Proceedings Paper:

Fakhoury, E, Culmer, PR and Henson, B (2015) The effect of indentation force and displacement on visual perception of compliance. In: Colgate, JE, Tan, HZ, Choi, S and Gerling, GJ, (eds.) Proceedings. 2015 IEEE World Haptics Conference (WHC), 22-26 Jun 2015, Chicago, IL, USA. IEEE , pp. 88-93. ISBN 978-1-4799-6624-0

https://doi.org/10.1109/WHC.2015.7177696

The Effect of Indentation Force and Displacement on Visual Perception of Compliance

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Abstract— This paper investigates the effect of maximum indentation force and depth on people's ability to accurately discriminate compliance using indirect visual information only. Participants took part in two psychophysical experiments in which they were asked to choose the 'softest' sample out of a series of presented sample pairs. In the experiments, participants observed a computer-actuated tip indent the sample pairs to one of two conditions; maximum depth (10mm) or maximum force (4N). This indentation process simulates tool operated palpation in laparoscopic surgery. Results were used to plot psychometric functions as a measure of accuracy of compliance discriminability. A comparison indicated that participants performed best in the task where they judged samples being indented to a pre-set maximum force relying solely on visual cues, which demonstrates the effect of visual information on compliance discrimination. Results also show that indentation cues such as force and deformation depth have different effects on our ability to visually discriminate compliance. These findings will inform future work on designing a haptic feedback system capable of augmenting visual and haptic information independently for optimal compliance discrimination performance.

I. INTRODUCTION

Laparoscopic surgery (LS) or minimally invasive surgery (MIS) is a type of surgery in which entire procedures are performed through small incisions in the abdomen via long tools. Surgeons use these tools to perform several tasks, including palpating tissue to check for tumors and unhealthy tissue [1]. Today, operations such as splenectomy and cholecystectomy are performed using laparoscopic surgery [2]. LS has gained considerable popularity all over the world due to its significant advantages which include shorter hospital stay, minimal invasiveness, reduced operating time and quicker recovery time. While LS is considered a viable substitute for open surgery in numerous procedures, it still has some disadvantages that are yet to be resolved. Surgeons rely on limited haptic feedback from tools which are inserted into small incisions, making the process more difficult than open surgery [3]. Perhaps the greatest limitation in LS is the reduced haptic feedback translated to the surgeons where they are forced to rely on feedback from long slender tools inserted into tiny incisions, as opposed to directly using their hands such as in open surgery [4]. Laparoscopic instruments can often result in excessive use of force leading to unintended tissue scarring [5]. Kazi investigated the effect of force feedback in LS [6]. Results showed that the introduction of force feedback could reduce the maximum exerted force by up to 40%.

Visual information is provided to the surgeon through a 2D monitor display as opposed to direct vision in open surgery. Tavakoli et al showed that haptic feedback can be replaced with visual on-screen feedback during basic LS tasks in order to reduce the exerted forces [7]. It is clear that both haptic and visual feedback play a vital role in haptic perception tasks such as palpation. Robotic assisted laparoscopic surgery (RALS) provides more haptic accuracy as well as an improved stereoscopic viewport as in the case of the DaVinci robot (Intuitive Surgical Inc., Sunnyvale, California) [8]. This sort of robot, however, lacks haptic feedback forcing the surgeon to rely on stereoscopic vision provided by the DaVinci [9]. Alternatively, the MiroSurge robotic system (DLR, Robotics & Mechatronics Center) allows performing minimally invasive procedures with force and torque feedback present. This system, however, remains a prototype mainly used for research.

A basic yet necessary method of examination in any kind of diagnostic or surgery is palpation. Surgeons and clinicians use either their fingers (open surgery) or tools and graspers (LS, RALS) to feel and examine properties such as the stiffness, size, and texture of tissue or organs. Stiffness perception can be thought of as the rigidity of an object. A major risk in LS is the potential for tissue trauma through factors such as reduced haptic and visual feedback resulting in an excessive use of force. Thus, it is important to understand the psychophysical mechanisms involved in palpation so this situation can be addressed. The simplest most repeatable form of palpation is indentation as it can be a controlled steady motion in a single axis. Previous work exploring the effect of haptic and visual feedback on the perception of compliance used experiments where participants actively or passively indented soft samples using either their index finger or a stylus [10], [11], [12].

Previous research has shown the importance of visual information during haptic discrimination [10], [11]. Fakhoury, Culmer & Henson [11] also revealed a visio-haptic cross-modal integration during compliance discrimination. This current paper builds on our previous work by highlighting the integration of indirect visual and haptic information. The work described in this paper investigates the effect of applied force and displacement during haptic indentation on our ability to accurately discriminate the softness of compliant objects using only indirect visual information. The experiments focus on the

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visual discrimination of compliant samples that are indented using either a maximum indentation force or depth.

II. BACKGROUND

A. Compliance and softness

Compliance is the inverse of stiffness. The stiffer an object, the greater its resistance to deform from an applied force and the less compliant it is. When surgeons palpate tissue either with their hands or with laparoscopic graspers, they get information about the mechanical properties of the tissue from its stiffness and elasticity. While the properties of tissue are non-linear, previous research uses linear models to approximate the properties of tissue [13]. Linear compliance can be expressed as the Young's modulus of Elasticity (E) or as its Stiffness constant (K). Compliance was chosen as the physical measure of interest in this study because of the reasonable assumption that there is a correspondence between compliance and people's perception of softness. While the perception of softness is likely to be also related to other physical measures such as the way in which a deforming surface distributes pressure over the fingertip [14], in this work we use the term 'softness' as the psychological reference to the human perception of compliance.

B. Compliance discrimination using a tool

Haptic perception using a tool has been extensively investigated by several researchers especially in the fields of LS and RALS. LaMotte showed that haptic perception using a tool can be as effective as haptic perception through direct cutaneous information [15]. However, other researchers concluded from their studies that the use of graspers while manipulating tissue greatly diminishes a surgeon's ability to accurately discriminate compliance of tissue [16].

C. Effect of vision on compliance discrimination

Visual information has been shown to greatly affect our ability to perceive the compliance of objects [12]. Kuschel et al focused on the integration and separation of vision and touch during haptic perception. Their results suggested that contribution of a sense cue depends upon its level of reliability at any given time [17]. Johnson, Burton & Ro (2006) investigated visually induced feelings of touch. Their results indicate that when haptic feedback is distorted, participants relied more on visual feedback. This further emphasizes the importance of visual information in LS. Using a pseudo-haptic feedback system, Li et al showed that visual information can be used to correctly identify virtual tumors [18]. By manipulating the speed and size of an on-screen cursor, they were able to simulate varying stiffness levels. Hachisu et al augmented vision and tactile vibration cues in a pseudo-haptic feedback system in an attempt to improve the vibrational sensory experience while exploring the material stiffness of fabrics and virtual objects [19].

Our previous work has investigated the effects of the varying types of visual sources on compliance discrimination [11]. Using four 'two alternative forced choice' (2AFC) indention tasks in which either direct visual cues, 2D indirect visual cues or no visual cues were present. Results showed that visual information influences compliance perception. Fakhoury et al also revealed a cross-modal integration between vision and touch that is in need of optimization [11].

III. METHODS

Twelve participants took part in two 2AFC experiments; one where maximum indentation force was fixed and the other where the indentation distance was fixed.

A. Participants

Twelve participants (9 male and 3 female) took part in both tasks of this study. All participants were postgraduate students at the University of Leeds with ages between 23 and 34. Participants had no eyesight impairments according to a completed questionnaire. None of the participants had any medical or surgical background. Ethical approval was acquired prior to the experiment.

B. Samples

Eleven silicone-mixture samples (Fig. 1) were used in this study. Silicone has been used in previous research to represent varying levels of compliance [11],[20]. Each sample measured 5 cm diameter base width by 2 cm depth, with a truncated conical shape. The samples were dyed in a skin colour pigment without affecting their material properties to mask any discoloration different samples had due to varying compliance values. With stiffness ranging between 0.1 and 0.16 N/mm, which is within the range of measured stiffness of pig tissue [21], each sample had a unique compliance determined by its stiffness and damping coefficients but all samples were identical in shape, size and colour.

1) Sample fabrication: The desired compliance values were obtained by mixing a two-part silicone-based polymer (Plastil, Mouldlife) with a plastisizer into different ratios. Plastils A and B were mixed with plastisizer (A : B : Plastisizer) to create samples with unique compliance values. These ratios ranged from 1:1:2.6 (least compliant) to 1:1:4 (most compliant). A mold was used to cast the samples. In order to prevent any adhesion or friction property inconsistency, all samples were encapsulated with a polyurethane coating.

2) Sample compliance testing: A Modular Universal Surface Tester (MUST) was used to measure indentation depth and force over time. Each sample was indented by a hemispherical hard tip with an 8 mm diameter at a rate of 0.2mm/s until a maximum force of 500 mN was attained, resulting in a force-displacement profile. This process was repeated 5 times for each sample. The responses show a viscoelastic force-displacement behavior similar to that in biological tissue [22].

3) Model fitting: The indentation force-displacement data were fitted to a Kelvin-Voigt model. Defined in (1), this model has been used to characterize the viscoelastic behavior of liver tissue [13] and similarly provides a good representation of the sample responses used in our previous work [11]:

$$\varepsilon(t) = \varepsilon_{\infty}\left(1 - \exp\left(\frac{-t}{\lambda}\right)\right) \quad (1)$$

Where , $\lambda = \frac{Kv}{Ke}$, K_e is the linear spring constant, K_v is the linear dashpot constant, $\varepsilon_\infty \equiv F/(K_eL_0)$ is the long time limit of the strain, μ is the damping coefficient, F is the applied force, L_0 is the deformation length, and t is the instantaneous time recorded.

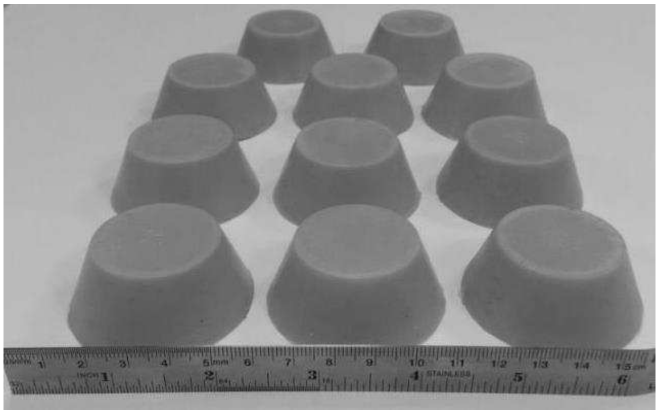

Figure 1. The set of 11 samples used in the study.

C. Experiment set-up

Eleven samples with spring and dashpot constants found in table 1 were used in these experiments. Each participant was presented with a total of 200 recorded clips of sample pairs being. For each of the fixed force and fixed depth experiments, 10 unique recorded video clips were created. Each of these clips was presented 10 times in random order resulting in a total of 100 clips per experiment per participant. In order to prevent extraneous factors from unknowingly affecting our results, the positions of the test sample and the reference sample were randomly altered and the order of all runs was selected for each participant using a 4×4 Latin square design [23]. Moreover, the order in which the fixed-force and fixed-depth condition clips presented was also randomized to avoid learning habits and errors.

The duration of each clip was 30 seconds in which the samples were indented 3 times in alternating order at a constant speed of 50mm/s. The indentation speed was the same in both fixed force and fixed depth conditions. In any given recording or run, one of the two samples presented side by side as seen in Fig. 2 was the reference sample; located at the centre of the sample compliance range (sample 6). The other sample which was continually changed was the test sample. It should be mentioned that the participants were not informed about the fixed conditions of the experiments (fixed force or depth).

We set up an indentation rig (Fig. 3) using a linear actuator (SMAC Inc. USA, LCA50-025-7) coupled with a 6 degree-of-freedom (6-DOF) force transducer (ATI, Nano17). Aluminium framework (Bosch, Rexroth) was used to assemble the rig. A hemispherical tip with a diameter of 8mm attached to the actuator end effector was used to indent the samples. Force and position data were controlled and measured using a LabVIEW (National Instruments) program. Using a high definition webcam (Microsoft Lifecam Cinema), we recorded all sample indentations at an angle typical of a person's line of sight while seated under constant lighting conditions.

1) Experimental condition #1 - Maximum depth: The actuator was programmed to indent the samples at a constant rate of 10 mm/s until a maximum indentation depth of 10mm into the sample was reached, disregarding the force required to reach that depth. Most tumor sizes range from a few millimeters to 20 cm [24], so an indentation of 10mm depth represents an approximate average depth within that range during palpation. The eleven samples had different compliance values and hence required different forces to reach the 10mm required depth.

2) Experimental condition #2 - Maximum force: The actuator was programmed to reach a desired indentation force of 4N in line with previous research investigation palpation of human tissue [25]. Using the load cell to measure the vertical loading force, values were communicated to the actuator which in turn indented the samples until that predetermined maximum force was reached.

D. Experiment design

Participants were seated in front of an HD (1920x1080p, 60Hz) monitor display (Dell P2214H) shown in Fig. 2. They were all given standard introductions to the experiment and given an experimental procedure and protocol to read and sign their agreement to take part in these experiments. At any given time, two samples were presented side by side on the screen. Participants were asked to observe as the metal tip of the actuator indented both samples within each pair, and clearly state which of the two was in their opinion 'softest'. Each clip showed 2 samples side by side numbered '1' and '2'. Participants simply stated the number referring to the sample they believe was softer. Since this was a 2AFC experiment, a response was always necessary. If unsure or needed more time to make a decision, participants were allowed up to three repeats for each run.

TABLE 1. Linear spring and damping constants for all eleven samples.

Sample	Ke (N/mm)	Kv (N.s/mm)
1	0.160	0.0251
2	0.156	0.0240
3	0.151	0.0229
4	0.139	0.0192
5	0.130	0.0164
6	0.127	0.0160
7	0.120	0.0131
8	0.116	0.0129
9	0.113	0.0121
10	0.103	0.0097
11	0.100	0.0100

E. Psychometric function fitting

A psychometric function shows the relationship between the participants' subjective response to a physical sample and the measured intensity of the sample [26]. In this study, it shows the probability in which the compliance of each sample can be distinguished from the reference sample. The data is processed using a model capable or representing the behavior of a psychometric function. This model is usually a mathematical function having an 'S' shape such as logistic, Gaussian, or Weibull functions.

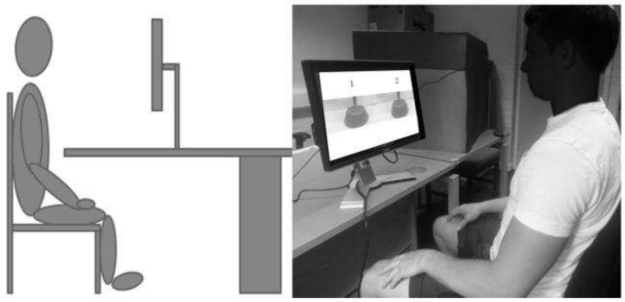

Figure 2. Experiment design and set-up.

The results of the two tasks were fitted with a parametric function referred to as the modified logistic function (2) which was found to be a good fit for psychometric functions in previous research [11], [27]. Using an iterative least squares method, the data collected from the participants was fitted to a logistic psychometric function P(x) using a mathematical modelling package (Mathworks, Matlab vR2011b).

$$P(x) = \gamma + (1\text{-}\gamma).\ \left(\frac{1}{1+(\frac{x}{\alpha})^{-\beta}}\right) \qquad (2)$$

Where γ is the probability of being correct by chance, β is the steepness of the function, and α is the sample intensity at the halfway point. Each of the two tasks is represented by a psychometric function defined by unique values of α, β and γ.

IV. Results

This paper used a two-alternative forced-choice experimental paradigm. The samples were presented in an order of increasing spring stiffness (K_e) and plotted against the percentages of correct responses by all participants. The psychometric data collected from the two experiments were fitted to the logistic model in Fig. 5. The x-axis represents the physical samples in order of increasing spring stiffness. The y-axis represents the participants' averaged responses, displayed as a 'percentage correct' proportion.

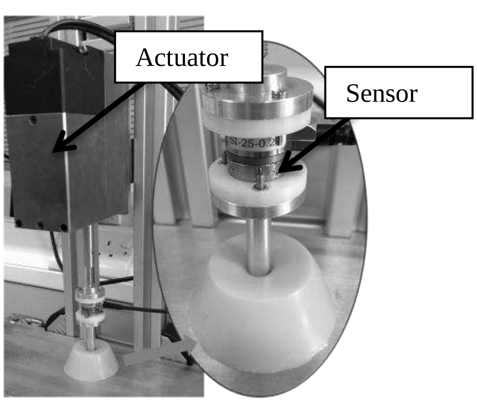

Figure 3. Sensor-actuator rig used to indent the samples.

The slope (β) of a psychometric function at the halfway point is an indication of compliance discrimination performance in our experiment. The more a psychometric function resembles a step function, i.e. the greater its slope at the halfway point (50% correct), the better participants are at precisely discriminating compliance. A psychometric function was used to analyze our data as our experiment implements the psychophysical method of constant stimuli in which a psychometric function is the most reliable function to determine the absolute threshold (α). The psychometric functions show that participants performed better when they were asked to visually judge compliance of samples being indented by the rig up to a set force of 4N than up to a set depth of 10mm ($\beta_{FF} = 80.82 > \beta_{FD} = 66.47$).

V. Discussion

The psychometric plots suggest that 2D visual compliance discrimination using maximum indentation force is superior to that using maximum indentation depth. In other words, visually judging the indention of compliant materials up to a set force provides better compliance discrimination performance than when samples are indented to a set depth. Participants were not informed about any indentation force or depth being set prior to the experiment and so they were naïve to the experimental conditions in both experiments. In the force controlled experiment, all the samples were indented until 4N was attained, disregarding indentation depth into each sample. Since the maximum force was fixed for all samples, the indenter tip traveled a longer distance into the more compliant samples than in the less compliant ones. This can be observed in Fig. 4. When participants are watching clips of samples being indented, they develop their own strategies to decide regarding the compliance properties of the samples. In the position controlled experiment, all the

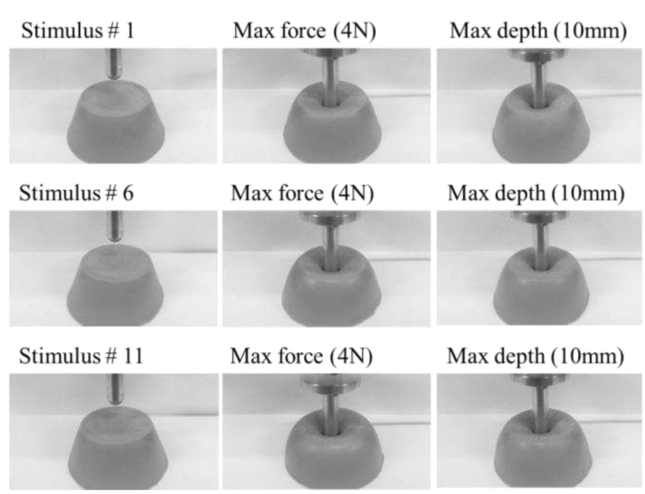

Figure 4. Samples # 1, 6, and 11 shown under maximum indentation force and depth.

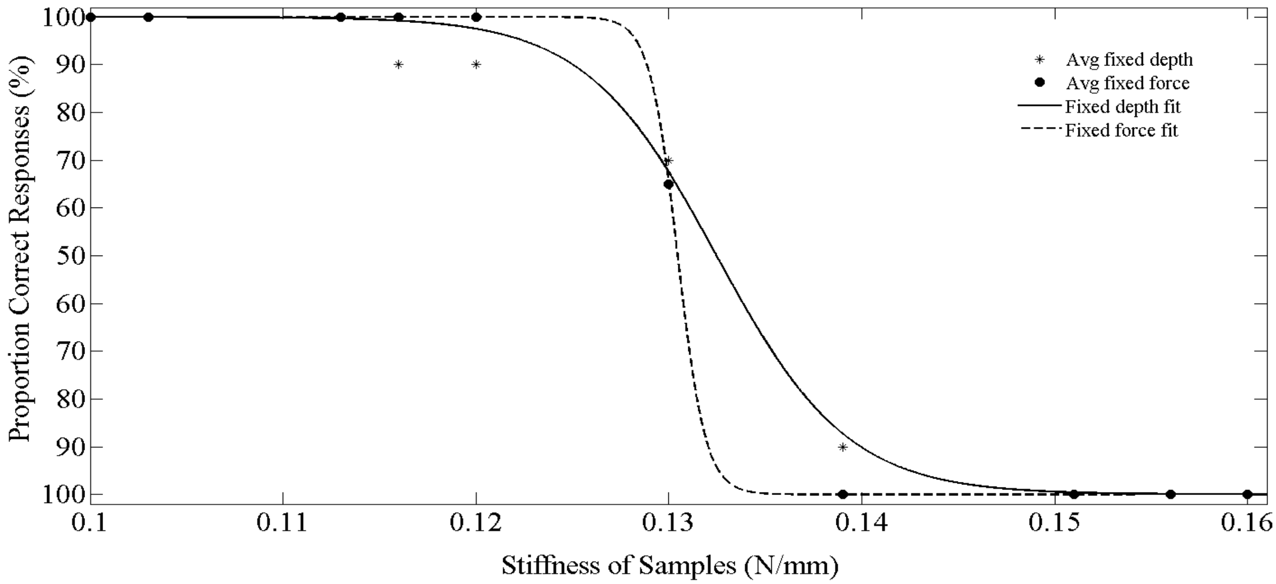

Figure 5. Psychometric functions plotted for the maximum indentation depth and force experiments, along with the averaged participants' responses for each sample.

samples were indented down to the same depth and so participants were forced to change strategies for this experiment. A post-experiment survey revealed that participants found this experiment more difficult than the fixed force experiment. A possible explanation for this phenomenon might be that in the fixed force experiment, participants unknowingly linked the variation in indentation depth with sample compliance. In the fixed depth task, however, participants were forced to focus on other cues such as the bulging of the sample edges, and the time it took for the samples' surface to reach its initial position after maximum indentation. Fig. 6 shows the standard deviations for both tasks. It can be observed that participants were less precise and hence found the tasks most challenging as the difference in compliance between the test and reference stimuli decreased. Samples 1 & 2 proved difficult to judge during the fixed depth experiment, possibly due to visual illusion dominance at low values of compliance.

The point of subjective equality (PSE), parametrized by α, is estimated from fitting our data to the logistic function. At the point of objective equality (POE), the test stimulus physically matches the reference stimulus (α = POE = 0.127). The closer the value of α is to the POE, the more accurate people are at matching physical stimuli to their corresponding stiffnesses at the centrepoint. From table 2, we can see that POE < α_{FF} < α_{FD} indicating that the fixed force experiment allowed the participants to more accurately judge compliance than in the fixed depth experiment. This result sheds light on how controlling force can influence our decision making process during compliance discrimination. Our results further demonstrate the impact of visual information on compliance discrimination which has been shown in previous literature [11],[12]. Moreover, indentation force and depth can influence our ability to accurately and precisely discriminate compliance. By independently analyzing the effects of indention depth and applied force on performance, we can use the data to set up a pseudo-haptic feedback system that could optimize this cross-modality in order to achieve better compliance discrimination performance in both real and virtual surgical tasks.

In LS, surgeons use long instruments to grasp and manipulate tissue while receiving haptic feedback via grasper handles. In RALS such as the DaVinci, surgeons remotely operate using graspers without the presence of any force feedback. Providing an on-screen visual force feedback during LS and RALS that displays a theoretical maximum force beyond which tissue damage would occur might reduce tissue scarring and improve surgeons' ability to discriminate the compliance of tissue.

TABLE 2. Extracted values of α and β for both psychometric function plots.

	$\boldsymbol{\beta}$	$\boldsymbol{\alpha}$ (Standard deviation)
Fixed force	80.82	0.1311 (0.5710)
Fixed depth	66.47	0.1336 (0.4786)

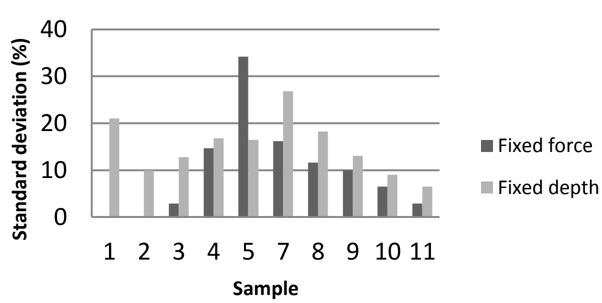

Figure 6. Standard deviations during the FF & FD experiments.

VI. CONCLUSION

In this paper, we investigated the effect of indention force and depth on our ability to discriminate compliance using only visual information. Previous work has shown the significance of visual cues during haptic discrimination [11],[12],[16]. Our results suggest that by controlling the force applied during indention, it is possible to improve our ability to discriminate compliance visually. Psychometric plots show that visual information alone, under constrained maximum applied force and depth, can be used to judge compliance of soft stimuli, shedding light on the importance of optimizing the visio-haptic cross-modality present during basic surgical tasks such as palpation in LS or RALS. Future work will focus on developing a haptic feedback system that separates visual and haptic information during indention to a maximum force or depth. The system will augment visual and haptic cues in an attempt to find an optimal combination of visual and haptic information that improves our ability to discriminate compliance.

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