450	4.361
208	.790**	.885	.375	.060	-.175	2.701
209	.735**	.758	1.191	.044	-.133	3.124
210	.860**	.859	.871	.002	-.029	2.629
211	.516**	.659	1.877	.023	-.099	3.498
212	.515**	.692	1.085	.334**	-.399	3.830
213	.934**	.882	.102	.021	-.095	2.136
214	.972**	.939	-.047	.004	-.043	1.914
Mean	**0.73**	**0.79**	**0.80**	**0.07**	**-0.14**	**2.95**
SD	**0.23**	**0.12**	**0.86**	**0.11**	**0.13**	**0.92**

*p<.05; **p<.005

Table 14b. Regression coefficients predicting observer estimated distance from actual distance and actual force for each participant for Task 2 in Experiment 2.

Task 2							
	Distance			*Force*			Count of breaks
Subject	r^2	Slope	Intercept	r^2	Slope	Intercept	
201	.975**	.907	-.022	.012	.008	1.695	6
202	.932**	.815	-.035	.007	-.047	1.482	1
203	.973**	.910	-.050	.007	-.054	1.896	2
204	.946**	.844	.022	.018	-.083	1.944	4
205	.954**	.873	.004	.009	-.061	1.904	6
206	.956**	.901	-.005	.02	2.104	-.093	0
207							0
208	.970**	.916	-.102	.007	-.056	1.861	9
209	.976**	.925	-.023	.000	.000	1.726	9
210	.966**	.868	.071	.001	-.022	1.828	4
211	.954**	.861	.012	.019	-.085	2.0	0
212							4
213	.981**	.901	.023	.002	-.026	1.852	3
214	.978**	.900	-.035	.002	-.031	1.811	0
Mean	**0.89**	**0.82**	**-0.01**	**0.01**	**0.14**	**1.66**	**3.429**
SD	**0.25**	**0.23**	**0.04**	**0.01**	**0.62**	**0.57**	**3.179**

Note. For transfer phase, trials resulting in a material break were not included in analyses. *p<.05; **p<.005

Closer examination of the individual performance coefficients revealed an exceptionally large intercept from participant #206 in Task 1. Further inspection within performance data sheets used during collection revealed uncertainties as to whether the participant truly understood instructions, as they applied nearly the maximum displacement possible for most trials. Closer inspection of participant #206 is displayed in Figure 15.

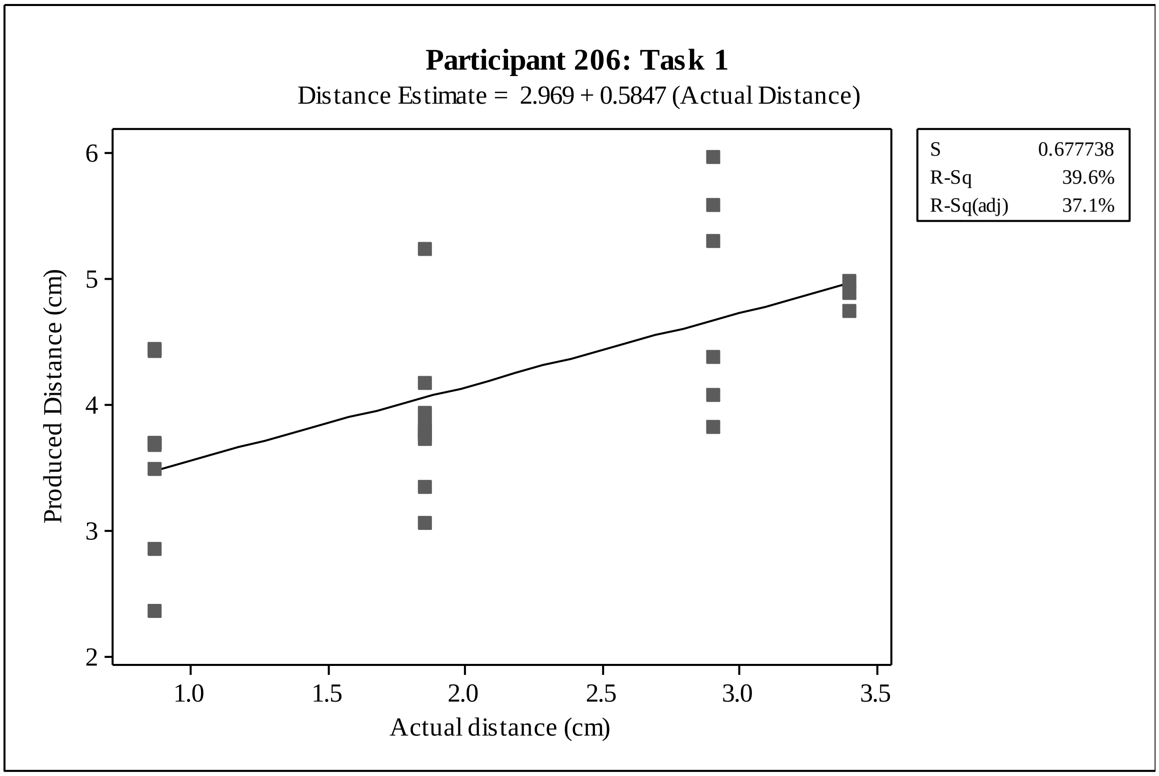


Figure 15. Linear regression of produced distance estimate on actual distance for Task 1 performance of participant 206.

As a result, it was decided to remove this participant from Task 1 analyses. The resulting mean and standard deviation for the individual regression coefficients after regression produced distance on actual distance are displayed in Table 15.

Table 15. Mean and SD for Task 1 regression coefficients after removal of participant 206 performance.

Task 1			
		Distance	
	r^2	Slope	Intercept
Mean	0.76	0.81	0.63
SD	0.22	0.11	0.61

Multiple regression analyses were also conducted to assess the contributors to perceptual distance estimates of surgeons. Using performance from Task 1, the independent variables of actual break point distance (.0867, 1.85, 2.9, and 3.4 cm), actual force (1.9, 3.7, and 5 N), and the interaction between the two were used to predict the produced haptic distances of observers. The overall model was significant, F (3,346) =168.24, p <.001, yielding an r^2 = .593. Coefficients for actual distance, actual force, the interaction term, and intercept are displayed in Model 1 of Table 16. Both actual distance and actual force were significant predictors of produced distance, though the interaction between the two was not so the term was consequently dropped from the model. Considering only the two primary independent variables, the overall model was significant as well, F(2,347)=249.82, p<.001, yielding an r^2=.590. Coefficients for actual distance, actual force, and the intercept for the repeated model are displayed in Model 2 of Table 16. Actual distance was a significant predictor and explained the majority of the variance in produced distance estimations: 53%. There was also a main effect of actual force, which accounted for nearly 6% of the variance.

Table 16. Regression models of actual distance, actual force, and the interaction on estimated distance for Task 1 in Experiment 2.

Model	**Variable**	***b***	**se *b***	***t***	**r^2 contribution**
1	Actual distance	.643	.118	5.45**	.534
	Actual force	-.282	.063	-4.45**	.056
	Interaction	.048	.030	1.64	.003
	Intercept	1.754	.246	7.14**	
	Note: r^2 = .593, adj. r^2 = .590, *F* = 168.24**, df = 3,346; *n* = 350				
		b	**se *b***	***t***	**r^2 contribution**
2	Actual distance	.826	.038	21.69**	.534
	Actual force	-.188	.027	-6.92**	.056
	Intercept	1.40	.122	11.52**	
	Note: r^2 = .590, adj. r^2 = .588, *F* = 249.82**, df =2,347; *n* = 350				

**p<.001.

Novice – Expert Comparison. Actual distance was the primary contributor of perceptual distance estimates for both novices and surgeons, so the reliance upon actual distance was compared between the two groups using performance in the pre-feedback phase of Experiment 1 and Task 1 performance in Experiment 2. Surgeons were more reliant than novices on actual distance during their initial break point estimation task, as can be seen in Figure 16.

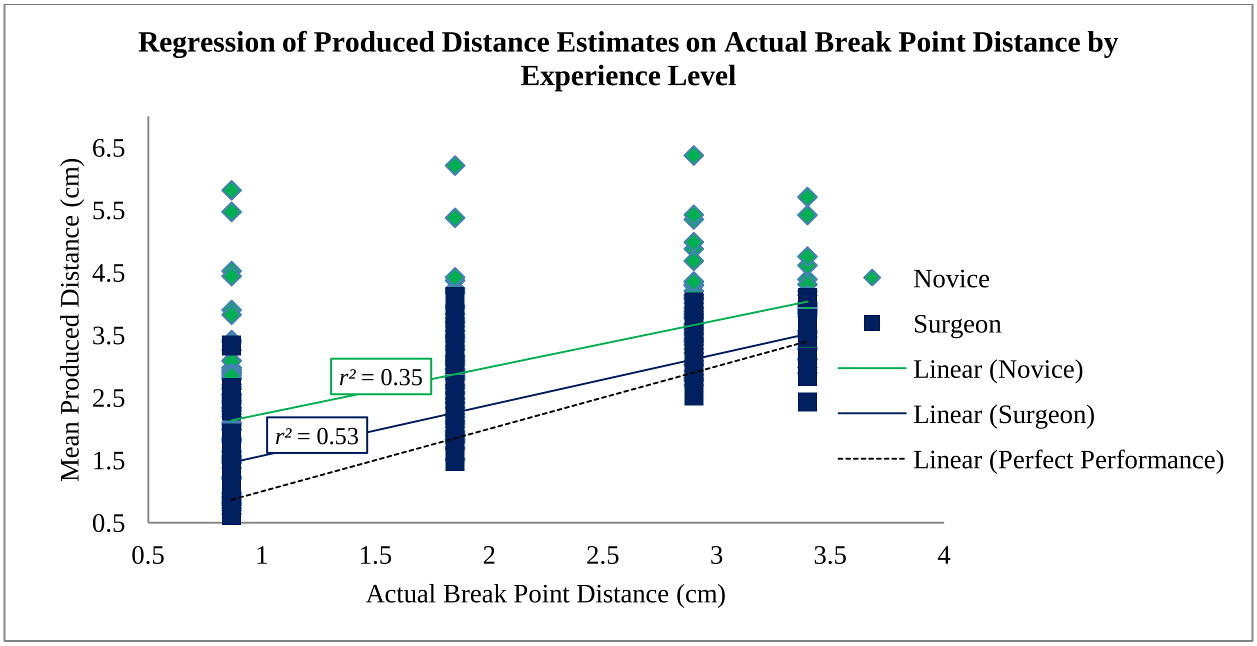


Figure 16. Regression of produced distance estimates on actual break point distance by experience level (novices: n=778 trials; surgeons: n=350 trials).

Multiple regression was conducted to assess the magnitude of difference in the perceptual distance estimations between novices and surgeons. Using data from the pre-feedback phase for novices and Task 1 for surgeons, actual distance (.0867, 1.85, 2.9, and 3.4 cm), experience level (novice or surgeon), and the interaction between the two were used to predict the produced haptic distances. The overall model was significant, $F(3,1124) = 283.35$, $p<.001$, producing an $r^2=.431$. There was a main effect of both actual distance and experience level, though not for the interaction between the two. The interaction term was consequently dropped from the model and the analysis repeated which was again significant, $F(2,1125)=425.85$, $p<.001$, producing an $r^2=.43$. Coefficients for the first and second regression model are displayed in Table 17 (Models

1 and 2, respectively). A main effect was found for actual distance, which explained the majority of the variance in the model: 37%. Experience level was also a significant predictor of performance in haptic distance estimates, explaining nearly 6% of the variance in estimates, and indicating that novices and surgeons were producing displacement differently. Further exploration into this difference revealed that novices were producing significantly more displacement than surgeons, as can be seen in Figure 17. Means and standard deviations of the produced distance estimations for each actual break point distance are displayed in Table 18.

Table 17. Regression models of actual distance, experience level, and the interaction on distance estimates.

Model	**Variable**	***b***	**se *b***	***t***	**r^2 contribution**
1	Actual distance	.709	.086	8.29**	.374
	Experience	-.687	.131	-5.23**	.057
	Interaction	.049	.062	.795	.000
	Intercept	2.149	.183	11.76	
	Note: r^2 = .431, adj. r^2 = .429, F = 283.35**, df = 3,1124; n = 1128				
		b	**se *b***	***t***	**r^2 contribution**
2	Actual distance	.773	.028	27.15**	.374
	Experience	-.593	.056	-10.57**	.057
	Intercept	2.025	.095	21.20**	
	Note: r^2 = .430, adj. r^2 = .429, F = 425.85**, df =2,1125; n = 1128				

**p<.001.

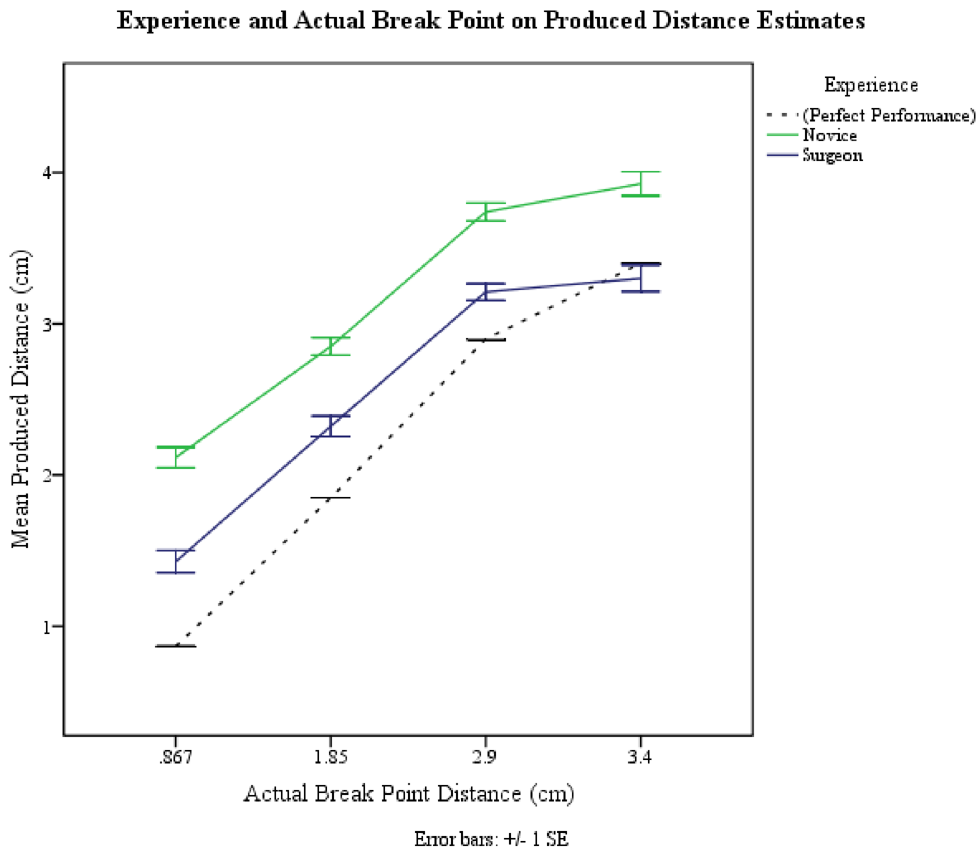


Figure 17. Produced break point distance estimates by actual break distance and experience level.

Table 18. Task 1 means and standard deviations of produced distance estimations for each actual break point distance by experience level.

Actual Break Point Distance (cm)	Task 1 Produced break point distance estimates (cm)					
	Novices			*Surgeons*		
	n	Mean	SD	n	Mean	SD
.0867	258	2.12	±1.10	117	1.43	±0.79
1.85	259	2.85	±0.93	116	2.32	±0.73
2.9	174	3.74	±0.878	78	3.21	±0.49
3.4	87	3.93	±0.74	39	3.30	±0.55

Individual performance at identifying break point distance was also compared between novices and surgeons. Using the individual regression coefficients obtained from regressing produced break point distance on actual break point distance, surgeons were compared to novices both before and following calibration feedback training. The regression coefficients used for this analysis are depicted in Tables 5a and 5c for novices (pre-feedback and post-feedback phases), and Table 14a for surgeons (Task 1). One-tailed independent samples t-tests were used to compare differences between surgeons and novices pre-feedback, and two-tailed independent samples t-tests were used to compare any difference between surgeons and novices post-feedback training. Results from these analyses are located in Table 19.

Comparing individual performance of surgeons and novices before feedback, while surgeons did have an overall higher mean r^2 value, the difference between the two groups was not significant. There was also no difference in overall mean slope between the two conditions. There was, however, a significant difference in mean intercepts between surgeons and novice performance before-feedback, indicating that novices produced significantly higher mean displacement than surgeons. Comparing surgeons to novice performance following feedback training, there was no difference in the regression coefficients between the two groups.

Table 19. Independent samples t-tests comparing mean individual produced break point distance regression coefficients between novices and surgeons.

Group means ± standard deviations			
	Surgeon Task 1	**Novices Pre-feedback**	**Novices Post-feedback**
r^2	.76 ±.221	.65 ±.245	.81 ±.198
Slope	.81 ±.107	.75 ±.185	.84 ±.171
Intercept	.63 ±.61	1.47 ± 1.08	.72 ±.704
n	13	29	26

Performance Comparison	**Mean difference**	***t***	**p**	**df**
Surgeon Task 1 – Novice Pre-feedback				
One-tailed				
r^2	-.101	-1.27	.11	40
Slope	-.054	-0.97	.17	40
Intercept	.838	2.58*	.01	40
Surgeon Task 1 – Novice Post-feedback				
Two-tailed				
r^2	.057	.84	.408	37
Slope	.032	.62	.619	37
Intercept	-.088	.39	.387	37

*p<.05

The produced distance judgments in Task 2 were also analyzed. Like performance in the transfer phase of Experiment 1, distance estimates were required to have been less than the actual breaking point distance or the material would truly break. Again, it was of interest to evaluate the relative distance 'remaining' in each material profile, or the relative region between the estimates and the true break point. Residual distance was calculated for each profile by dividing the absolute error of each estimate by the entire length of each profile. Percentages are listed in Table 20, which includes the relative residual percentages from novice performance in Experiment 1 (Table 7) for easy comparison.

Relative residual remaining percentage can be thought of as a metric of discretion, where higher percentages indicate more conservative estimates. Considering the actual break point distance and actual break point reactionary force for each material profile, relative residual distance appears to have been affected by both profile constraints. As the actual break point distance decreased, novices and surgeons both produced more conservative haptic distance estimates. And as the required applied force before breakage increased, the haptic distance residual percentages increased as well, indicating increasing caution. While this trend appears for both experience groups, surgeons appear to be making slightly more conservative estimates for nearly each material profile. The interaction between actual break point distance and required force before breakage on relative residual distance remaining for both novices and surgeons is displayed in Figure 18.

Table 20. Relative residual distance and area remaining before breakage in Task 2 of Experiment 2.

Profile	**Actual Break Location**		**Task 2 Residual Remaining**		**Novice Transfer Task Residual Remaining**	
	Distance (cm)	Reactionary Force (N)	Distance (cm)		Distance (cm)	
			M	±SD	M	±SD
1	.0867	1.9	7.26%	±4.30%	5.85%	±3.28%
2	.0867	3.7	15.67%	±6.36%	11.91%	±5.94%
3	.0867	5.0	23.13%	±9.62%	25.15%	±9.27%
4	1.85	1.9	3.64%	±3.72%	3.06%	±2.87%
5	1.85	3.7	10.30%	±3.96%	8.58%	±5.06%
6	1.85	5.0	21.23%	±8.45%	16.17%	±5.84%
7	2.9	1.9	5.30%	±3.92%	5.11%	±3.02%
8	2.9	3.7	10.15%	±4.55%	9.77%	±4.59%
9	3.4	5.0	17.12%	±4.55%	15.55%	±4.18%
n trials			318		688	

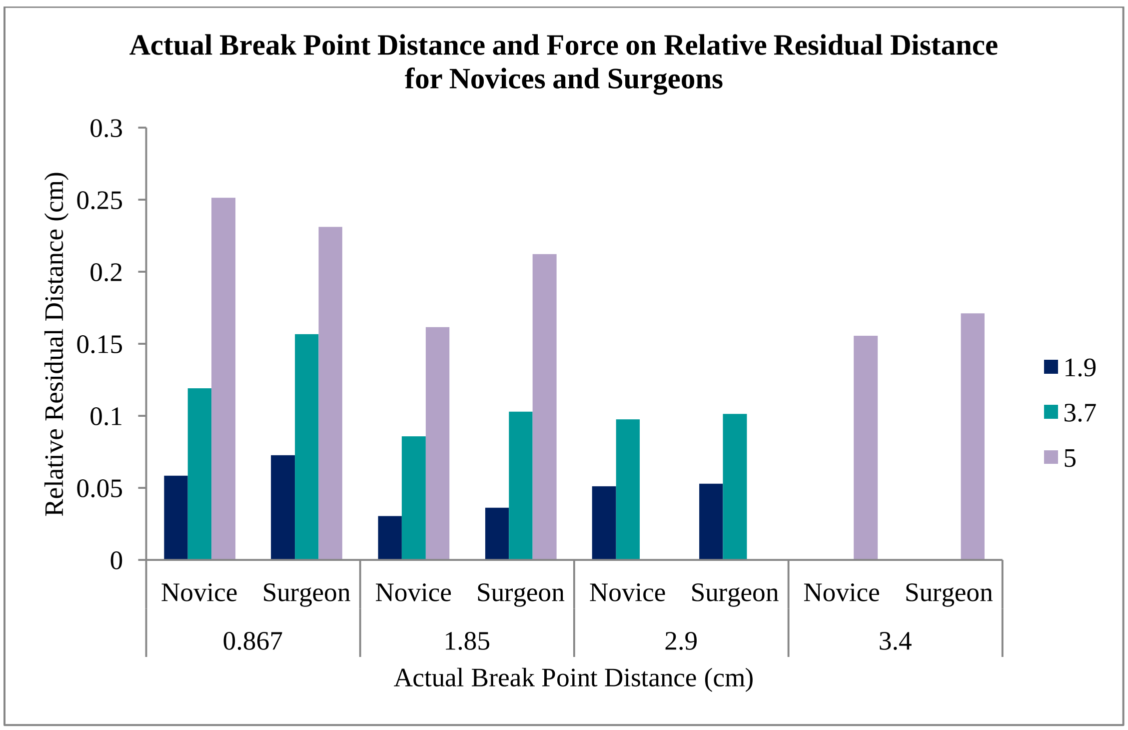


Figure 18. Relative residual distance remaining before break point for novices and surgeons, by actual break point distance and actual force.

Break Analysis. Both novices and surgeons participated in Task 2, which was more realistic in that the material profiles truly emulated breakage. Break frequency is depicted in Table 5d for novices and 14b for surgeons. The number of breaks and the simulated materials in which they occurred were also compared and are displayed in Table 21. Comparing the percentage of breaks between novices and surgeons, both groups caused breakages similarly across the material profiles. For both groups, the majority of breaks occurred in the materials containing the lowest required force before breakage (profiles 1, 4, and 7). However, break occurrence tapered off as the actual break point distance increased. This interaction is visually depicted in Figure 19.

Table 21. Break frequency occurrence across material types for novices and surgeons.

Profile	Novice		Surgeons		Total
1	44.13%	79	46.55%	27	106
2	6.70%	12	3.45%	2	14
3	2.79%	5		0	5
4	27.93%	50	27.59%	16	66
5	2.79%	5	3.45%	2	7
6		0		0	0
7	15.64%	28	15.52%	9	37
8		0	3.45%	2	2
9		0		0	0
Total		**179**		**58**	**237**

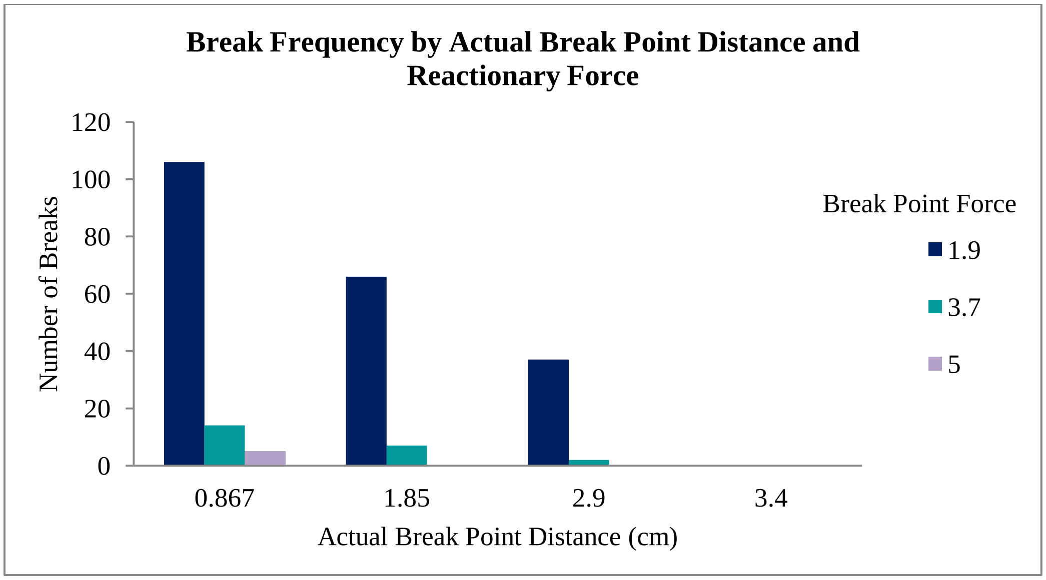


Figure 19. Break frequency by actual break point distance (cm) and reactionary force (N) for both experience groups combined.

Experience and Performance. Surgeons were asked a series of demographic questions pertaining to their experience with minimally invasive surgery (see Table 10 and Appendix C) and it was of interest to explore any association between experience and performance. The individual r^2 regression coefficients from Task 1 depicted in Table 14a were correlated with the demographic information obtained from surgeons. Pearson correlations revealed no significant relationship between Task 1 r^2 regression coefficients and age (r=-.09, p=.78), years experience with general surgery (r=-.08, p=.8), or with years experience conducting MIS procedures (r=.07, p=.81). However, there was a significant relationship between Task 1 performance and the number of MIS procedures performed, r= -.53, p=.05. Interestingly, the association was negative, indicating that performance actually *decreased* as the number of MIS procedures performed increased. However, this relationship was predominantly the result of two attending surgeons who reported having performed more than 1,500 surgeries. Excluding these two surgeons in the analysis, there was no significant relationship between performance and number of procedures performed, r=-.39, p=.22. Figure 20 displays this relationship.

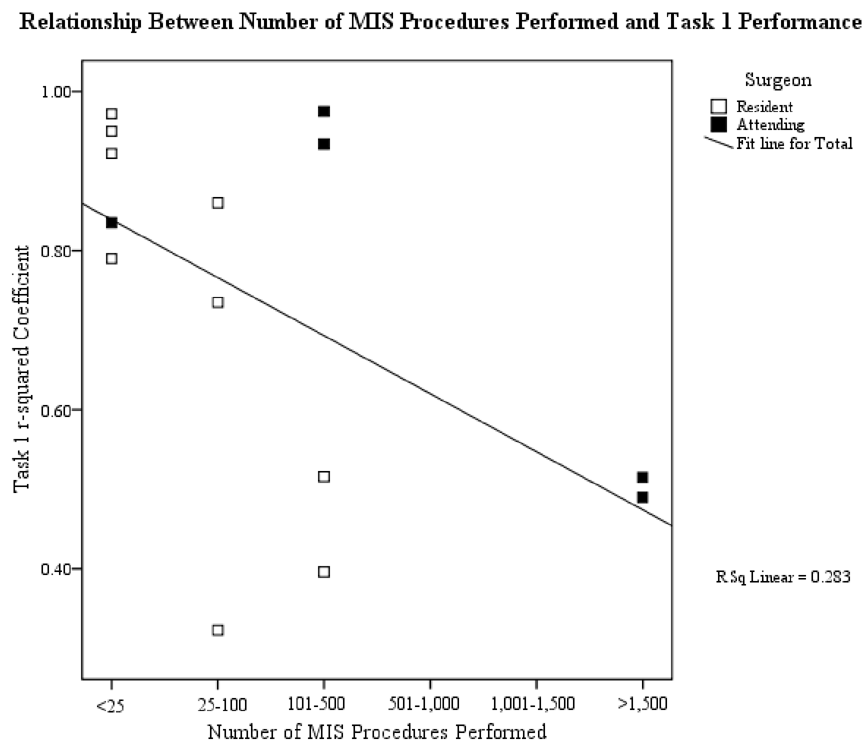


Figure 20. Relationship between number of MIS procedures performed and Task 1 performance of surgeons.

CHAPTER FOUR

GENERAL DISCUSSION

The goal of the present work was to explore the ability of subjects to detect information specifying breakage in a compliant material, particularly in the context of minimally invasive surgery (MIS). Two experiments were conducted to investigate whether participants were sensitive to a mechanical property denoting nonlinear material failure, referred to as Distance to Break (DTB), through haptic force application on a surgical tissue simulator. The first experiment examined whether DTB was reliably perceptible through force application even as lower-order mechanical variables differed between material profiles. Further, sensitivity to DTB was also assessed through calibration and attunement, where incorporating feedback training sought to improve perceptual judgments. The second experiment examined the extent to which perceptual sensitivity of DTB may be affected by experience with haptic force application onto compliant soft tissue by comparing surgeon performance to that of novice observers. Together, these experiments investigated three hypotheses which are discussed in detail in the following.

Hypothesis 1: Perception of DTB

It was hypothesized that the application of force onto a compliant material would yield haptic information specifying the distance remaining until material failure. Performance in both experiments support the first hypothesis that DTB is perceptible through haptic force application, as observers used the *change* in force during displacement into the material to locate the break point distance. Regression analyses revealed that the primary contributor to perceptual displacement estimates was the actual break point distance locations, indicating that the reactionary force of each material profile was used as a basis for the perceptual judgments. Participants must have been utilizing the haptic force change information to locate the distance correctly and thus, cause actual distance to be the primary predictor of haptic estimates. Perception of material break point was not through the magnitude of reactionary force at any particular location, but through the rate of change in reactionary force as distance into the material was actively manipulated. Therefore, participants could perceive and indicate different break point location distances for materials that contained the exact same required force before failure, and likewise they could indicate similar break points for materials that required different levels of force to create the breakage (though as discussed later, some effect of force level was evident). The high percentages of explained variance for actual break point distance indicate a higher-order relationship available within each material profile that observers are able to perceive. Even as the lower-order mechanical parameters of applied force and actual distance differed among profiles, actual break point distance was still the primary contributor to perceptual estimates of break point location. For the experimental design used presently, such use of distance was indicative of a sensitivity to DIB. It is hypothesized that this exponential change in reactionary force during active haptic displacement specifies DTB, and future research should confirm this through the use of profiles containing different relationships between applied force and displacement. For instance, it is of interest to know whether observers would be able to perceive any information denoting DTB along a material profile defined by a linear relationship between applied force and displacement.

This perceptual coupling between displacement and applied force was also well demonstrated though evaluation of the residual distances of Task 2. Considering Figure 18, an interactive pattern of break point displacement estimates emerged across profile types that fluctuated according to the actual break point distance and the applied force required, with this pattern existing regardless of experience level. In short, observers were attuning to an invariant relationship between distance and force, which can be characterized by the rate of change in force as distance was manipulated. When the actual break point distance was shorter, however, residual distance tended to increase, indicating more conservative perceptual displacement estimates. As the actual break point distances grew, overall residual distance decreased. The participants were more accurate at locating the break points when the materials were compliant, as evidenced by less cautious displacement estimates. That is, observers became more conservative in their estimates as the applied force increased. A similar phenomenon was observed by Lee and Reddish (1981) in their investigation of the use of optical time-to-contact by sea birds diving into water. The timing of the birds' closing of their wings was predicted by time-to-contact, rather than by the lower-order parameters of distance, velocity, dive duration, etc. However, with dives involving higher velocities the birds tended to be more conservative, folding their wings at earlier time-to-contacts.

Performance in the transfer task, or Task 2, also indicated an ability to perceive DTB. Incorporating actual consequences from over application of force may have encouraged more perceptual awareness to the useful mechanical information available, as the haptic estimates of both novices and surgeons became more precise and more cautious. While breaks did occur, the large majority of trials (80% for novices, 87% for surgeons) contained haptic estimates occurring before the break point and with high levels of precision, demonstrating strong support for the perception of DTB. Further, with novice participants, the actual break task was conducted following calibration feedback training, and future studies should assess the ability to perceive DTB in a more realistic task such as Task 2 prior to any formalized training procedures.

Hypothesis 2: Attunement and Calibration to Increase Perceptual Sensitivity

It was hypothesized that sensitivity to the higher-order invariant of DTB through force application could be improved through perceptual training. After undergoing a brief training session in Experiment 1, novice observers significantly improved in their ability to differentiate DTB from the haptic array. These performance improvements were demonstrated across all nine materials in the post-feedback phase, even though the calibration feedback phase only employed five of the materials. Overall, r^2 coefficients of multiple regression analyses improved from pre- to post-feedback sessions, suggesting an increased reliance upon both actual break point distance and applied force. Considering individual improvement attuning to actual break point distance between pre- and post-feedback sessions, mean r^2 percentages increased by nearly 20% and mean intercepts significantly dropped, signifying that perceptual estimates of break point locations became more precise and less excessive. From this, novices became more sensitive to the mechanical information contained in the simulated haptic array and they were more accurately scaling their perceptual judgments.

Using visual feedback as a calibration mechanism, observers became better able to discriminate the useful mechanical properties available within the material profiles and better able to scale their judgments. In line with the specificity theory of perceptual learning (E. Gibson, 1953; 1963; 1969; J. Gibson & E. Gibson, 1955), sensitivity to DTB increased as the important information within the haptic array was better isolated in the material profiles. Haptic force exploration revealed specific stimulus energy that acted as invariant perceptual information for observers, providing information about the specific amount of displacement that would lead to material failure. Visual feedback during the training phase allowed observers to view their haptic estimate and then calibrate their use of haptic information for more precise perceptual judgments. Performance following the training phase showed a significant increase in precision of displacement estimates, indicating that observers were better able to scales their use of DTB when making their perceptual judgments.

Previous research in our lab using a feedback calibration approach has found similar MIS performance improvements. Evaluating force perception across three core laparoscopic haptic skills tasks of probing, grasping, and sweeping, Singapogu et al. (2012a) implemented a training phase incorporating visual feedback to improve the accuracy of force application. Observers applied differing amounts of forces onto simulated materials both before and after a training session. Across the tasks, observers were more precise in their force estimates onto simulated materials. Training also resulted in overall decreased force magnitudes produced during grasping and probing tasks, indicating an improvement in performance.

Observers in the present experiments participated in a relatively brief feedback training phase to better isolate DTB, and it is unknown whether more time spent practicing would have increased perceptual sensitivity further. Following the feedback phase, displacement precision improved by almost 20% (individual r^2 increased from .63 to .81), and the mean overshooting distance decreased by more than half (mean intercept decreased from 1.51 to 0.67 cm). Training involved the completion of only thirty trials over five different material profiles, which lasted about twenty minutes. While improvement was significant, more trials, more material profiles, and/or more time may enhance performance further. Future studies aimed at quantifying the impact of more and less calibration feedback training, as well as distribution and arrangement of practice, will be beneficial to the development of improving perception of DTB. Just as it is important to understand whether more training will lead to even more successful outcomes, it is as important to quantify the most optimal types and schedule of perceptual training.

The calibration training increased sensitivity to DTB to such an extent that the performance of the novice subjects in the post-feedback phase was similar to, if not slightly better than, surgeon performance collected in Task 1 of Experiment 2. Comparing the individual regression coefficients between novices and surgeons, mean r^2 for novices was 0.81 compared to 0.76 for surgeons (Tables 5c and 15, respectively). The mean individual intercept also dropped for novices after training, indicating less displacement overshooting, becoming comparable to that with individual surgeon performance.

Hypothesis 3: Effect of Experience on DTB

Surgeons have more experience perceiving biomechanical constraints in soft tissue through force application, and it was hypothesized that this experience would result in improved performance over novice observers at perceiving DTB with the surgical simulator. This hypothesis was largely supported by the findings of Experiment 2. When compared with novice observers who had not yet received training, surgeon performance on Task 1 reflected an increased ability to perceive DTB within the simulated profiles. Surgeons were more reliant upon actual break point distance when making their haptic estimates, as the percentage of explained variance was nearly 20% higher for surgeons than novices (53% compared to 35%), indicating an overall increased attunement to the change in force with their displacement. In addition, experience also showed to be a significant predictor for amount of force application when making perceptual estimates, as novices tended to apply more excessive force when estimating break points and make displacement estimates beyond the true break point.

The higher degrees of displacement produced by novices in the present work are in concordance with previous findings from our lab using simulator-based tasks. Singapogu et al. (2012a) compared novice and surgeon performance in reproducing forces learned on simulated material profiles with differing stiffnesses and found that novices produced significantly more amounts of force than surgeons. When asked to produce the precise amounts of displacement, novices applied overall more force across the locations along the simulated profiles. In addition, using grasping and sweeping haptic tasks as well as probing, Singapogu et al. (2012b) found that novices applied greater overall force magnitudes than surgeons for each of the three tasks. These previous studies have concluded that force magnitude profiles on a laparoscopic simulator could be used to reliably differentiate surgical skill, and findings from the present work support that proposition.

Previous studies have found that more experience has resulted in greater overall forces and torque application when using real, non-simulated materials. Zhou, Perreault, and Schwaitzberg (2008), found that experienced surgeons tended to produce higher overall forces than novices during a similar laparoscopic probing task onto silicone mediums, though the overproduction of force was still within the range of tissue safety. Further, Richards, Rosen, Hannaford, Pelligrini, and Sinanan (2000) found that novices and surgeons tended to produce higher amounts of forces and torques onto porcine tissue depending on the type of MIS task. A potential explanation for this discrepancy with the present findings may have to do with the material type and potentially the use of visual feedback. The profiles used in the current experiments were virtual materials, and observers applied force onto them in the absence of any visual feedback. Under unfamiliar circumstances such as these, surgeons may have simply approached the task more conservatively than did novices.

Interestingly, there was a negative relationship between the number of MIS procedures performed and performance of surgeons in Experiment 2. Closer inspection of Figure 20 revealed two attending surgeons who performed more than 1,500 procedures, though did not perform as highly as the other three attending surgeons in Experiment 2. A possible reason for this may have to do with the *recent* number of MIS procedures and training of these individuals. It is not uncommon for attending surgeons to oversee and manage the skill development of less experienced resident surgeons, who may be performing the majority of procedures and thus, may be gaining more current haptic force perceptual skills. Similarly, the resident surgeons may be receiving much more current MIS training than tenured attending surgeons. Assessing the number and types of recent surgical procedures and relevant training, as well as any effects of perceptual skill decay among expert surgeons in future studies may prove valuable.

Considerations

The nine material profiles were designed to break based on three distinct distance intervals, though empirical testing of these distances by measuring tool travel revealed four discrete distance lengths. Materials 1 – 8 all failed at the intended distance locations, while the ninth profile truly broke at a slightly longer distance. The algorithms specifying break point location were accurate for this profile, though the extreme nature of the material may have affected simulator output. It required a high degree of torque to render reactionary force at the longest distance possible, and it is speculated that imprecision from the amplifier and torque generating mechanisms may have caused a slight inaccuracy with feedback rendering. By transforming the encoder units for profile 9 to new values reflecting the actual centimeter distance, error in analyses was minimized.

Break point distance was able to be empirically tested and measured from the simulator, though actual break point reactionary force was not. The system generated torque in response to user input through current output to two motors attached to one end of the input device. Actual voltage generated by the amplifier was assessed by measuring the output at the three break point force locations, though was unable to be empirically confirmed through direct measurement. From the amplifier output, force was estimated using the transformation from volts to Newtons described in the Methods section of Experiment 1. As a result, the true reactionary forces at the three breaking points were not precise. Future studies in our lab will determine the actual reactionary forces the core haptic skills simulator is capable of rendering, as well as directly measure the forces applied onto the simulated materials by observers.

As a first effort towards evaluating DTB, haptic observations were examined in the absence of visual feedback, which is strongly related to perceiving compliancy (Kuschel, Di Luca, Buss, & Klatzky, 2010). Visual and haptic information are used in concert when making physical perceptual judgments (Ernst & Banks, 2002) and it is reasonable to speculate that visual cues provide information useful for determining material constraints, especially in the context of a surgical environment. Of interest for future research is to further understand the role of vision in force application and DTB perception. In the present experiments observers were relying heavily upon actual break point distance when making their break point location estimates, though as a whole, were also overestimating distance. In the absence of visual feedback, it is possible this over application of force may have been the result of observers attempting to gain more compliance information from the haptic array. In the case of Task 2, where material breaks were observed for both groups, materials containing the least amount of reactive force resulted in a disproportionately larger number of breaks. Participants may have been searching for more haptic information in the profile to make a perceptual judgment and as a result, applied too much force and overestimated distance. Similar studies assessing kinesthetic target judgments have found similar overestimations of distance when no visual feedback was present. Examining target location through a pointing task, Chapman, Heath, Westwood, and Roy (2001) assessed the effect of delay on kinesthetic judgments while attempting to rule out visual memory. With no visual feedback of their judgments, observers tended to overshoot the distance of their pointing estimates. It is possible that the lack of visual cues in the present work may have contributed to the over-estimation of break point locations by both novice and surgeons observers, and future studies should assess any moderating factors vision may have on both attunement and calibration to DTB.

While surgeons did anecdotally comment on the authenticity of the simulated soft tissue profiles, Experiment 2 lacked any formal debriefing questions to assess the extent to which the feedback mirrored real tissue they have interacted with in actual surgical contexts. A series of questions at the end of the study would have helped to corroborate the design of the simulated profiles as well as assess the degree to which the materials felt lifelike. While several surgeons did relate simulated materials with types of tissue they were familiar with during experimental trials, including a post-experimental questionnaire will allow future work to verify the lifelike qualities of the profiles.

More haptic skill tasks covering a wider range of mechanical forces would help us to better understand perception of DTB. The present dissertation examined only tensile force loading through probing, which is one of three tasks identified in MIS where proficient force perception is critical to successful performance (Singapogu et al., 2012a; 2013). Applying force onto a compliant soft tissue via pushing and palpating effectively causes reactionary stretching of the material, which provides a perceptual experience similar to that of stretching a rubber band and is only a single method of applying force through normal haptic interaction. The core haptic skills simulator used in the present series of experiments is also capable of emulating sweeping and grasping behaviors used in MIS. Incorporating sweeping would have added a second skill focused on tensile force application, perhaps demonstrating differences in the perception of DTB due to different muscular and receptor systems used in application. Having included grasping, however, would have allowed the present dissertation to also explore perception of DTB via compressive force application. A requirement of MIS interactions is handling tissues and materials with forceps and other tools, effectively squeezing and condensing soft tissue. No different from excessive tensile force application, too much uniaxial compressive force will result in biomechanical tissue failure (Fung, 1993; Rosen, Brown, De, Sinanan, & Hannaford, 2008; Yamada, 1970). Compressive force loading is inherently different from tensile loading and it is of interest to explore perception of DTB through condensing soft tissue by over-squeezing.

In addition, sensitivity to DTB was evaluated in an isolated probing task under very controlled experimental circumstances. Displacement was applied uniaxially onto simulated tissues using a discrete motion pathway, and reactive forces were emulated as arising from the same location of the surgical tool. Very few, if any, manual tasks applying forces onto tissues in MIS are conducted discretely as they were assessed in the present experiments, as interactions with bodily tissues typically involve multiple combined actions performed together synergistically. Probing tissue often occurs in conjunction with twisting, grasping, and tugging behaviors along multiaxial pathways. Decomposing complex surgical tasks into separate units is critical for understanding the basics of a perceptual theory of DTB, though it is unknown how much improvement in performance on a single task would transfer to a dynamic MIS procedure.

Future studies should quantify the extent of perceptual transfer from interactions with simulated profiles to real materials. In the present work, the perceptual invariant of

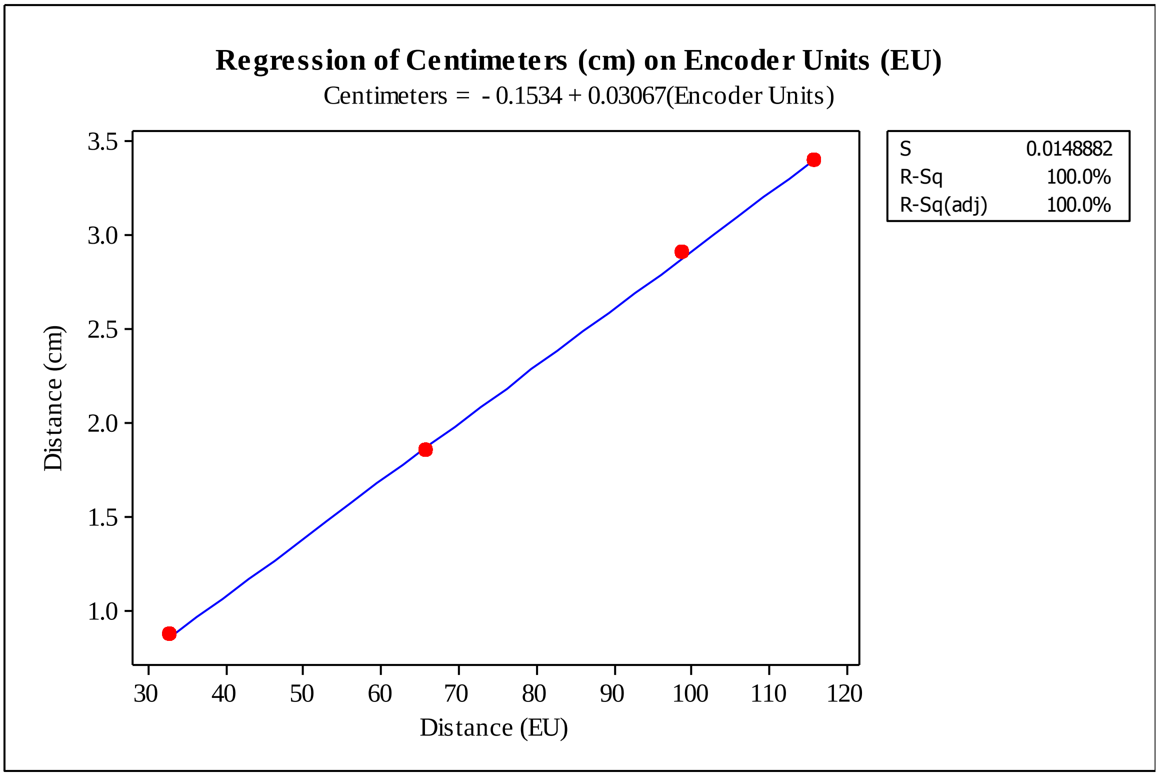
DTB was supported through the use of simulated nonlinear materials, though it is hypothesized that observers would be able to attune to this information in real nonlinear compliant materials as well. Performance gains through calibration feedback training should also be substantiated using real-world MIS tasks. The ultimate goal of any simulator training paradigm in MIS is to improve real-world operational performance, and future work must be aimed at substantiating functional improvements.

Conclusion

Accurately perceiving information specific to the biomechanical properties of tissues is imperative for minimizing tissue trauma and preventable injuries in MIS. Thus a better understanding of the mechanical variables involved in the perception of tissue constraints will promote more effective training paradigms. The proficient application of forces is of considerable concern as many procedures in MIS are prone to force-related errors resulting from impoverished haptic perception (Deml et al., 2005; Nisky et al., 2012; Puangmali et al., 2008; Trejos et al., 2010; Westebring-Van Der Putten et al., 2008; Xin et al., 2006), and this effect increases among surgeons with less experience and training (Tang, Hanna, & Cushieri, 2005; Xin, Zeleck, & Carnahan, 2006). Haptic perception, in general, is underemphasized in traditional surgical simulators, even though proficient haptic perception is critical for successful MIS performance (van der Meijden & Schijven, 2009; Westbring-van Der Putten, Goosens, Jakimmowicz, & Dankelman, 2008). Understanding material constraints and effectively tailoring force application in response to them is a chief component of this haptic perception. Surgeons, for example, need to fundamentally understand the location of tissue failure point *before* perforation. Inspired by this, the present studies explored the mechanical contributors to perception of material break point, which supported the presence of a higher-order relationship of DTB that is perceptible in simulated pliable materials. Through haptic exploration, observers are able to attune to information specifying the remaining distance until the tissue would fail and identify the displacement point at which more force would result in breakage. Understanding the underlying mechanical variables involved in the perception of DTB is critical for being able to render them in any simulator, and in MIS this information will undoubtedly work to optimize surgical training. Future research will continue to explore the presence of DTB and validate the presence of this invariant information within real materials, with the ultimate goal of promoting an understanding of how observers are able to perceive mechanical constraint information through haptic exploration.

APPENDICES

Appendix A. Centimeter Distance Transformation Linear Regression Model.



Appendix B. Experiment 1 Demographics Questionnaire.

ID	
Date	

Demographics

Age:

Sex: (circle one)   Male   Female

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

If yes, please describe:

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

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

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

If yes, please describe:

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

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

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

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

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

Please describe:

Appendix C. Experiment 2 Demographics Questionnaire.

ID	
Date	

Demographics

- Age: ________
- Dominant hand: (circle one)

  Left **Right**

- Sex: (circle one)

  Male **Female** **Prefer not to answer**

- Which of the following best describes you: (circle one)

  Attending **Resident** **Other (please specify):**

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

If yes, please describe:

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

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

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

If yes, please describe:

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

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

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

5. Approximately how many years have you been practicing general surgical procedures? ________

6. Approximately how many years have you been performing minimally invasive surgical procedures? ________

7. Approximately how many minimally invasive surgical procedures have you performed? (circle one):

<25 **25-100** **101-500** **501-1,000** **1,001 – 1,500** **>1,500**

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