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Investigation of Distance to Break Using Compliant Nonlinear and Linear Materials in a Simulated Minimally Invasive Surgery Task

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INVESTIGATION OF DISTANCE TO BREAK USING COMPLIANT NONLINEAR AND LINEAR MATERIALS IN A SIMULATED MINIMALLY INVASIVE SURGERY TASK

A Thesis
Presented to
The Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Applied Psychology

by
Leah Suzanne Hartman
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Accepted by:
Christopher C. Pagano, Committee Chair
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Dr. Ben Stephens

Abstract

Accurate interpretation of the mediated haptic information in minimally invasive surgery (MIS) is critical for applying appropriate force magnitudes into soft tissue with the aim of minimizing tissue trauma. Force perception in MIS is a dynamic process with surgeon's administration of force into tissue revealing information about the remote surgical site which will further inform the surgeon for additional haptic interaction. The relationship between applied force and material deformation rate has been shown to provide biomechanical information specifying the distance remaining until the tissue would fail, which has been termed distance-to-break (DTB). The current study continues the investigation of whether observers can use DTB to stop before a tissue's failure point. Similar to past results, observers could reliably perceive DTB in simulated nonlinear biological tissues.

Dedication

"Other things may change us, but we start and end with family" —Anthony Brandt

This is dedicated to my family and friends whom I have been blessed with in life. Your love and support knows no bounds. Thank you for always helping me to find the humor in the darkest of times and giving me the confidence and support to pursue my dreams.

Acknowledgments

This thesis would not have been made possible without the support of numerous individuals. I will forever be grateful for their intellectual and time contributions to this work.

First, I would like to thank my mentor Dr. Christopher Pagano for his unfailing guidance, time, and patience throughout this process. Under his tutelage, I have rediscovered my passion for perception research and furthering my education. Words cannot express my gratitude for his mentorship and all of his constant support and advice.

I would like to thank my wonderful committee Dr. Tim Burg and Dr. Ben Stephens for their thoughtful insights which greatly influenced the development and shaping of this thesis. I am exceptionally grateful for the donation of their time and their generous flexibility during this process.

I am also so thankful for my fellow members of the Haptic Interaction Lab: Irfan Kil, Kumar Prateek, and Karla Romero. This lab has allowed us to intellectually stimulate one another in our different fields and I have learned so much from them. Their technical support made this work possible and I am so grateful for their time and help for this work.

Lastly, I would like to state my gratitude to my fellow Perception and Action (PAC) Lab mates, Lindsay Long and Bliss Altenhoff. I am so thankful to have the opportunity to be a part of this incredible lab and to collaborate with both the past, present, and future members. This work would not have been possible without Lindsay's trailblazing dissertation which began the development of this theory. I am also thankful for my current lab mate Bliss whose guidance, support and humor have made each and every work day a phenomenal experience.

Without each and every one of you, this work could not have been completed and I am truly blessed and thankful to have had the opportunity to work with you.

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Introduction

Haptic Force Perception in Minimally Invasive Surgery

Surgeons require a different perceptual-motor skill set for minimally invasive surgery (MIS) than for open surgery. This is due to the different methods of interaction between the surgeon and the surgical site in these two types of surgery. In contrast to traditional open surgery, where surgeons are able to freely manipulate internal organs through large openings and are able to interact directly with organs using their fingers and other various instruments; MIS takes place through small openings in the body where surgeons interact with the remote surgical site through various hand-held MIS tools. This requires surgeons to perceive the physical properties of the surgical site through haptic perception gained via the hand-held tools. Therefore, the mediated relationship created by MIS gives the surgeon a unique perceptual experience that requires increased training and practical knowledge in order to obtain the necessary expertise for the required perceptual-motor skills (Basdogan De, Muniyandi, Kim & Srinivasan 2004; Xin, Zeleck & Carnahan, 2006).

Westbring-van Der Putten, Goosens, Jakimmowicz & Dankelman (2008) state that remote interaction in MIS creates perceptual problems for surgeons. Vision-related problems are due to the use of the endoscopic camera and include hand-eye coordination complications and decreased visual depth perception. The complications in the hand-eye coordination as well as the decreased visual depth perception can also be seen in other teleoperated robotic conditions. These are due to what is referred to as the “remote perception problem,” and occurs when the normal three-dimensional visual environment becomes decomposed into a two-dimensional one through the use of a camera (Gomer, Dash, Moore & Pagano, 2009; Moore, Gomer, Pagano & Moore, 2009; Tittle, Roesler & Woods, 2002). Another perceptual problem that Westbring-van Der Putten, et al. (2008) discussed was a decrease in haptic perception due to degraded haptic information. Unlike the vision-related problems, this decrease in haptic perception is unique to the context of MIS.

Consequently, forces felt through the remote manipulations in MIS are inherently different than those in open surgery due to the use of the mediating tools, and this leads to degraded haptic information. One result is an increase in surgeon errors from misapplication of forces. These errors are especially noted in MIS procedures that require high levels of precision (Xin et al., 2006). Excessive force applications are cited as the surgical errors that result in the most tissue damage (Tang, Hanna & Cushieri, 2005).

Haptic perception is the combination of kinesthetic and tactile sensation operating together (Loomis & Lederman, 1986; Pagano, Carello & Turvey, 1996). The haptic perception necessary for MIS requires surgeons to use a combination of both of these senses. Tactile sensation arises from mechanoreceptors which are located within the skin. These types of receptors relay information such as pressure, surface texture, and temperature. Kinesthesis provides the observer with awareness of the static positions and locations of their limbs within space, along with an awareness of limb movements and applied forces. This awareness comes from mechanoreceptors found in the muscles, joints, and connecting tissues. These mechanoreceptors become stimulated by movement, respond to the muscular effort, and relay the necessary information. This not only provides information about the body, but also about properties of hand-held objects, such as their extent, weight and orientation, as well as properties of other objects and surfaces probed with the objects (e.g., Barac-Cikoja & Turvey, 1993; Burton, 1993, 2004; Carello & Turvey, 2000; Gibson, 1966; Pagano, 2000; Pagano & Turvey, 1998; Peck, Jeffers, Carello & Turvey, 1996; Turvey, 1996). This type of active haptic exploration relies on biomechanical effort which gleans the information available from the haptic array. The use of kinesthesis for the perception of hand-held objects and the perception of surfaces manipulated with hand-held objects is often referred to as "dynamic touch" (Gibson 1966, Pagano 2000; Pagano & Cabe, 2003; Pagano et al., 1993; Pagano & Turvey, 1998; Turvey 1996). With the scope of MIS, kinesthetic sensation is responsible for the manipulation of remote tissues through the surgical tool.

Thus, force perception in MIS is a dynamic process in which the surgeon gains useful information from the manipulations at the surgical site via the tools and adapts future manipulations on the basis of that information. Surgeons can use information from the tissues, such as material compliancy, to determine contact with a material as well as when the material could potentially break (Bergmann Tiest, 2010). Material compliancy is the extent to which a tissue deforms in response to applied force. Information about a material's compliancy can be revealed through pressure application, as it is given by the ratio between the amount of applied force and a material's surface deformation (Bergmann Tiest & Kappers, 2009; Di Luca, 2011; Srinivasan & LaMotte, 1995; Mugge et al., 2009; Vincentini & Botturi, 2009).

The surgeon can be informed of material fragility through the amount of applied force and the resulting amount of tissue deformation (Srinivasan & LaMotte, 1995). For many biological tissues, the reactionary forces generated by the tissue increase in a nonlinear fashion as the deformation distance into soft tissue progresses towards the point of breakage. That is, the farther one deforms a tissue the harder it becomes to further deform that tissue. The break point is where the materials' structural limit has been reached and further force will lead to the tissue breaking (Rosen et al., 2008; Yamada & Evans, 1970). Long, Hartman, Pagano, Kil, Burg, & Singapogu (2014) determined that through force application observers were able to reliably identify the break point of materials, i.e. the point at which any addition force would cause the material to break in deformable tissues.

Perceptual Theory

The haptic relationship of force application and the deformation rate of the soft tissues is analogous to visual "time-to-contact" (TTC). The theory of TTC is that as one approaches an object the area subtended by its projection on the retina increases or "looms" in the visual field. The nature of this looming provides information about the time remaining until collision with the object will occur. Specifically, TTC at any instance in time is given by the ratio of the area of the object's projection on the retina and its rate change at that time (e.g., Hoyle, 1957; Lee 1976; Lee & Reddish, 1981). Long, et al. (2014), determined that for a certain type of soft materials there is a corresponding relationship between the force needed to maintain an amount of deformation and the rate of increase in force needed to deform the tissue any farther. For certain types of tissues, this ratio is information about the amount of deformation remaining until the tissue will fail, referred to as the distance-to-break (DTB). As the rate of change in tissue displacement increases so does the perceived tissue reactionary force yielding the information required for an observer to determine DTB (Long, et al. 2014). They proposed the DTB equation as:

$$DTB = \frac{Force}{\Delta\, Force / \Delta\, Displacement} \qquad (1)$$

This proposed formulation of the DTB equation is based on the mathematically similar relationship for TTC, which describes physical approach to a surface during locomotion. The resulting optical looming that occurs with the approach will specify when the point of impact with the surface will occur. This relationship is represented in Figure 1. In DTB, the remaining distance before mechanical failure is determined by the muscular exertion (which is necessary for stimulating the kinesthetic receptors in the muscles, joints and connective tissues) required for force application to the material. Thus the haptic perception of DTB is a type of “dynamic touch.” Long et al. (2014) found evidence that observers were able to haptically perceive DTB in nonlinear compliant materials through force application. Observers were able to use that information in identifying the remaining distance before the mechanical failure of the tissue.

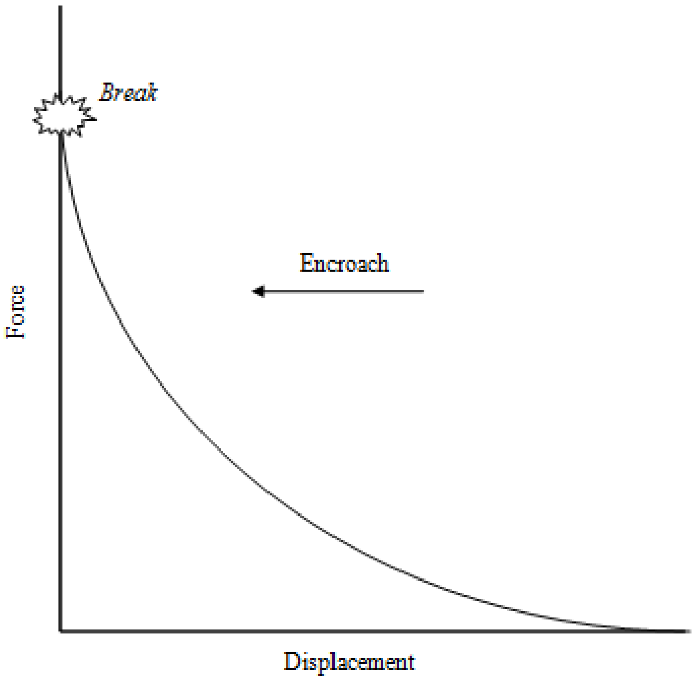

Figure 1. Relationship between material displacement and the mechanical force required for further material displacement for a hypothetical compliant material.

Training Perception

Long et al. (2014) utilized a haptic simulator which was developed at Clemson University to emulate various MIS surgical tasks (Singapogu et al., 2011, 2012a; 2012b; 2013; in press). They demonstrated that prior to explicit feedback observers were able to attune to DTB and were calibrated in a feedback stage in order to more accurately attend to DTB. Thus, their work added to a growing body of literature demonstrating that Virtual Environments (VEs) are useful for training complex skill. The use of VEs for surgeon training is highly desirable, because it allows surgeons and novices to interact with various situations repeatedly and safely in a controlled environment. For example, with a simulator in a VE context, surgeons can repeatedly break tissues over and over in order to understand different tissue compliances. The use of VE for laparoscopic surgeons increases the freedom of making mistakes while training, unlike the use of cadavers which is expensive and only allows few errors before the cadaver's tissues are rendered useless (Coles, Meglan, & John, 2011). Also the use of the simulators allows for interaction with different type of tissue scenarios that are more difficult to present in cadavers.

Gibson (1969) found that through training, observers became more attuned to perceptual information within the haptic array. Similar to our visual system, our haptic system is continuously exposed to a plethora of limitless information. In the context of a specific object, the observer may not attune to perceptual information pertaining to the specific object's properties. The experience and feedback given to observers allow for them to attend to useful information and ignore haptic information which is creating "noise." Observers can be thought of having "tuned" to specific mechanical properties that are useful in information and are lawfully related to the perceptual variables, also known as specifying variables (Wagman, Shockley, Riley, & Turvey, 2001; Withagen & Michaels, 2005). Gibson (1969) referred to perceivers learning to differentiate ambiguously-related stimuli from salient invariants and attune to those salient invariant as the "education of attention," also known as "attunement."

This theory proposes that efficient learning comes through perceptual attunement to useful and meaningful information and not the use or development of complex mental structures (Gibson, 1969). Perceptual judgments become more accurate and the perceptual system's output is adjusted to the mechanical properties through the feedback and experience process. The calibration of the perceptual system enables the participant to attune to the specifying information while ignoring other non-specifying information, resulting in accurate perceptual judgments.

Previous work conducted in our lab has demonstrated this perceptual training through attunement and calibration with the use of our virtual haptic simulator (Singapogu et al., 2011, 2013, in press; Long et al., 2012; Long et al., 2014). The current study will employ a training phase to assist observers in the particular task since this type of task is not one that is done on a daily basis.

Purpose and Overview

Long, et al. (2014) designed materials that had three material strengths and four different displacement location values. The construction of these materials in this fashion allowed for Long, et al. (2014) to analyze materials across one measurement while the other remained constant. The current study used training materials with completely unique breaking points in both the distance and force variables. It also changed the materials for the testing phase, so that during the testing phase the participants were asked to indicate DTB for a completely new set of materials. This design of materials will assist in the support of Long et al. (2014) proposed DTB equation.

It is desired to investigate whether observers are truly using DTB to stop before the failure point of the tissue if they are using some other component such as just the increase in force. Thus, adding different forms of materials will allow us to test for other components that the observers may be using instead of DTB. The current study will include linear materials that have certain profile characteristics that will potentially express maximum force threshold points that participants are attuning to instead of the proposed DTB invariant. Another concern is that observers may simply wait until any amount of force is felt and then state that point as the material's breakpoint, since all previous work with our simulator has assumed that as soon as observers pushed into the simulator it was as if the tissue was located at the end of the surgical tool. Therefore, the testing phase will render the tissues with space before the tissue begins.

Long et al. (2014) allowed observers to freely explore the tissue using a probing task. The observers could haptically feel the increased resistance as they applied more force through the standard MIS instruments. The current experiment also used a probing task, similar to that of Long et al. (2014).

It was hypothesized that participants will be able to selectively attune to DTB. Essentially, observers will be able to attune to DTB in nonlinear materials even with other types of materials without DTB invariant present, e.g. the linear materials. We hypothesize the data will enable us to explore the proposed equation further and provide further support for it.

Methods

Participants

Due to the effect sizes observed in previous similar work (Long et al. 2014), 30 participants were sufficient for this study. A total of 31 participants were recruited using mass advertisement and received $10 for their participation (Male= 18, Female 13; Mean Age= 26.56, SD= 2.93). Due to one participant not being able to complete the training phase under the parameters, only 30 participants' data was used in data analyses. All participants had no previous experience practicing MIS or performing MIS. Participants used their dominant or preferred hand through the experiment.

Materials and Apparatus

Simulator. Using a simulator that was developed at Clemson University, the Core Haptic Skills Trainer, nonlinear soft tissues and linear tissues were rendered for observers (see Figure2) (Long et al., 2014; Singapogu et al., 2011, 2012a, 2012b, 2013). Two direct-drive DC motors (Tohoku Ricoh^{TM}, Miyagi 987-0511, Japan) located at the center and the end of the forceps shaft delivered force feedback to the input device of the robotic motion system. The input device used was a modified laparoscopic surgical scissor grip handle forceps tool with pinchers removed (a Covidien Autosuture™ Endo® device, Dublin, Ireland). Force feedback was rendered through a series of computer algorithms (Singapogu et al., 2011, 2012a, 2012b, 2013) which then generated torque in response to the user's unilateral motion.

The participants received haptic feedback through the input device by grasping the handle and pushing the tool forward during the probing task. The simulator then emulated the tool moving through a body cavity, coming into contact with, and deforming into soft tissue.

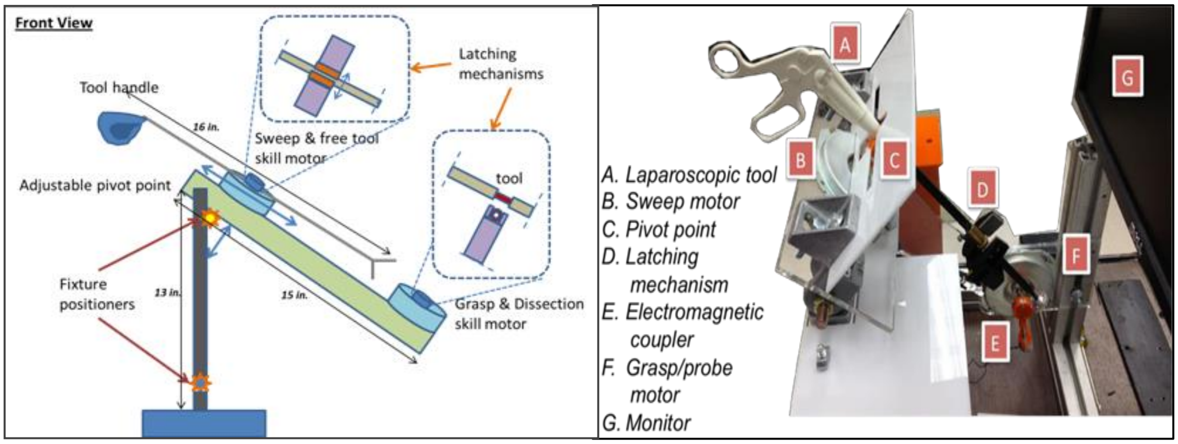

Figure 2. Schematic and photographic representation of the Core Haptic Skills Training Simulator (reprinted from Singapogu, et al., 2013).

Visual Feedback. During the feedback training phase, observers were given visual feedback to view their errors and adjust their force application during each trial. Through the use of the custom graphic used in Long, et al. (2014), observers saw displayed on a computer screen the penetration distance of the tool relative to the tissue's break point. The dynamic marker moved from right to left encroaching to the simulated actual break point marker as the observer applied varying amounts of force through the input tool. The location of the blue break point indicator remained static and only the application of force moved the red indicator marker. This can be seen in Figure 3. The tissue will break when the red movable marker reaches the blue break point marker. Participants made their initial judgment without the visual feedback. Once they indicated that they had reached the breaking point, those positions were marked and then the visual feedback was put on their monitor so they could see their estimations and recalibrate to where the break point actual was located.

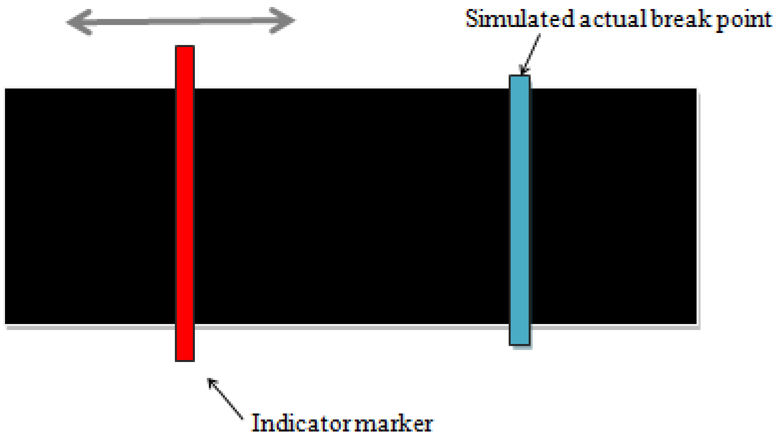

Figure 3. Visual Graphic used in Calibration Feedback Stage.

Simulated Material Profiles. To determine if observers were using the DTB invariant, two sets of materials were developed, one for use in the training phase and the other for use in the testing phase. This change in materials between phases was done so that any significant findings could be attributed to participants using DTB to determine the break point. If results are similar to Long, et al. (2014), the high percentage of explained variance could be attributed specifically to observers using the DTB invariant. Essentially, since participants were never trained on any of the testing materials, they should only be able to perform well if they are using the DTB invariant to determine break point.

Training Phase: Seven nonlinear materials were simulated using seven different material strengths *(F)* and seven different displacement locations *(d).* These materials were rendered such that excessive force would cause the simulated material to break (See Figure 4).

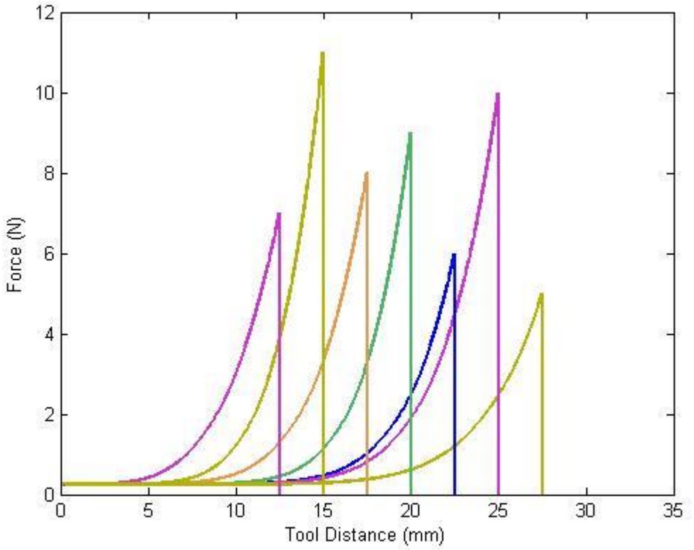

Figure 4. *Training profiles*. The seven simulated material profiles and their designated breaking point location. Materials are numbered from left to right, 1-7.

Testing Phase: Seven nonlinear materials were simulated using the same material strength of 8 N with similar displacement locations as the training phase. These materials were also rendered at a different distance to material (*dm*), which is the distance from the starting position of the tool to the point at which the material began to require force application to deform. This distance was 7 EU or 1.75mm from the tool start position. Two types of linear materials were also simulated using two material strengths (*F*: 8N and 11N) at one displacement locations (*d*: 20mm*)*. The first linear material profile had a slope of 0.3875 and broke at the same material strength as the other nonlinear testing materials, 8N. The second linear material had a slope of 0.5125 and broke at the highest force value presented in the training phase, 11N. Testing materials were rendered with a break point, however they did not truly "break". The force feedback remained constant after the participant had pushed past the designated break point. Thus, participants could continue pushing into the simulator without any haptic feedback of the material truly "breaking" on them. This enabled participants to potentially make overestimations or go beyond the breaking point. Testing materials can be seen in Figure 5.

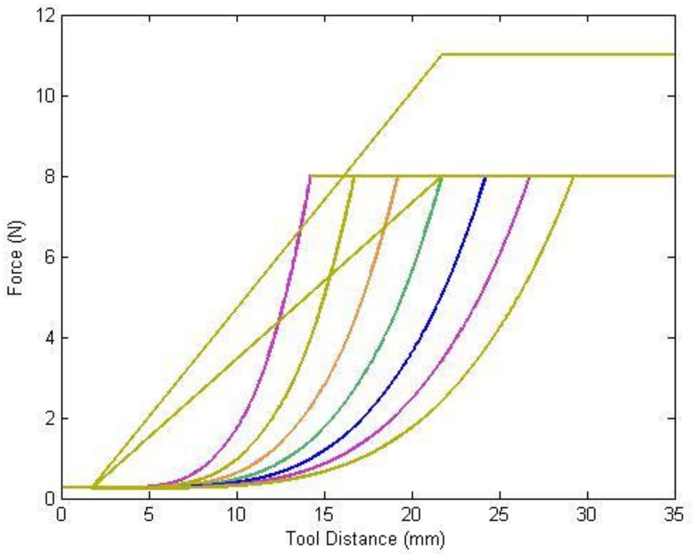

Figure 5. *Testing profiles.* The nine simulated material profiles and their inflection points where tissues would normally break. Initial material contact location is 7 EU or 1.75mm. Materials are numbered starting with the nonlinear materials from left to right, 1-7. Linear materials are numbered from lower to higher force value, 8 and 9. Materials 1-8 break at the force value of 8N and 9 breaks at a force value of 11N.

The simulated tissue profiles were constructed as piecewise functions.

Training Nonlinear Materials (Break):

$$f(x)\left\{\begin{matrix} K*x^n + C & d_1 \le x \le d_2 \\ 0 & x > d_2 \end{matrix}\right\} \qquad (2)$$

(2)

Testing Nonlinear Materials (Non-break):

$$f(x)\begin{cases} C & 0 \le x < d_1 \\ K * x^n + C & d_1 \le x \le d_2 \\ K * (d_2)^n + C & x > d_2 \end{cases} \tag{3}$$

Testing Linear Materials (Non-break):

$$f(x)\begin{cases} C & 0 \le x < d_1 \\ K * x + C & d_1 \le x \le d_2 \\ K * (d_2) + C & x > d_2 \end{cases} \tag{4}$$

Where C is a constant value given as an initial input force to simulate the observer moving the tool within a body cavity or a friction component from a trocar, $K*x^n$ was taken from the simulated nonlinear materials found in Long et al. (2014), d_1 is the location where tool makes contact with the actual material (training=0mm, testing= 1.75 mm), and d_2 is the location of the break point. It should be noted that the C in this experiment is very small (0.25N) in order to give slight force for the beginning of the testing profiles and kept constant in the training profiles to eliminate any effects it could have on participants.

Procedure

After completing an informed consent and a series of demographics questions (Appendix A), observers were briefed on the overview of the experiment and the tasks they were to complete. An introductory training phase was conducted before the experimental phases which presented the observer with a single nonlinear material in both break and non-break conditions. First, observers explored the version of the nonlinear material containing a true breaking point; this demonstrated actual failure of a tissue with excessive force. They then explored the same material using a non-break profile where the force would remain constant at the designated breakpoint. Presenting the tissues in this order allowed for observers to understand the theoretical break point in non-break materials. This phase allowed for observers to become familiar with the laparoscopic tool and simulator as well as the basic nonlinear properties of the virtual materials. The observers used their self-chosen dominant hand in all pre- and experimental trials

This experiment utilized a training phase and a testing phase. The training phase used materials that would truly break and the testing phase used the theoretical non-breaking materials that were previously discussed. In both phases subjects were asked to probe forward, pause, and state when they felt they had reached the material's breakpoint which was recorded.

Training Phase. For the first task, observers explored the seven simulated materials by applying forces until they felt they had reached the breakpoint (see Figure 4). If they used excessive force, resulting in the material breaking, it was marked as an error and terminated that particular trial. Trials in which observers applied excessive force and caused the tissue to break were repeated at the end of the list of profiles. If they did not break the tissue then after they stated that they had reached the break point (which was recorded) they were allowed to look at the visual feedback to correct their estimation to the point of break. If the participants' stated break point was less than 75% of the distance to the actual break point then the participant was informed of this fact and the trial was also repeated at the end of the list of profiles. Thus the observers repeated trials where they either broke the simulated tissue or where they indicated the break point to be too far from the actual break point until they successfully completed the 28 trials (7 materials x 4 presentations).

Once they had used the visual feedback to correct their estimation, they then were instructed to break the material, return to the starting position and break it again. This allowed for participants to feel the entire material's profile as well as to receive haptic feedback.

Testing Phase. Observers took a five-minute break between the training phase and the beginning of the testing phase. This task allowed for participants to push into the material and reverse the tool until they felt comfortable that they had reached breakpoint. This phase used the seven nonlinear materials and the two linear materials (see Figure 5) and was presented to the observer in a randomized order three times for a total of 27 trials (9 materials x 3 presentations).

Metrics for Analysis

Distance. The distance which the participant moved the tool within a trial is broken down by distance to material (*dm*) and displacement distance (*d).*

Distance to Material* (*dm).This distance is defined as the distance traveled by the input device from the beginning of the movement to the point where the simulated material began to deform. This was 1.75 mm for all of the testing materials.

Displacement distance (d). This distance is defined as the distance traveled by the input device into the simulated material after the material had begun to deform. It is represented by encoder units in the simulator and transformed into centimeters by physically measuring absolute distance traveled by the input device to the breaking point for each material. Essentially this is the overall distance profile for a material (the start and end of the material).

Reactionary force. Force is broken down into two groups, absolute reactionary force (*F*) and rate of change in force *(*ΔF*).* Rendered voltage were used in the designing of the material profiles meaning that the parameters for material breaking point and the material's rate of change in force (ΔF*)* can be defined by the rendered voltage.

Currents were recorded from the simulator and transformed into Newtons using the following equation:

$$Force\ (N) = \frac{Torque}{radius * \sin(\theta)} = \frac{K\tau \cdot i}{radius * \sin(\theta)} \tag{6}$$

Where

$$K\tau = 1.5\ {}^{Nm}/_{A}$$

radius= 33mm and θ is the angle between the force vector and the lever arm vector. The angle is changing with the movement of the tool from 60° to 130°.

Reactionary force in terms of both current (i) and Newtons are displayed in Table 1 for training materials and table 2 for testing materials..

Table 1. Metric qualities defining each training material.

Material Profile	K	Power	Distance at starting point		Distance at break point		Reactionary Force at starting point		Reactionary force at break point	
			EU	mm	EU	mm	i	N	i	N
1	$7.2*10^{-7}$	4	0	0	50	12.5	0.17	0.25	4.67	7
2	$1.5361*10^{-10}$	6	0	0	60	15	0.17	0.25	7.33	11
3	$4.3916*10^{-11}$	6	0	0	70	17.5	0.17	0.25	5.33	8
4	$3.4769*10^{-15}$	8	0	0	80	20	0.17	0.25	6.00	9
5	$8.9051*10^{-16}$	8	0	0	90	22.5	0.17	0.25	4.00	6
6	$6.5*10^{-16}$	8	0	0	100	25	0.17	0.25	6.67	10
7	$1.4773*10^{-16}$	8	0	0	110	27.5	0.17	0.25	3.33	5

Table 2. Metric qualities defining each testing material.

Material Profile	**K**	**Power**	**Distance at starting point**		**Distance at break point**		**Reactionary Force at starting point**		**Reactionary force at break point**	
			EU	mm	EU	mm	i	N	i	N
1	$8.2667*10^{-7}$	4	7	1.75	57	14.25	0.17	0.25	5.33	8
2	$3.9866*10^{-7}$	4	7	1.75	67	16.75	0.17	0.25	5.33	8
3	$2.1519*10^{-7}$	4	7	1.75	77	19.25	0.17	0.25	5.33	8
4	$1.2614*10^{-7}$	4	7	1.75	87	21.75	0.17	0.25	5.33	8
5	$7.8748*10^{-8}$	4	7	1.75	97	24.25	0.17	0.25	5.33	8
6	$5.1667*10^{-8}$	4	7	1.75	107	26.75	0.17	0.25	5.33	8
7	$3.5289*10^{-8}$	4	7	1.75	117	29.25	0.17	0.25	5.33	8
8	N/A	N/A	7	1.75	87	21.75	0.17	0.25	5.33	8
9	N/A	N/A	7	1.75	87	21.75	0.17	0.25	7.33	11

Absolute Reactionary Force (F). This force is defined as the force the observer encounters as a result of increase displacement of the tool. The reactionary force that the simulator renders is transformed into Newtons from rendered voltage that is recorded by the simulator. Performance is compared to this metric to determine any perceptual thresholds for DTB estimates. The material breaking points were defined by the *maximum reactionary forces* or the maximum voltage rendered by the simulator. Each material had its own breaking point voltage.

***Rate of change in Force* (Δ*F*).** The materials' profiles are defined by rate of change in the force: whether they are nonlinear or linear, the physical profiles of the materials (i.e. a steep slope is a rapid rate of change in the force component.) Performance is compared to this metric to determine any perceptual thresholds for DTB estimates.

Performance. As previously defined in Long et al. (2014), accuracy is the difference between the participants' estimated breaking point location and the actual breaking point location for each profile (estimated location- actual location). This accuracy metric was used for both the breaking point location and material contact location for each material and is considered the Constant Error (CE) (Schmidt &Lee, 1988). Since non-break profiles allowed for the possibility for observers to go beyond the hypothetical breaking points, the difference between the estimated and actual location could be positive, which would indicate participants went beyond the hypothetical break points, or it could be negative which would indicate that the participant did not apply enough force to break the material. Absolute Error is the average absolute deviation without respect to direction from target. This measure is especially sensitive to the degree of error in an observer's estimation. (Schmidt & Lee, 1988).

Results

One participant (22) was excluded from the study due to more than 28 breaks in the training phase. An additional three participants (14, 25, and 28) were excluded from the data analysis due to their inability to comprehend and complete the testing phase. Therefore, a total of 27 participants' data was used in conducting analysis. Due to simulator error or experimenter error, there were 15 trials that were lost in the training phase and 2 trails lost in testing phase. These account for about 1% of the total number of trials.

Outlier analysis

Linear regression models predicting distance estimates from actual distance were conducted for training and testing phases in order to obtain standardized residuals. These standardized residuals were analyzed and were determined to not contain any outliers.

Performance

Distance: Distance was assessed by analyzing the displacement into the simulator material in millimeters. Table 3 displays means and standard deviations of the estimated distances by material type and experimental phase. A visual depiction of the estimated break point distance and the actual break point distance with the different types of materials are depicted in Figure 6a for training and 6b for testing. While material 8 and 9 were both linear they were treated as different types of materials for the visualization. There were 27 participants used in this analysis.

Table 3. Material profiles' break point distance estimate means and standard deviations by experimental phase.

Metric	Training				Testing			
Distance	Profile	Actual Distance	M	±SD	Profile	Actual Distance	M	±SD
(mm)	1	12.5	11.42	0.67	1	14.25	14.79	4.62
	2	15	13.25	0.65	2	16.75	17.07	4.53
	3	17.5	16.12	0.80	3	19.25	18.86	3.91
	4	20	18.62	0.63	4	21.75	20.96	4.04
	5	22.5	21.60	0.59	5	24.25	23.63	4.62
	6	25	22.82	0.96	6	26.75	25.34	4.73
	7	27.5	26.38	0.94	7	29.25	27.35	4.34
					8	21.75	17.48	6.81
					9	21.75	13.41	6.21
Overall			18.58	5.03			19.86	6.69
n Trials			741				727	

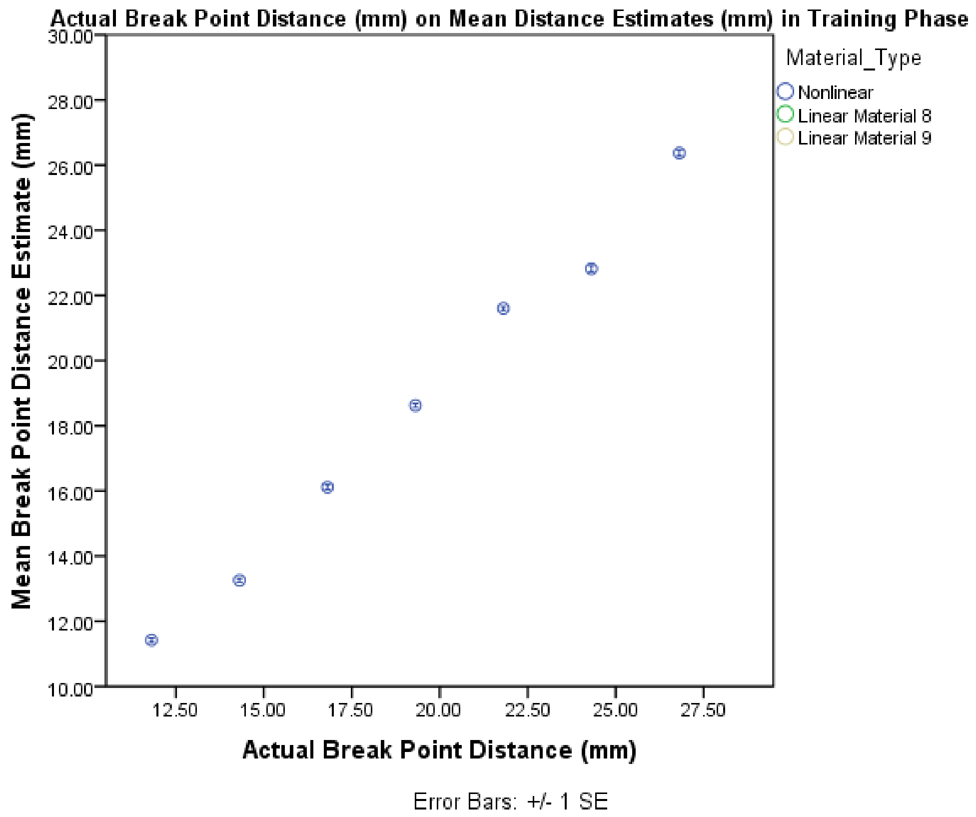

*Figure 6a***.** Mean break point distance judgments as a function of actual break point distance for the training phase

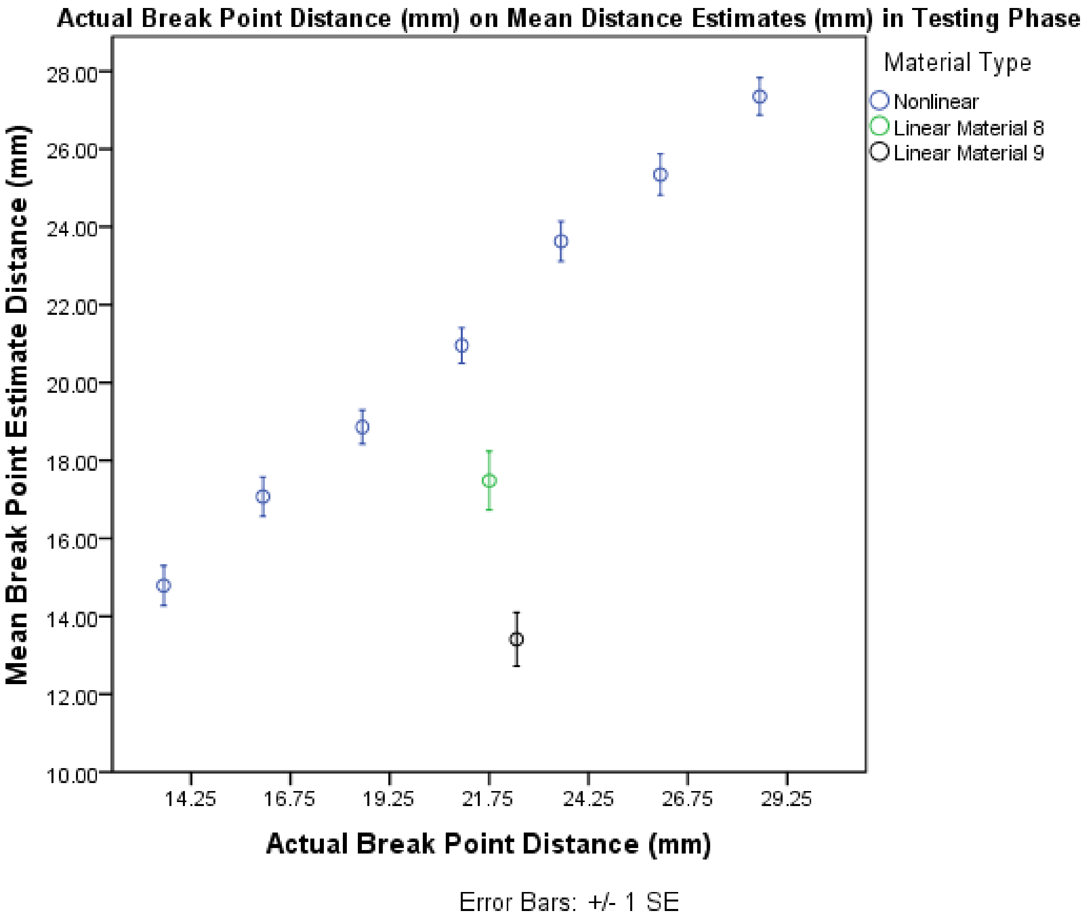

*Figure 6b***.** Mean break point distance judgments as a function of actual break point distance for the testing phase

An independent samples t-test was conducted to compare the distance estimates of the two linear materials. It was determined that there was a significant difference in the distance estimates for material 8 (M= 17.482, SD=6.409) and material 9 (M=13.408, SD= 5.715); t(52)=2.465 , p=0.017. These results indicate that participants were unable to determine the break point of the linear materials due to the lack of the DTB invariant.

To measure accuracy, the difference between participants' estimates and actual target distances were calculated and combined for each participant between each type of tissue. The linear tissues were separated and labeled as their material numbers. Therefore, there were three type of tissues examined: nonlinear (materials 1-7, ordered from least to greatest distance), linear material 8 and linear material 9 (with the higher force value at breakage). Nonlinear materials were also broken down by task. Constant Error (CE) and Absolute Error (AE) were calculated using the techniques discussed in Schmidt (1988). These measures were conducted only using the distance metric in mm. Individual participants' CE and AE for the different types of material and tasks where applicable can be seen in Table 4. A visual depiction of the CE for the different types of materials and task can be seen in Figures 7a and 7b. A perfect performance would be result in a zero. Positive numbers indicate participants going past the breakpoint and negative numbers indicate stopping before the breakpoint. It was better performance to have stopped before the breakpoint i.e. not breaking the material with excessive force, causing trauma.

Table 4. Constant Error (CE) and Absolute (Error) of deformation estimations between materials and tasks.

	Training		Testing Nonlinear		Testing 8		Testing 9	
Participant	CE Dist	AE Dist	CE Dist	AE Dist	CE Dist	AE Dist	CE Dist	AE Dist
1	-1.47	1.47	-2.61	2.61	-10.40	10.40	-17.04	17.04
2	-2.15	2.15	-4.88	4.88	-14.03	14.03	-16.43	16.43
3	-1.11	1.11	-2.69	2.69	-4.87	4.87	-8.66	8.66
4	-1.31	1.31	-1.21	1.41	-5.98	5.98	-8.01	8.01
5	-1.10	1.10	-.73	1.73	-3.63	3.63	-4.74	4.74
6	-1.41	1.41	-1.99	1.99	-7.10	7.10	-12.05	12.05
7	-1.32	1.32	1.01	2.62	2.60	2.60	-1.32	1.35
8	-1.12	1.12	-1.93	3.46	-10.93	10.93	-12.54	12.54
9	-1.31	1.31	-2.71	2.93	-7.96	7.96	-10.36	10.36
10	-1.80	1.80	-.10	1.83	-2.76	2.76	-2.81	3.17
11	-1.52	1.52	-6.82	7.55	-13.17	13.17	-17.50	17.50
12	-1.39	1.39	-3.14	3.77	-.45	.45	-5.28	5.28
13	-1.62	1.62	5.93	6.31	6.85	7.15	2.93	2.93
15	-1.17	1.17	1.27	2.82	.74	2.70	-11.93	11.93
16	-1.54	1.54	-2.01	2.15	-7.59	7.59	-10.19	10.19
17	-2.10	2.10	-2.73	2.73	-11.84	11.84	-9.29	9.29
18	-1.32	1.48	-1.96	2.01	-5.20	5.20	-11.10	11.10
19	-1.31	1.47	-2.15	2.20	-6.68	6.68	-13.08	13.08
20	-1.30	1.30	-2.83	2.83	-7.39	7.39	-11.76	11.76
21	-1.44	1.44	2.38	4.45	6.85	6.85	-3.18	6.76
23	-1.55	1.55	-.98	3.31	-8.96	8.96	-11.72	11.72
24	-1.28	1.28	-2.22	2.22	-7.71	7.71	-9.45	9.45
26	-1.04	1.04	2.39	3.97	.87	2.82	-3.51	3.51
27	-1.28	1.28	-2.50	3.74	-9.20	9.20	-13.50	13.50
29	-1.86	1.86	2.99	6.00	9.41	9.41	4.58	5.46
30	-.94	.94	3.74	3.80	5.04	5.04	-3.63	3.63
31	-.85	.85	3.44	3.53	-1.73	1.73	-3.67	3.67
Mean	-1.39	1.39	-0.85	3.32	-4.27	6.82	-8.34	9.08
STD	0.31	0.31	2.88	1.48	6.41	3.52	5.72	4.60

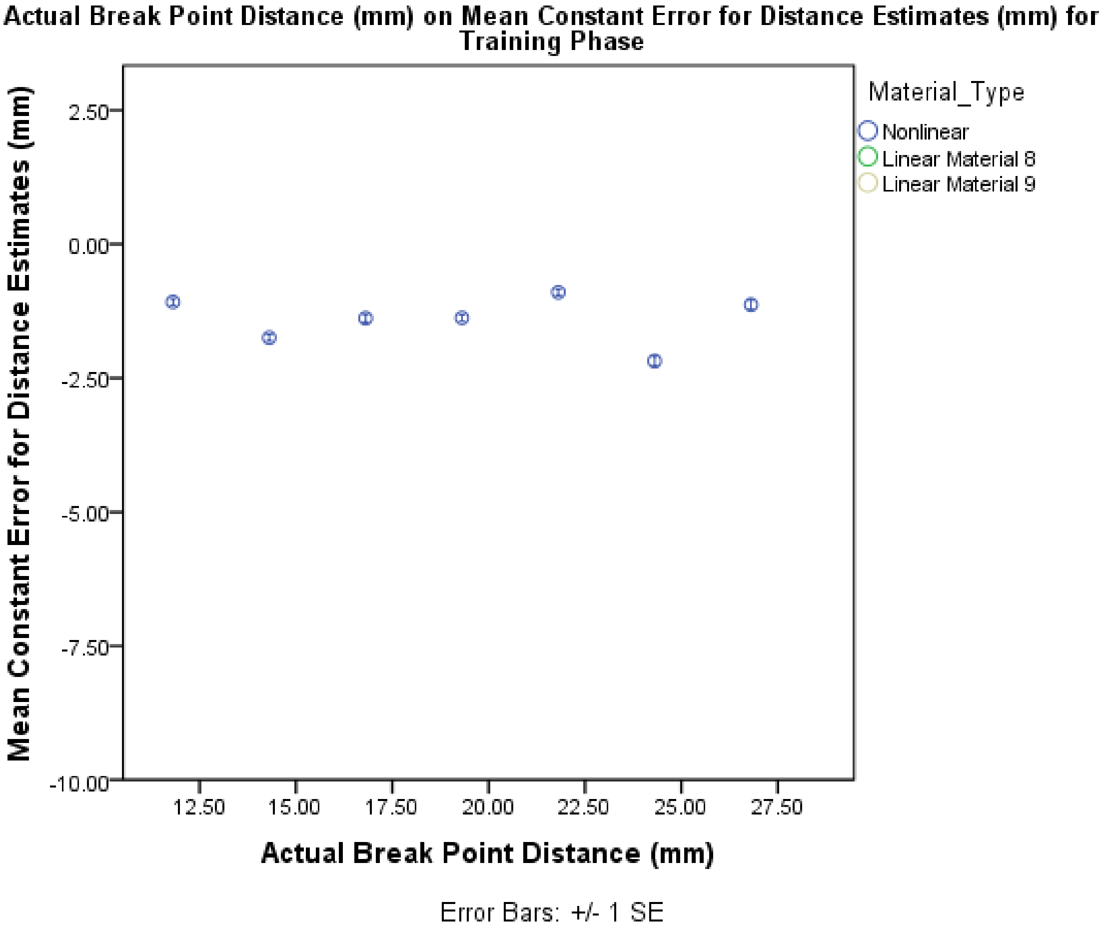

Figure 7a. Mean constant error for the participants' distance judgments as a function of actual break point distance for the training phase.

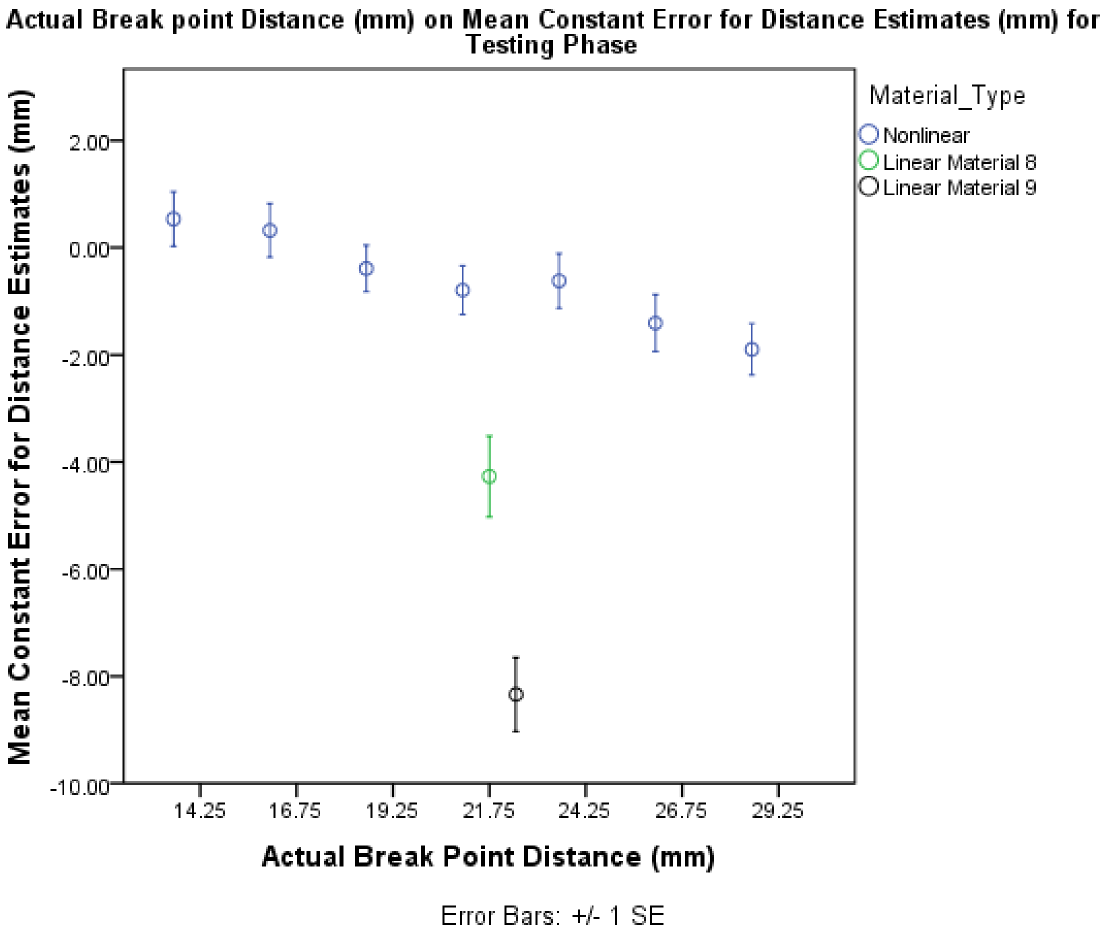

Figure 7b. Mean constant error for the participants' distance judgments as a function of actual break point distance for the testing phase.

A simple regression was conducted to determine if AE means could be predicted from trial numbers in the training phase. The model was significant, *F*(1,740)=10.17, *p*=0.001, yielding an r^2=0.014. The regression can be seen in Figure 8. The negative slope of -0.009 indicates that as the participants become more attuned to the DTB invariant through the training their error rate reduced.

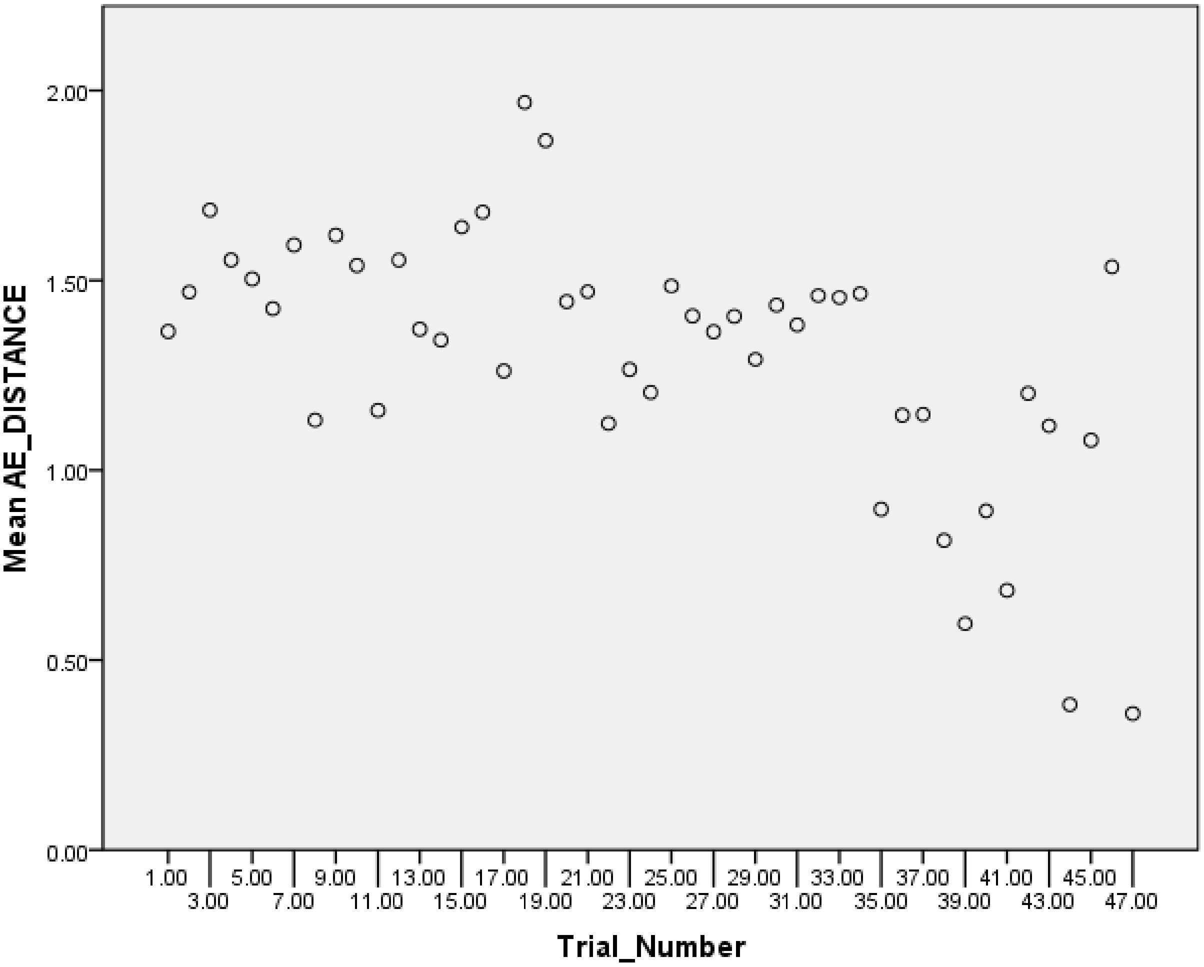

Figure 8. Mean absolute error for the participants' distance judgments as a function of trial number for the testing phase.

A one-way ANOVA was conducted to compare the types of materials in the testing phase (Nonlinear, material 8, material 9) with both constant error and actual error. There was a significant difference between the constant error values between the different types of materials at the $p<0.05$ level [$F(2, 78)= 13.882$, $p<0.001$]. Post hoc comparisons using the LSD test indicated that the mean CE score for the nonlinear materials (M=-

0.852, SD=2.88) were significantly different than both the material 8 profiles (M=-4.268, SD=6.410, $p = 0.019$) and the material 9 profiles (M=-8.342, SD=5.716, $p < 0.001$). It also showed that the two types of linear materials 8 and 9 were also statistically different from each other in constant error ($p<0.01$).

There was a significant difference between the absolute error values between the different types of materials at the $p<0.05$ level [$F(2, 78) = 19.127$, $p<0.001$]. Post hoc comparisons using the LSD test indicated that the mean AE score for the nonlinear materials (M=3.316, SD=1.481) were significantly different than both the material 8 profiles (M=6.822, SD=3.517, $p<0.001$) and the material 9 profiles (M=9.078, SD=4.598, $p< 0.001$). It also showed that the two types of linear materials 8 and 9 were also statistically different from each other in constant error ($p= 0.019$).

Force: Force performance was assessed by analyzing the displacement into the simulator material in Newtons. Table 5 displays these means and standard deviations of the estimated distances by material type and experimental phase. A visual depiction of the estimated force point distance and the actual break point force with the different types of materials are depicted in Figure 9a for training and 9b for testing.

Table 5. Material profiles’ break point force estimate means and standard deviations by experimental phase.

Metric	Training				Testing			
Force	Profile	Actual Force	M	±SD	Profile	Actual Force	M	±SD
(N)	1	11	5.046	1.027	1	8	5.808	2.057
	2	7	5.545	1.502	2	8	6.087	1.988
	3	8	5.146	1.362	3	8	6.002	1.982
	4	10	5.347	1.288	4	8	5.987	2.032
	5	6	4.484	0.839	5	8	5.956	1.875
	6	9	5.172	1.586	6	8	5.747	2.075
	7	5	3.682	0.886	7	8	5.641	1.935
					8	8	5.852	1.864
					9	11	6.340	2.849
Overall			4.924	1.374			5.936	2.090
n Trials	741				727			

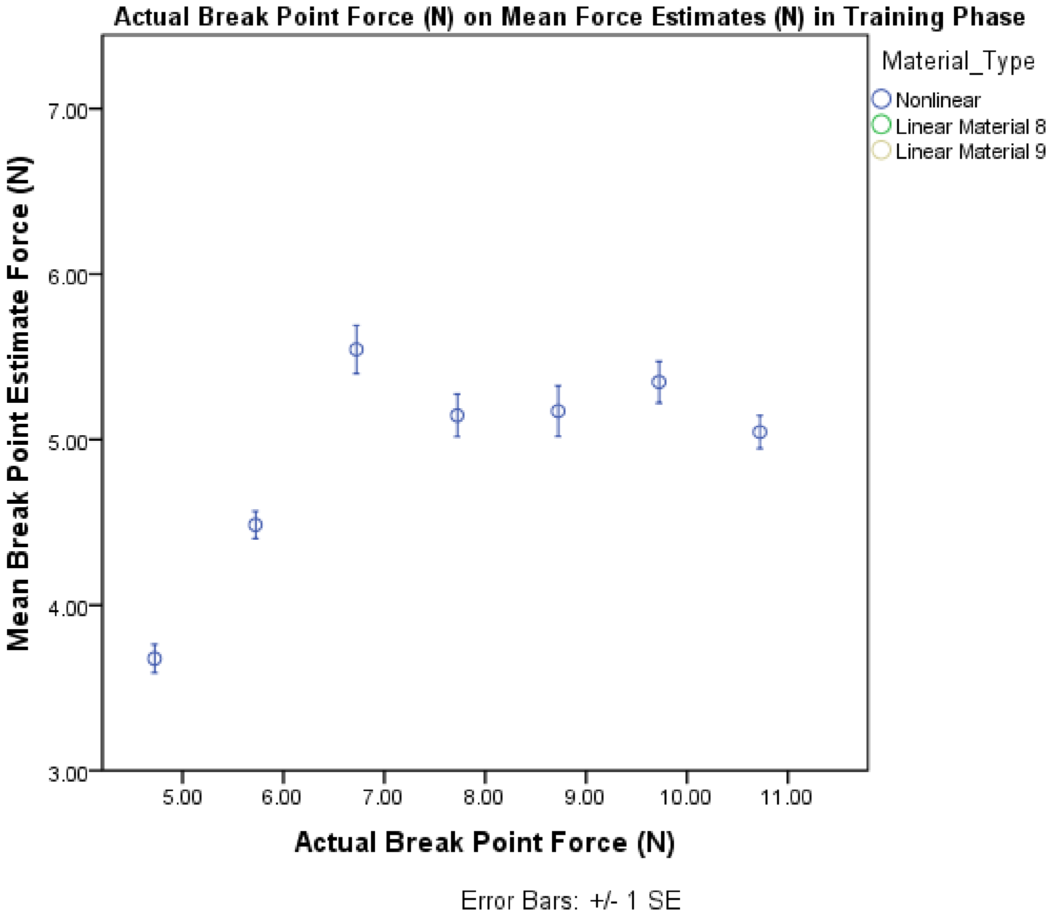

*Figure 9a***.** Mean break point force judgments as a function of actual break point force for the training phase. [Note: Force estimate values do not track as well to actual values compared to the estimated and actual distance values, because the force values have an exponential relationship. Therefore, while only being a small value of distance off, the participants could be very off in the force estimation.]

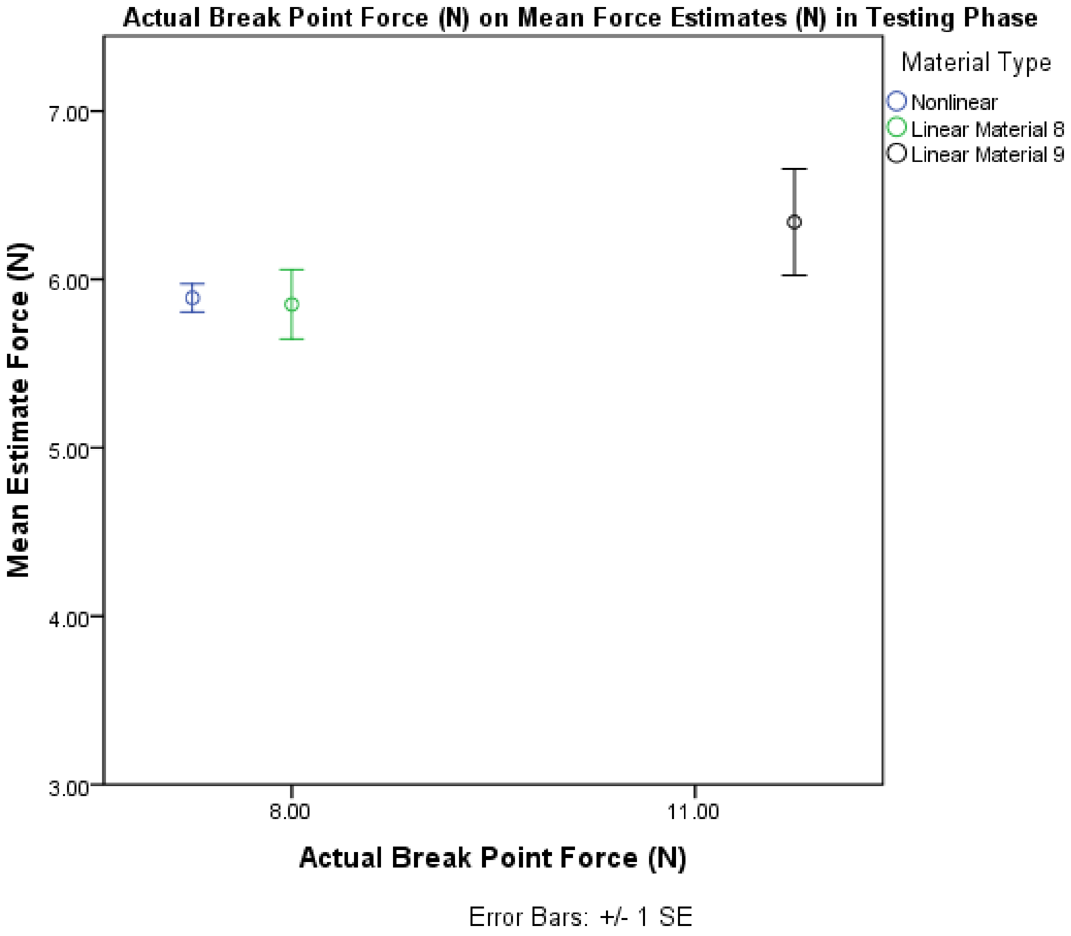

*Figure 9b***.** Mean break point force judgments as a function of actual break point force for the testing phase

A one-way ANOVA was conducted to compare the estimated force values between each of the materials in the testing phase with a force value of 8N at the breaking point. There was not a significant difference between the estimated force values between the different types of materials at the $p<0.05$ level [F (7, 638) = 0.458, $p=0.865$]. This demonstrates that overall, participants were estimating similar force feedback for the materials with the same actual force.

A one-way ANOVA was conducted including the 9th material which broke at a force value of 11N and was also found to not have a significant difference between the estimated force values between the different types of materials at the $p<0.05$ level [$F(8, 718)= 0.784$, $p=0.617$]. This demonstrates that overall participants were estimating similar force feedback for all of the materials regardless of the actual force breaking point. This suggests that there could potentially be a maximum force threshold that participants will not push past regardless of the invariant. An LSD post hoc test also showed that there was not a significant difference between material 8 and 9 ($p=0.138$).These findings between the two linear materials that have two different force break point values demonstrates that participants were unable to perceive the breaking point for both of them accurately.

Perception of DTB

To ascertain if observers were using the DTB invariant to determine the break location for the materials, simple regression models were used to find the slopes and intercepts to predict estimated distance from both actual distance and force for each participant in both phases. The r^2 values, slopes and intercepts for the training phase for both distance and force for each participant can be seen in Table 6. The 7 original training profiles depicted in Figure 5 resulted in an $r^2=0.33$, a slope= -0.23, and an intercept of 12.6 for simulated break distance estimated from the force at the break distance. For the testing phase only the nonlinear profiles were included, because of this and the use of the same actual force used for all profiles, a simple regression was not conducted for actual force for this phase. The r^2 values, slopes and intercepts for the testing phase for the distance metric can be seen in Table 7.

Table 6. Training phase: Individual participants' regression coefficients predicting observer estimated distance from actual distance and actual force.

Training						
	Distance			Force		
Subject	r2	Slope	Intercept	r2	Slope	Intercept
1	0.98**	0.98	-1.02	0.26**	-1.25	28.82
2	0.96**	1.04	-2.92	0.39**	-1.65	31.03
3	0.98**	0.97	-0.43	0.37**	-1.48	30.74
4	0.98**	1.03	-1.78	0.38**	-1.62	31.57
5	0.98**	0.97	-0.46	0.37**	-1.49	30.98
6	0.98**	0.97	-0.85	0.35**	-1.45	30.19
7	0.98**	0.95	-0.28	0.26**	-1.22	28.28
8	0.99**	1.04	-1.84	0.34**	-1.52	31.06
9	0.98**	1.02	-1.81	0.36**	-1.60	31.40
10	0.97**	0.93	-0.34	0.36**	-1.39	29.31
11	0.97**	0.95	-0.59	0.31**	-1.35	29.25
12	0.98**	1.01	-1.59	0.36**	-1.54	30.93
13	0.96**	0.98	-1.24	0.37**	-1.52	30.53
15	0.98**	0.96	-0.36	0.31**	-1.34	29.56
16	0.99**	0.95	-0.59	0.32**	-1.36	29.31
17	0.97**	1.02	-2.41	0.39**	-1.61	30.80
18	0.97**	1.05	-2.34	0.38**	-1.67	32.07
19	0.97**	1.04	-2.34	0.28**	-1.40	29.88
20	0.98**	0.98	-0.85	0.31**	-1.38	29.73
21	0.97**	0.97	-0.91	0.29**	-1.34	29.07
23	0.97**	0.96	-0.74	0.38**	-1.50	30.43

24	0.99**	1.06	-2.45	0.36**	-1.59	31.51
26	0.99**	0.98	-0.75	0.31**	-1.38	30.35
27	0.99**	1.01	-1.38	0.36**	-1.51	30.82
29	0.97**	1.00	-1.77	0.37**	-1.53	30.35
30	0.99**	0.98	-0.58	0.22**	-1.19	28.20
31	0.98**	1.01	-0.94	0.33**	-1.49	30.89
Mean	0.98	0.99	-1.24	0.34	-1.46	30.26
SD	0.01	0.04	0.78	0.04	0.13	1.02

*p<0.05, **p<0.01

Table 7. Testing phase: Individual participants' regression coefficients predicting observer estimated distance from actual distance for the nonlinear profiles.

Testing

	Distance		
Subject	r2	Slope	Intercept
1	0.81**	0.74	2.61
2	0.96**	0.79	-0.26
3	0.99**	0.90	0.75
4	0.95**	0.95	0.60
5	0.89**	0.69	6.32
6	0.94**	0.93	-0.39
7	0.74**	1.04	1.26
8	0.96**	0.77	1.57
9	0.88**	0.85	1.29
10	0.85**	0.99	1.18
11	0.34**	0.61	-1.06
12	0.94**	0.98	0.32
13	0.31**	0.79	12.34
15	0.92**	0.95	0.41
16	0.96**	0.88	0.32
17	0.93**	0.89	-0.11
18	0.95**	0.88	1.01
19	0.94**	0.86	0.88
20	0.97**	0.88	-0.16
21	0.29*	0.65	12.00
23	0.96**	0.80	1.60
24	0.96**	0.91	0.25
26	0.56**	0.61	12.55
27	0.86**	0.70	2.42
29	0.38**	0.80	9.94
30	0.87**	1.11	1.15
31	0.88**	0.88	5.82
Mean	0.81	0.85	2.75
SD	0.22	0.13	4.16
	*p<0.05, **p<0.01		

For each participant, the number of actual breaks in the training phase and the trials that would have resulted in breaks had the material actually broken in the testing phase were monitored. Also, the trials that participants failed to deform the material past 75% of the distance profile were recorded for both tasks. The number of breaks and the number of trials that were less than75% of the profile for both tasks are presented for each individual participant in Table 8. The number of breaks and number of trials that were less than 75% of the profile for each of the materials in the testing phase are recorded in Table 9.

Table 8. Sum of trials that broke or failed to deform the tissue less than 75% of distance profile by participant for both tasks.

	Training		Testing	
Participants	Breaks	<75%	Breaks	<75%
1	10	0	0	3
2	0	0	0	3
3	6	0	0	3
4	5	0	2	3
5	5	0	7	1
6	12	0	0	3
7	5	0	18	0
8	5	0	0	3
9	8	0	1	2
10	7	0	11	1
11	6	0	0	3
12	11	0	5	1
13	7	0	23	0
15	9	0	7	3
16	4	0	0	3
17	4	2	0	3
18	7	1	1	3
19	11	0	1	3
20	7	0	0	3
21	13	0	19	3
23	4	0	0	3
24	5	0	0	3
26	19	0	20	0
27	9	0	0	3
29	4	0	26	0
30	19	0	22	0
31	13	0	20	1
Mean	7.96	0.11	6.78	2.11
SD	4.38	0.42	7.00	1.23

Table 9. Sum of trials that broke or failed to deform the tissue <75% of distance profile by materials for the testing phase.

Material	Breaks	<75%
1	24	0
2	28	0
3	23	0
4	21	0
5	23	0
6	23	0
7	14	0
8	18	0
9	9	57

A one-way ANOVA was conducted to compare the nonlinear and linear profiles for the number of breaks and the number of failed <75% distance trails in the testing phase. Breaks and failed trials were coded with a "2" while correctly completed trials were coded with a "1" in SPSS. There was a significant difference in the number of breaks between the two types of materials at the $p<0.05$ level [$F(1, 725)= 9.302$, $p=0.002$]. Nonlinear profiles (M=1.28, SD= 0.448) had statistically more breaks than linear profiles (M=1.16, SD= 0.368). There was also significant difference in the number of failed (<75%) distance trials between the two types of materials at the $p<0.05$ level

[*F*(1, 725)= 9.302, *p*=0.002]. Nonlinear profiles (M=1.00, SD= 0.000) had statistically less failed distance trials than linear profiles (M=1.35, SD= 0.479).

Discussion

The present study's goal was to further the exploration of the DTB theory. It was important to investigate whether observers were truly using DTB to stop before the failure point of the tissue or if they were stopping on the basis of some other component such as just the increase in force. Therefore, linear materials were added to the testing phase that enabled us to test for the use of a specific force value to determine breaking point instead of DTB, as well as if observers were simply stopping once they felt any amount of force. We hypothesized that participants would be able to attune to DTB even with the non-specifying variables being included in the testing phase.

Regression analysis of the estimated distance predicted from actual distance in the testing phase replicated the findings of Long et al. (2014). We can infer from this replication that the reactionary force was the basis for the perceptual judgments even though we were unable to do regression analysis for this task. This can also be seen with the regression analysis of the training phase. Since participants had to make their first initial judgment before feedback, we can determine that they were using the rate of change in reactionary force as they actively deformed the material. The material profiles used in the testing stages strengthen these results with the 7 nonlinear profiles breaking at different distances but at the same force values. These results demonstrate that participants were able to perceive the different break points using the change in reactionary forces as the distance into the materials increased. This perceptual coupling indicates that observers were attuning to the DTB invariant with a high level of sensitivity. This is also evident since the only material that had failed <75% distance estimates was material 9. If participants were simply stopping when they felt any type of force change, more of the materials would have failed distance estimates. We can conclude from this that participants are not basing their estimates just off of an arbitrary change in force but instead were using the rate of change in reactionary force coupled with the displacement distance as the tissue was penetrated.

Another indication that the DTB invariant was needed to determine the breaking point was the results of the independent samples t-test between the two linear materials. This test showed that the distance estimates were different between the two materials even though they have the same distance profiles. Thus, participants were unable to determine the breaking points for these profiles. The results from the CE and AE between the nonlinear profiles and the two types of linear profiles also demonstrate that participants needed the DTB invariant for accuracy and precision for their estimations. As seen in Table 3, Material 9 had the highest amount of variance as well as the highest estimated force mean. This indicates that participants were unable to accurately determine the break point for this material. It also suggests that participants may have been using the knowledge from the nonlinear materials with their break points and attempted to apply it with the linear profiles even though the linear materials do not have the DTB invariant like the nonlinear materials.

We had hoped that this study would enable the further development of the DTB perceptual theory and give the necessary data to support the equation that was previously proposed for DTB. Unfortunately, the effects of the linear materials were not considered when this study was initially developed. Based on the decrease in the r^2 values from the training phase to the testing phase (individual r^2 values decreased from 0.976 to 0.814), we cannot determine if it was due to the difference in the tasks or if it was an effect of the linear materials on the performance of the nonlinear materials.

We were also not able to determine if the linear materials actually created a maximum force threshold. This maximum force threshold would be a force value that participants stopped at regardless of where they were in the material. The one-way ANOVA that was used to analyze the estimated force values between the materials showed that there was not a statistical difference between the different types of materials. This could be because there is a maximum force threshold but it could also be a result of the linear materials affecting the estimations of the nonlinear profiles.

It should be noted that the average estimated force values increased from the training phase to the testing phase. We cannot confidently attribute this to any one aspect without performing a future experiment without the inclusion of the linear profiles. If the force values increase from the training phase to the testing phase then it could be attributed to participants becoming more sensitive to the DTB invariant through the training. If it does not increase from the training phase or decreases then the linear profiles positively influenced the nonlinear profiles of this study.

Unlike what we originally predicted, the nonlinear profiles were broken more than linear profiles in the testing phase. However, material 9 was the only material that had failed <75% of the distance trials. The breaks of the nonlinear profiles could have been affected by the inclusion of the linear profiles. It is necessary to conduct an experiment without the linear profiles to determine if the linear profiles affected the ability for participants to determine the breaking point of the nonlinear profiles especially the 9th material that had steeper slope and a higher force value of 11N than the rest of the materials.

As previously discussed, one of the future experiments that are necessary to find further support for the DTB perceptual theory and equation is this current experiment without the linear profiles in the testing phase. This "control smaple" would enable us to compare a control sample without the linear profiles with this present study's results. This comparison would allow us to infer about the findings in this current research such as any effects that the linear profiles had on the nonlinear profiles. Even if the linear profiles affected the nonlinear profiles, there was still a high amount of variance that was explained in this research. It is believed that without the effects of the linear profiles, we will get a more accurate understanding of DTB and that will enable us to either find evidence for the proposed equation or determine a different equation.

Additionally a replication experiment with testing profiles that broke at 11N should also be conducted to determine if there is a maximum force threshold. If participants still maintain similar force estimation points as the current research, then it can be inferred that they are stopping at some maximum force point that they do not feel confident in passing or perceive as a breaking point because of the force value.

Another experimental idea is looking at absolute force threshold. This experiment would be designed to investigate absolute threshold sensitivity for material contact as well as DTB in nonlinear compliant materials. It is hypothesized that observers would be able to attune to initial contact with the materials with faster rate of force change and will have smaller deformation distances for the linear materials. This is an important experiment because it will also expand our understanding of how sensitive surgeons are when coming into contact with materials.

Conclusion

The ability to accurately perceive biomechanical information in MIS is necessary for minimizing unnecessary tissue trauma and errors. Understanding the sources of haptic information, such as DTB, that MIS surgeons can utilize in performing their tasks and establishing that users can become attuned and calibrated to these sources of information can assist in developing proper training simulators, tools, and even independent surgical robotic systems. The present study explored nonlinear and linear materials to find further support for the perception of DTB. This study determined that observers were still able to attune to the DTB invariant even when linear tissues, which did not have the DTB invariant, were interspersed in the testing materials. The findings of this study also replicated and strengthened the previous findings of Long et al. (2014). Understanding this theory is imperative for programing training simulators as well as surgical robotic systems that requires the equation so that it can artificially “feel” the invariant similar to the haptic perception of its human counterparts.

The current experiment and proposed future experiments enable the development of not only the DTB theory but also our basic understanding of how humans perceive forces during haptic exploration. This is beneficial not only in our comprehension in haptic perception in MIS but could also assist in redesigning other types of work environments. For example, if we can successfully determine the DTB equation, this haptic feedback can be artificially rendered for controllers in aviation and robotics or other applications where users must attune to information pertaining to changes in force application. This opportunity to develop more types of haptic feedback for human users can evolve our warning systems and our ability to develop more artificial sensory technology to assist everyday users.

Appendix

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:

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