REQUIREMENTS FOR A TACTILE DISPLAY OF SOFTNESS

Salima Ahmed Abreiak

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Abstract

Developing tactile displays is an important aspect of improving the realism of feeling softness in laparoscopic surgery. One of the major challenges of designing a tactile display is to understand how the perception of touch can be perceived with differences in material properties. This project seeks to address this limitation by investigating how the interaction of material properties affects perception of softness and to present the perception of softness through a tactile display.

The first aim explores how the interaction of material properties affects perception of softness through the use of two psychophysical experiments. Experiments used a set of nine stimuli representing three materials of different compliance, with three different patterns of surface roughness or with three different coatings of stickiness. The results indicated that compliance affected perception of softness when pressing the finger, but not when sliding; and that compliance, friction and thermal conductivity all influenced the perception of softness.

To achieve the second aim of reproducing various levels of softnesses, the tactile display was built at the University of Leeds. The displayed softness was controlled by changing the contact area and tension of a flexible sheet. Psychophysical experiments were conducted to evaluate how well humans perceive softness through the display. The data was analysed using MatLab to plot psychometric functions. The results indicated that the tactile display might be good for some applications which need to compare between simulated softnesses, but it might be insufficient for other applications which need to compare between simulated softness and real samples.

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Chapter 1
Introduction

1.1 Background

This research focuses on the perception of softness, which might be affected by other material properties such as compliance.

The perception of softness and compliance are important aspects for comparing between healthy and unhealthy tissues in the context of laparoscopic surgery. Compared to open surgery, laparoscopic surgery has several advantages such as minimizing tissue trauma, less post-operative pain, shorter recovery time, reduction in the length of hospital stay, and reduction in health care costs. In contrast, there are disadvantages; for example, higher injury rates, increased need of technical expertise, longer duration of surgery, difficultly of removal of bulky organs, and reliance on visual feedback to make decisions and complete procedures because of lack of haptic feedback. The lack of tactile feedback information leads to high demands on the surgeon’s skills and experience, and they must learn to adapt to this lack of information which is time-consuming and costly in terms of patient safety. It seems that loss of tactile feedback is a major disadvantage and plays an increasingly important role (Lee and Nicholls, 1999, Bholat Os Fau - Haluck et al., 1999, Eltaib and Hewit, 2003, Heijnsdijk et al., 2004, Tholey, 2005, Zhou, 2007, Cao et al., 2007, Schostek et al., 2009, Motoji et al., 2010).

Interest in using laparoscopic surgery is growing worldwide, although it removes much of the surgeons’ tactile sense. Surgeons do not just manipulate tissues and organs, also they detect physical properties: compliance and textures. Tactile information could be conveyed from an inaccessible location to the surgeon’s fingertips by sensors, signal processing algorithms, and tactile displays (Peine et al., 1994, Howe et al., 1995). In fact, a satisfactory solution for optimal tactile display has yet to be found, because there are still many unanswered questions about human softness perception and its relationship with material properties.

Laparoscopic surgery is a specialized technique for performing surgery and uses a laparoscope which is similar to a thin telescope which has a light source, inserted through small incisions to light up and magnify the structures inside the abdomen (Xin, 2009). While laparoscopic surgery has many advantages over conventional open surgery major disadvantage is the lack of any tactile information to the surgeon, which would normally be used in actions such as palpation. For this reason, research is being carried out into ways of providing tactile information in laparoscopic surgery through tactile sensors and tactile displays. It is envisaged that in such a system, the signals from the sensors would be sampled by a dedicated computer system, then conveyed to the surgeon through a tactile display recreating the remote pressure distribution on the surgeon's fingertips (Figure 1.1). The tactile sensors to be used would depend on the tactile properties to be displayed, and might measure tissue compliance, pressure distribution and/or pulsation. There are three approaches that could be used to display the tactile information to surgeons, each using different perception channel: tactile displays, visual displays and auditory displays. Visual displays present the tactile data visually to the surgeon, while tactile displays permit the surgeon to perceive the tactile data through the sense of touch. Auditory displays present the tactile data by acoustic signals. A tactile display might be the solution for presenting tactile data to the surgeons. The sensation of touching a soft object is given by increasing the contact area to the finger with increasing palpation force. The tactile display has the requirements of simulating feelings of softness and other physical properties (Schostek et al., 2009).

In order to present the information about texture, shape and compliance and to present tactile feedback in laparoscopic surgery, a tactile display could be used (Moy et al., 2000, Eltaib and Hewit, 2003). When the user cannot manipulate objects directly, building tactile displays which express small scale information about objects could be an alternative. One of the applications of these displays is in minimally invasive surgery (MIS) (Eltaib and Hewit, 2003, Ottermo et al., 2004, Moy et al., 2000, Jungmann and Schlaak, 2002). These requirements have been addressed through my research and emulated through the University of Leeds' tactile display.

This work is relevant because firstly, we need to understand how people can perceive softness and other material properties to know what to sense within the human body. These are addressed through the first two experiments in Chapters 3 and 4. Secondly, we need to know how this information can be displayed to laparoscopic surgery for discriminating tissue softness. For that reason, the tactile display has been tested as discussed in a third experiment in Chapter 5. In an implementation of the system, the tactile display combines with sensors and a laparoscopic tool. This system might be realised as shown in Figure 1.1. The figure shows that the system contains sensors and a tactile display. The tactile sensor measures a certain property through direct contact with the objects; for example, when the sensor is in a contact with patient's organs, tissue compliance is measured. Moreover, the tactile display provides the surgeon with tactile data obtained by the sensor. These data need to be presented to the surgeon in a convenient way. For that my research focuses on how we can test the display.

In this work, a softness haptic display based on the fingertip contact area was assessed to test whether humans can feel softness through the display. From previous researches, there are different tactile displays which present softness feeling. The display used in my research was built at University of Leeds based on research from University of Tokyo, 2012 (Kimura and Yamamoto, 2012). The softness feeling can be controlled by changing the contact area and pressure distribution over the fingertip . This device was tested and validated through this research.

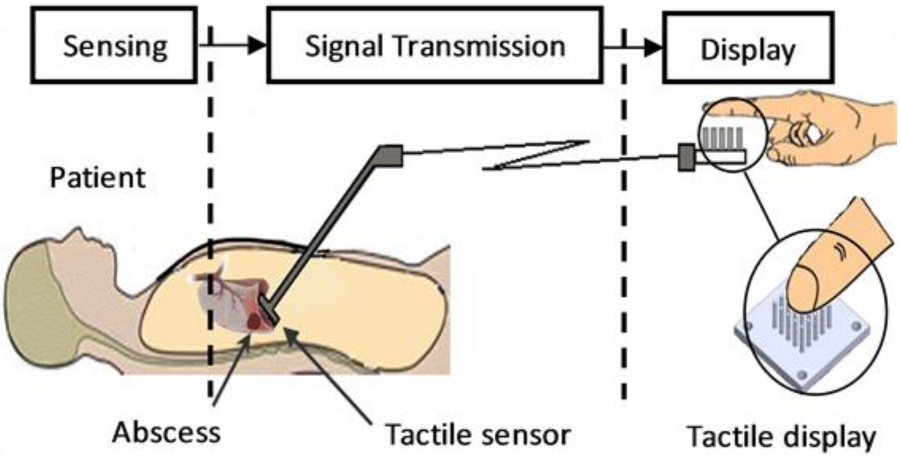


Figure 1.1 Example of a tactile perception system (Nader A. Mansour, 2014)

The display systems previous researchers have different implementations. A new tactile display has been made from a watery gel. Richter and his colleague combined this display with robotic surgery in order for surgeons to feel what robot fingertip feels. It also appears to be a good tactile display for communicating information for blind people (Richter and Paschew, 2009). Moreover, there is another application of tactile display by Massachusetts Institute of Technology researchers who will create new tactile display; this display depends on human skin to convey the information instead of the eyes. It will be a wearable display for impaired hearing or in noisy environments (Whitwam, 2013). An addition application of tactile displays is the new tactile system and algorithm which was developed by Disney researchers. This display might transform visual information into tactile sensations. This algorithm seems to lead to new applications for rendering tactile information (Harper, 2013). The tactile display is combined with a web cam to allow blind people to feel others' emotions. A novel thesis at Umea University in Sweden created Braille codification which combined with a tactile display and web cam to help blind or impaired in vision people to see other people's emotions (Dillow, 2010).

It seems to be difficult to design an ideal tactile display because of many questions about human perception and the lack of clear requirements of tactile display. One of the major challenges of designing the display is to match the perception of touch and how different material properties can be simulated in a virtual environment as opposed to a real environment. Moreover, tactile perception of a given property (such as softness) does not depend on that property alone. Therefore, a tactile display will need to compensate these properties to fully address the lack of feedback (Skedung et al., 2013).

Another challenge is the combination of cues; Shao et al. (2010) and others have done work to examine the relationships between perception and material properties and they determined some regression models. Therefore, we need to determine how cues are combined by investigating how the interaction of material properties affects the perception of softness. To test our findings from that, we tested a tactile display for softness and find out whether humans can feel softness through display as they can with real materials.

1.2 Motivation

There are many situations in which being able to judge the compliance of a surface is important. Surgery is one example, where tumours are detected by palpation, looking for harder patches amongst softer, healthy tissue. Yet we know that mechanisms by which the body detects material properties can be influenced by other factors. This can be important both in terms of determining how human judgements of material properties, such as softness, can be affected by other factors, and also in accurately reproducing sensations through tactile displays, which are proposed for use in situations such as laparoscopic surgery, where direct tactile feedback is not available.

A range of studies have explored the relationship between surface properties and human perception of them. Hollins et al. (1993) identified hardness-softness as one of the main subjective responses used by humans to discriminate surfaces, the other being roughness-smoothness. However, subjective perception of roughness and compliance can be affected by more than one physical parameter. For example, Chen et al (2009) found that judgements of hardness-softness depended on both compliance and cooling rate. Perceptions of softness or hardness can also be affected by factors such visual feedback and the mode of interaction (static or dynamic touch, for example) (Nakatani et al., 2010).

Shao’s research (2010) examined the relation between perception and physical properties. Their finding is the start point of our research. The people’s feelings were related to physical properties. For example, the hardness perception depends on compliance and thermal properties. Also, the perception depends on the material of samples. However, the samples tested were packaging materials and these material properties could not be controlled. My research assessed the regression model of relationship between material properties and perception of softness by making samples to control physical properties independently with the same compliance and different roughness and vice versa, and samples with the same compliance and different stickiness and vice versa .

This work investigates how subjective human perception of material softness is affected by the compliance, roughness and adhesion of a given material, and how these findings can affect presenting information through a tactile display. Displaying various softness feelings depends on the size of contact area and the pressure distribution over the fingertip. Leeds’s tactile display could present sensations which depend on the Young’s modulus applied to control contact area and the pressure distribution, as explained in Section 5.9.1.

1.3 Aim of thesis

This project seeks to address the limitations of designing tactile displays, by investigating correlations and relationships between material properties and the perception of softness, and emulating these relationships and softness feelings through a tactile display which has been constructed at the University of Leeds. The objectives and research questions are explained in Section 2.6.

1.4 General Contribution

This research presented a number of contributions to the field of application of perception of softness and softness tactile display. These are as follows:

1. Characterisation of the interactions between compliance, roughness, and adhesion that, in the context of my experiments, affect the perception of softness.
2. Confirmed previous work that, in the context of my experiments, shows that compliance, friction and thermal conductivity can affect perception of softness when the finger is sliding and pressing respectively.
3. Developed and demonstrated an approach to assessing the performance of a tactile display for softness.

1.5 Outline of the thesis

This thesis is organized into six chapters. This chapter provides an introduction to and motivation for my research in touch perception and tactile display and lists of contributions of this work.

Chapter 2 provides relevant background in human tactile sensing and perception. The role of human mechanoreception is outlined. This chapter also provides an overview of methods from psychophysics that are useful for evaluating human performance. Specific attention is given to the methods employed in experiments reported in Chapters 3, 4 and 5.. It provides a review of the literature related to haptic perception of compliance, and the effect of sensory cues on evaluation of the magnitude of compliance. Moreover, it provides investigation of compliance discrimination, investigation of the human fingertip’s discrimination and memory for perception of softness, and discrimination of softness for indirect contact. It provides a review of the literature in research related to tactile and force feedback in the medical field, the design of artificial systems, impact of force feedback, vision feedback and the experience of the surgeon. In addition it points out the review of the artificial tactile feedback in laparoscopic surgery, and the usefulness of haptic feedback for the expert and the novice surgeons.

Chapter 3 describes an experiment aiming to investigate the effect of surface roughness on perception of softness, describes the methodology and discusses the results and draws some conclusions.

Chapter 4 describes an experiment aiming to investigate whether the perception of softness is affected by adhesion, describes the methodology and discusses the results and draws some conclusions.

Chapter 5 describes experiments with the objectives to determine how well humans perceive the softness of compliant materials, and then compare it to how well we perceive softness through a tactile display. The method used to collect data, the experimental procedure, and the method used to analyse data are described.

Chapter 6 contains concluding remarks and discusses the results to draw conclusions. Suggestions for future work are also presented.

Chapter 2

Literature Review

The first section of this chapter will identify the extant research on the relationship between compliance and other material properties, such as roughness, and compare them to both direct and indirect touch. The second section will then review the research literature relating to the haptic perception of compliance, the effect of sensory cues on the evaluation of the magnitude of softness, compliance discrimination, the human fingertip's discrimination and memory for perception of softness, and discrimination softness for indirect contact. The third section will review the human's integration of information from different senses. That is, it will provide a review of integration modalities, such as the integration of visual and tactile signals and audio-tactile interactions. The final section will then provide a review of the research literature relating to tactile and force feedback in the medical field with reference to the design of artificial systems, the impact of force feedback, vision feedback and the experience of the surgeon, artificial tactile feedback in laparoscopic surgery, the usefulness of haptic feedback for both expert and novice surgeons, and the use of virtual reality simulators in the medical field.

2.1 Tactile sensation

The brain identifies sensory information about objects and their properties from the activity by the receptors of finger skin. This information is transferred from the finger to the brain as signals generated by receptors, which transmit information about the object that is touched by the finger, and the signals are mainly provided by glabrous skin (Hidaka, 2009, Riener and Harders, 2012). Srinivasan and LaMotte (1995) studied tactile sensation experiences in human beings, which enabled them to explain the relationship between the shear strain energy near tactile receptors and nerve signals. A stick-slip condition was identified through the examination of the shear strain distribution pattern inside an elastic finger at the finger surface during precision gripping (Maeno et al., 1998), and shear deformation inside finger skin has been found to play a role in recognising the geometry of objects. The most important elements used for investigating complex surfaces are thus the deformation of the finger and shear strain inside the finger.

The features of a human finger play a role in texture perception (Hidaka, 2009); the structure of the fingertip consists of tissue, bone and nail arranged in a roughly oval form, made up of tissue surrounding the bone to allow for precise grasping and manipulation. The role of the nail is to help secure the tissue and prevent the finger deforming too much. The skin is composed of different layers: the epidermis, the dermis and subcutaneous tissue. Within these layers are the mechanoreceptors, which encode the tactile information that is produced when people make contact with objects. There are four types of mechanoreceptors in the human finger—Meissner's corpuscles, Pacinian corpuscles, Merkel's discs, and Ruffini endings—two of which (Merkel's disks and Meissner's corpuscles) are located close to the surface near the epidermis, at 0.7-0.9mm below the surface, whilst the other two (Ruffini endings and Pacinian corpuscle) are located deeper in the skin, at 2mm below the surface (Figure 2.1) (Maeno et al., 1998, Hidaka, 2009). The mechanoreceptors detect different types of information: Meissner's and Pacinian corpuscles can detect surface roughness, with frequencies below 100Hz for Meissner's Corpusles and higher frequencies for Pacinian Corpuscles (Hidaka, 2009, Chouvardas et al., 2005, Siegel, 2002). The Merkel disks are associated with pressure and texture sensation, whilst Meissner's corpuscles are associated with low-frequency vibration (around 30Hz), Pacinian corpuscles are related to high-frequency vibration (with an optimal sensitivity of roughly 250Hz), and Ruffini endings detect skin stretch. Two characteristics categorise mechanoreceptors: their adaptation rate to stimuli (rapid or slow adaption “SAI, SAII”) and the size of their receptive area (a small or large area). Table 2.1 shows the summary of mechanoreceptor properties (Chouvardas et al., 2005, Siegel, 2002, Tegin and Wikander, 2005, Riener and Harders, 2012).

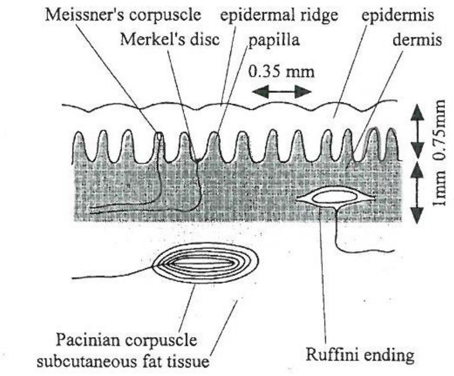


Figure 2.1 Types of mechanoreceptors in the human finger (Maeno et al., 1998).

Different mechanoreceptors produce different subjective sensations, depending on their mechanical stimulation. Tactual pressure sensation and vibratory sensation are considered to be the basic ones that the sensory receptors of the human skin produce and combine to provide tactile sensation. The lowest frequency at which a simple vibratory sensation can be detected is 89Hz (Konyo et al., 2003), and complex sensations appear to be produced by vibrations that combine frequencies (Konyo et al., 2000). Table 2.1 summarises the different functions and range of responsiveness of the different mechanoreceptors.

Table 2.1 Summary of mechanoreceptor properties (Tegin and Wikander, 2005, Riener and Harders, 2012)

Mechanoreceptor	**Type**	**Important stimulus**	**Type of response**	**Function**
Meissner’s corpuscles	FAI	Low frequency vibration (tapping) 10-60Hz	Transient	To detect low frequency motion and discriminate spatial localisation
Pacinian corpuscle	FAII	High frequency vibration (tbuzzing) 50-1000Hz	Transient	To detect high frequency motion and the travel of mechanical vibrations
Merkel’s cells	SAI	Perpendicular indentation (pressure) DC-30Hz	Sustained	To distinguish pressure magnitude and rates of change in pressure
Ruffini cylinder	SAII	Tangential displacement (friction and stretch) DC-15Hz	Sustained	To perceive skin stretch and discriminate spatial localization

Tactile sensation is received based on these skin receptors. Skin mechanoreceptors are responding to deformation of the skin and sense the material properties. The mechanoreceptors play an important role in tactile perception.

2.2 Tactual Perception

Tactual perception refers to sensations related to the sense of touch. Touch refers to the sensation arising through contact between skin and an object. Touch includes five sensations—contact, pressure, heat, cold and pain. As Berkeley (2003) puts it, “By touch I perceive hard and soft, heat and cold, motion and resistance, and all of these more or less either as to quantity or degree”. Berkeley (2003) reflected that objects and their physical properties could be accessed through touch. Objects can be pressed against the skin or slid over it, which can provide information based on shape, weight, temperature and material (Sabiri et al., 2008). My research focuses on information that can be provided through touching material, such as roughness, compliance, coldness and slipperiness. This research focuses on compliance and the perception of softness, as these forms of sense data are relevant for laparoscopic surgery, where human tissue is considered to be soft material.

Hollins et al. (1993) found that people receive many pieces of information from drawing their finger across an object’s surface. For example, (Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)(Hollins et al., 1993)multidimensional scaling analysis of the tactile texture perception of stimuli showed that perceptual space is most likely three-dimensional. Multidimensional scaling is used to position tactile surfaces into a perceptual space when the distance between two objects reflects their perceptual differentness. By using five rating scales to judge the stimuli, the two dimensions of smooth or rough and hard or soft could be identified (while the third dimension did not relate to rating scales).

The roughness of a surface through sliding contact has an impact on individuals’ feelings about that surface. This phenomenon has been examined in relation to cosmetics packaging, in which it was found that feelings which are dependent on surface roughness might be expressed better by some words. It was found that positive feelings are created in subjects when a surface is smoother than the subject’s fingertip (for example, an acid-etched rough glass surface), while negative feelings are generated when the subject rubs a surface that is rougher than their fingertip (for example, a grit-blasted rough glass surface) (Barnes et al., 2004).

Experiments to determine whether textures and touch conditions affect tactile form perception using “the sensory discrimination of a pattern or outline” have been undertaken by (Nakatani et al., 2010). They found that touch conditions (i.e. passive touch, active touch and static touch) may influence the effect that texture has on the perception of form.

Some studies have investigated the relationship between physical properties and texture perception. For example, Shirado and Maeno (2005) examined the relationship between physical properties and texture perception using multivariate analysis, and built a texture perception model of this relationship. To build the model, two steps were followed. First, they utilised Fechner’s (1907) finding that that there is a proportional increase in the magnitude of subjective sensation with the logarithm of stimulus intensity. The magnitude of sensation could determine from this equation: $\gamma = k\ (\log \beta/b)$ where k= a constant, dependent upon the unit selected and also the logarithmic system, b = a second constant which stands for the threshold value of the stimulus, at which the sensation g begins and disappears and β = relative stimulus difference. Secondly, they used a multiple linear regression analysis to measure the effect of rates of material determination. They found that the tactile factor score affected the physical values of the object’s surface and the rates of material determination. Using this work, they built a model to show the relationship between physical properties and textural perception. This relationship between human perception and material properties can be used as evidence for the current research, especially in terms of showing how physical properties affect perception of softness and hardness. The results suggest that the textures of different materials, together with their surface properties, influence the subjective ranking of compliance.

Bergmann Tiest and Kappers (2006) examined the relationship between perception and physical properties, using a free sorting of different material samples to compare psychological data with physical measures (compliance and roughness) rather than subjective impressions about samples. A wide range of materials was used in order to provide a basic understanding of the process of haptic perception of materials. They used two sets of stimuli for this; one for psychological characterisation, and another for the physical measurements of material parameters. The parameters examined were compressibility and roughness, which were the ones most mentioned in the literature. The samples were put in piles of at least two groups, and the results showed that perceptions of roughness and softness may depend on more than one physical parameter of the stimuli, and on correlations between physical properties.

Childs and Henson (2007) conducted experiments to evaluate people’s reactions and feelings about the physical features of surfaces based on touching patterns using two different types of polymer-based ink. Linear multivariate regression analysis established that the touch position depended on the roughness of the surface and the coefficient of sliding friction. The same group also examined the relationship between perception and physical properties. In of their studies they evaluated the feel of different materials using a multi-sensory tactile measurement system, and tested the relationship between the physical properties of materials and people’s feelings. Friction coefficient, roughness, compliance and thermal properties are the most common properties which relate to sensory feel (Chen et al., 2009b). Using multi-regression analysis, Shao et al. (2010) found that the feelings touch produces in people are related to more than one property; that is, people’s touch judgments depend on different physical measurements. Moreover, they found that thermal measurement strongly correlates to compliance of measurements, and that this relationship depends on the materials used in the samples. Their results thus explain an aspect of the relationship between physical properties and people’s feelings. They designed a new approach to identify whether touch perception was dependent on material properties, as it seemed to display a relationship between the perception of compliance and thermal properties. The same experimental design will be used in my research as that used by (Shao et al., 2009, Shao et al., 2010).

In addition, Chen et al. (2009b) studied the tactile textures used for food packaging in order to investigate the relationship between touch perceptions of tactile textures and physical properties (surface roughness, friction coefficient, compliance and the cooling rate of an artificial finger). According to Chen et al.’s (2009a) findings, touch perception is related to more than one physical property—for example, responses to the word pair (touch perception) wet-dry depended on the friction coefficient, compliance and surface roughness. Further research should be done to investigate the relationships that were found in this study, but these results nonetheless provide grounding for work on understanding these relationships.

Petrie et al. (2004) studied the relationship between physical characteristics and psychological perceptions of a set of stimuli using magnitude estimation to compare softness and smoothness between a test stimuli and a reference stimulus. They found that the relationship between the perception of the smoothness of a surface and the physical hardness of the samples was not significant, and that interactions with other variables (such as surface shape) were also not significant. They reported that the perception of softness and Shore hardness values seem to have a strong correlation. The reason for this is the complex relationship between adhesive forces which develop between the skin and the material’s surface, and how much the material and finger deform during stroking. The deformation depends on two factors; contact force and the stiffness of the material compared to the finger.

Carnahan et al. (2010) focused on the effect of temperature on surface perception. They examined illusory moisture perception—illusory wetness perception and the perceptions of illusory surface moisture—and its effect on temperature perception by the finger. They did this by using the friction coefficient between the surface and finger with cold surfaces and surfaces at room temperature. Using previous research, the effect that an object’s temperature had on grasping it was studied, and the illusory wetness perception by fingers was examined as an effect of force generation during grasping. The results showed there to be no significant difference in coefficients of friction between room temperature and cold conditions. In addition, more force was generated when participants held cold objects. (Tsuchimi et al., 2012) evaluated the relationship between tactile softness and stiffness through an experiment using silicone blocks having the same dimensions as each other but different Young's modulus values. A force sensor was used to measure the contact force when subjects touched the objects, and a paired comparison method was used to evaluate between the stiffness of blocks. The results showed that tactile softness depends on contact force, displacement of a finger, as well as size of contact area between the finger and object and variation of this size. These results could be used to design a tactile sensor system.

However, very little psychophysical work on wet-dry perception has thus far been undertaken, perhaps because none of the tactile receptors in the finger respond directly to water (Kandel et al., 2000).

Understanding the ways in which humans obtain the information about objects through their hand and skin sense has implications for designing tactile displays. For an example of the implications, it is important to understand to what extent humans can discriminate effectively through a tactile display. Also, how the tactile perception of material properties (compliance, roughness, thermal conductivity and friction) could emulate in a haptic display needs to be understood.

2.2.1 Active and passive touch

Katz and Krueger (1989) studied the way in which the relative motion of a sense organ can provide information about the object that it touches. The surface properties of objects (material, stiffness and roughness) can be discovered through finger motion across a surface (Katz and Krueger, 1989).The name given to this phenomenon is active and passive touch, where active touch refers to moving the finger over the surface of an object (the act of touching an object), and passive touch refers to moving an object over a fixed finger (being touched) (Gibson, 1962, Katz and Krueger, 1989).

Roughness can be detected by both active and passive surface touch (Hollins et al., 1993), and researchers have found that the active and passive methods produce similar perceptions of it (Lamb, 1983,(Lederman, 1982, Verrillo et al., 1999, Lederman, 1981) as well as similar degrees of accuracy in judgments concerning the haptic perception of roughness (Heller, 1989). In terms of the accuracy of static (passive) and dynamic (active) touch, dynamic touch appears to provide a better perception of the curvature of a surface than static touch does (Gandevia et al., 1992), although Pont et al. (1999) found that the perception of surface curvature was similar for both static and dynamic touch. This suggests that the mode of touch does not influence texture perception, and this is supported by the findings of other researchers (Taylor and Lederman, 1975).

In order to explore differences in discriminating information about rigid and deformable objects using active and passive touch, Srinivasan and LaMotte (1995) asked the participants to touch samples using active touch (kinaesthetic and cutaneous information), or using passive touch (cutaneous information). Kinaesthetic information refers to the sense of position and motion of limbs, while cutaneous information refers to the sense of the object’s nature through the skin. They found that more accurate information about deformable objects could be discriminated through passive touch than through active touch. On the other hand, the discrimination of information about rigid objects is better through active touch than through passive touch. In contrast, Bergmann Tiest and Kappers (2006) permitted participants in their experiment to use active touch because its use is believed to be less complicated. Other research has investigated which sensory cues (kinaesthetic and cutaneous) can influence the evaluation of the magnitude of softness through active and passive touch, and has found no significant difference in the softness ratings between two modes of contact (Friedman et al., 2008).

2.3 Compliance Discrimination and Contact Area

Haptic perception is important when interacting with compliant materials. Compliant materials are flexible and able to transfer mechanical forces through their rigid bodies. As such, compliant materials can form themselves around a finger, thus increasing the contact area which, in turn, has an effect on the perceived slipperiness and coldness of the material (Bergmann Tiest, 2010). When handling compliant materials, people have subjective perceptions of hard or soft, rough or smooth, sticky or slippery and warm or cold, but perception of hardness and perception of softness are the most important perceptions in relation to compliant materials. Softness can be measured by physical and measurable properties of compliance. Although a compliant object is not necessarily soft, ‘compliant’ and ‘soft’ are often used interchangeably (Srinivasan and LaMotte, 1995, Fujita and Ohmori, 2000, Xin, 2009). Soft objects are flexible and can change according to how they are used, while the compliance of objects is a fundamental property for discriminating between them, as well as for classifying and identifying them. An important property is human tissue softness in term of detection of tumours in surgery. The reason is because different tissues and organs have different softness; for example, tumours are harder than healthy tissues.

The purpose of this section is to provide a review of the research literature relating to the haptic perception of compliance, the effect of sensory cues on evaluation of the magnitude of compliance, the discrimination of compliances, the discrimination and memory of the perception of softness, and the discrimination of perception of softness during indirect contact.

To study the touch perception of compliance, both compliance and subjective perception must be quantified. Harper and Stevens (1964) used a range of compliant materials in their study of the touch perception of compliance, and the participants in their study were asked to rate the relative softness or hardness of each specimen made from these different materials, including close-textured sponge rubber, close-textured Neoprene and open-textured sponge rubber. Indentation was used to quantify the compliance of materials using the same weight, and the physical hardness was defined using the ratio of force to indentation (F/I). The subjective perception of hardness and softness increased as physical hardness increased, with an exponent of 0.8 or -0.8 respectively. The results of this study showed that there are significant limitations in the human ability to discriminate compliance, with more compliant material being difficult to discriminate. For extreme values of compliance, objective measurements and subjective judgments about softness differed significantly. Researchers (Harper and Stevens, 1964) were able to relate the objective measure (compliance) and the subjective sensation (perceived softness) by building a quantifiable model of compliance discrimination using a numerical ranking of perceived softness. This study had one shortcoming, however, which was that compliance was quantified without a control for surface texture. This means the influence that the textures of different materials and their different surface properties could have had on the subjective ranking of compliance are uncertain. Moreover, some factors were not taken into account in this research, such as the scaling of the hardness or softness of objects through kinaesthetic cues, tactile cues, and different modes of contact.

A study by (Friedman et al., 2008) was investigated which sensory cues (kinaesthetic or tactile) affect the evaluation of the magnitude of compliance. They used silicone rubber specimens with a range of compliances, all of which were more compliant than the finger pad. The experiment was designed to judge the magnitude of softness of five stimuli with different types of sensory cues and different compliance when participants were unable to see either their hands or the specimens. The tasks used in the experiments involved active and passive indentations made with a finger or stylus by pressing down with a finger or tapping with a tool. Kinaesthetic and cutaneous cues were available in some tasks and restricted in others. The displacement of both the finger and the specimen provided kinaesthetic cues, while the changing pressure distribution on the skin provided tactile cues. From the statistical analysis, the results showed that the magnitude estimates of softness increased as a function of compliance for pressing or tapping with the finger pad, but there was no significant difference in the softness ratings between the two modes of contact. In relation to the indentation of the passive finger pad, however, kinaesthetic cues and peak compressional force has no effect on the scaling of softness. In addition, the mean rating of softness did not differ significantly for one- and two-finger tapping tasks. The results also showed that the classification of objects as ‘hard’ or ‘soft’ depended on the compliance of the finger pad. In conclusion, it appears that judgments about softness and hardness depend on the degree of conformation of the body or an object.

Another study taking sensory information into account examined the ability of humans to discriminate softness and to isolate factual information using compliant materials that were represented as deformable and rigid objects (Srinivasan and LaMotte, 1995). Deformable objects were represented by transparent rubber specimens that varied in compliance, and the rigid objects used were springs and hollow cylinders. Various compliances of deformable and rigid objects were achieved by controlling the amounts of diluents involved, and by using several springs inside the hollow cylinders, respectively. There were no differences in the objects’ surface characteristics, colour or shape. Although perceptions of softness used cutaneous and kinaesthetic information, the effects of that information were isolated using active or passive conditions. Psychophysical experiments were established under three conditions: active touch with the normal finger, where cutaneous and kinaesthetic information was used; active touch with kinaesthetic information available; and passive touch, where the subject was provided with cutaneous information alone. From the results, Srinivasan and LaMotte (1995) concluded that the ability of participants to discriminate compliance was excellent with deformable objects using active touch, but poor with rigid objects. Moreover, they found that tactile information alone was sufficient for discriminating pairs of deformable objects, but kinaesthetic information alone was not, and that to distinguish between a pair of rigid objects, both tactile and kinaesthetic information were necessary. They found that the indentation velocity affected the tactile information. Consequently, in spite of the fact that deformable and rigid objects are compliant, rigid objects are discriminated through both cutaneous and kinaesthetic information, while deformable objects are discriminated using cutaneous information alone.

In another study of a number of cues for the haptic perception of compliance, the discrimination thresholds of different thicknesses of silicone rubber stimuli were measured for compliance (Bergmann Tiest, 2009). Three different experiments were conducted using stimulus sets to study whether hardness is perceived directly or not. Bergmann Tiest (2009) created three different compliance ranges (soft, medium and hard stimulus sets) and three stimulus configurations (thick, thin and sandwich). Each set had a reference stimulus and eight test stimuli. The first experiment that was conducted had two purposes: to determine whether the discrimination threshold depends on compliance, and to establish the effect of finger spread on the discrimination threshold. Bergmann Tiest used the three compliance levels and three stimulus configurations for the first and the second purposes respectively, and ten repetitions of the tests were performed. There was no time limit, on touching tests and reference stimuli, in order to produce ideal conditions. The results suggested that hardness is not perceived by calculating the ratio between force and displacement or by estimating stiffness, but by other cues, such as the shape of the deformation of the stimulus surface. Thus, it was found that hardness is best perceived directly, as there were no significant differences between the three stimulus types.

The second experiment investigated the contribution of the cue of surface deformation to the perception of hardness. This involved comparing the information about the compliance of an object with a rigid surface with one having a deformable surface. The final perception was produced by combining the surface deformation cue with the force-displacement cue. In that experiment, the surface deformation cue was absent, so little useful information about the compliance of the object was provided. It was found that the surface deformation of the compliant object was approximately nine tenths of the information that was used to assess the hardness of an object.

In the third experiment, Bergmann Tiest (2009) studied whether perceived hardness was equal in terms of physical compliance. Two reference stimuli were used for one test stimulus, and stimuli were presented differently between trials. The stimuli were the same ones used in the first experiment. It was found that the importance of a cue depends on the stimulus compliance. In addition, the object’s thickness is taken into account by the perceptual system when the compliance material is assessed. Bergmann Tiest suggested that subjects pay more attention to stiffness information for softer stimuli and more attention to surface deformation information for harder stimuli, which means that subjects judged softer materials based on stiffness or Young’s modulus (Bergmann Tiest, 2009).

In a study investigating compliance discrimination, Bicchi et al. (2000) investigated whether information for discriminating softness could be conveyed by simple tactile data, while allowing for the construction of devices for practical applications such as minimally invasive surgery. They investigated the discrimination of different objects via their compliance using a remote haptic system, which consists of a telemanipulator and a haptic perceptual channel. It should be noted that haptic systems are referred to as a form of cutaneous tactile information, although Bicchi et al.'s literature review shows that the reduction of the human capability for haptic discrimination caused by the loss of the tactile channel is dramatic, both kinaesthetic and cutaneous, and relates to the ability to discriminate softness by touch. Bicchi et al. (2000) proposed using a contact area spread rate (CASR) as a simple way for predicting the ability to discriminate softness, as the contact area on the finger’s surface is the only part of it that affects softness discrimination. There are two ingredients that a psychophysical validation and a practical implementation of sensors and actuators for testing the CASR hypothesis must have. In order to validate experiments, very simple devices were described: the CASR sensor and CASR display. The CASR display consists of a set of cylinders of different radii in a telescopic arrangement. Regulated air pressure acts on one end of the cylinders, and the operator finger probes the other end of the display. When the probing finger is lowered by an amount, an area of contact is approximately evaluated. An optoelectronic sensor placed within the chamber allows measurement of the displacement. Several psychophysical experiments were designed to validate the CASR hypothesis, with volunteers using CASR sensing and display equipment. A single device with variable compliance was used to minimise the effect of using different technology and the appearance of the kinaesthetic display. This revealed that subjects are able to discriminate differences in compliance better with the CASR haptic display than they are with the kinaesthetic display.

The softness of an object can be displayed by the fingertip contact area that reaches a target level. Skedung et al. (2011) found that the contact area is larger while touching a soft object than a hard one when the same force is applied to objects. The contact area increased with increased contact force. Given this, some researchers have studied the relationship between contact area and display softness. Fujita and Ohmori (2000), for instance, investigated the hypothesis that the softness display is better when the contact area is being dynamically controlled, as when a human touches the compliance using their finger. They used a softness display system, which consists of a softness display device with a load cell, a servo controlled pump, a DC servo controller, and contact area control software. Four kinds of material were used; gelatine, two kinds of silicone rubber and cylindrical acrylic polymer disk plates. The relationship between contact force and contact area was measured by touching the material installed on the load cell. A numerical material model was used to measure the required contact area from the detected contact force and developed softness display system was plotted. It was found that the average actual contact area was 306 percent greater. A softer material than the displayed softness was chosen, and the dynamic control of the fingertip contact area used to display the softness of the object.

Another useful group of studies investigated the human fingertip's discrimination and memory of the perception of softness. Liu and Song (2008) tested the ability to discriminate softness and the short-term memory of the haptic perception of it using a human index finger, with the relationship between haptic perception and stiffness being examined. A pilot study and two psychophysical experiments were constructed to achieve these goals. In order to examine the relationship between haptic perception and stiffness, participants pressed the touch cap of the device more than once with similar movements of the finger. In the first experiment, participants pressed a standard stimulus and compared it with other stimuli that had a range of different stiffnesses in order to feel the stiffness of different stimuli. They judged that the comparison stimulus was harder than the standard stimulus in 50% of the guessing rate. The second experiment was designed to study the human haptic memory by identifying points of different stiffness that people could remember. Participants recalled the stiffness of the stimuli points for a two-stimulus set (incorporating one soft and one hard stimulus) and ordered them. The results showed that the probability of correctly recalling the soft test points was much higher than the correct recall for the hard test points (with subjects remembering three to four items). This means that people can distinguish more compliant objects easily than less compliant ones through the use of touch. In that paper, the authors also suggested studying the capabilities and limitations of the human sense of touch in order to improve the design of haptic displays.

The afore-mentioned studies dealt with direct tactile interaction in which participants were able to touch compliant objects directly, but there have been studies of the discrimination of softness when using various tools. These are relevant here, as direct contact with objects is not possible in surgical laparoscopy at all. LaMotte (2000) measured people’s ability to discriminate softness under different conditions with a stylus, using stimulus objects from a range of ten different compliances. Two testing procedures were used to measure softness discrimination, and participants used different modes of contact to rank the softness of rubber objects of differing compliance: active tapping of the index finger, active tapping by pressing the top of a stylus using the index finger, active tapping with two fingers gripping the stylus, and passive tapping by pushing the specimen on the stylus against the index finger. The force between the stylus and specimen was measured to quantify the force involved in tapping and pressing.

Many factors affect touch friction, including the type of surface material used, the surface finish, the condition of the skin (dryness, firmness and thickness), the test conditions, and the contact area between the fingertip and the surface (Liu and et al., 2008). The results showed that the difference between direct (finger tapping) and indirect (stylus tapping) contact was not significant for compliance discrimination. However, the accuracy of compliance discrimination is significantly affected by the exploration strategy, with tapping being the more effective method of exploring a surface. The stylus is shorter than the laparoscopic instrument, and a tapping strategy will not be employed in laparoscopic surgery because tapping might bruise tissue. However, the results of this study are useful for comparing direct and indirect contact.

It can be concluded that discrimination of softness is difficult with less compliant materials. Judgement of softness seems to depend on deformation of objects when touched by the fingertip.

2.4 Multisensory integration

In our world, modalities are integrated together to form perception. For example, a typing task involves the integration of a number of sensory modalities (vision, touch, auditory) involving the contact of the finger with the keyboard. Previous research studies have integrated information from different senses, such as a combination of auditory and tactile stimuli, visual and olfactory stimuli, and visual and tactile stimuli. There is a large body of literature relating to the integration of information from different senses that points out that human senses can assess different properties: for example, vision can be used to assess colour information, shape and size; information about texture properties (roughness, hardness, stickiness) as well as about weight and temperature can be acquired through touch; hearing can be used to generate temporal information; and olfaction and taste can be used to assess information about chemical composition.

Researchers point out that different senses might affect each other in a variety of ways (Cinel and Humphreys, 2005). For instance, auditory cues can change the perception of a number of objects’ properties when participants touch them (Zampini and Spence, 2005). McGee (2002) examined audio-tactile interactions for perceiving virtual roughness, and found that different textures are likely to be evaluated differently with the input of auditory feedback. LaMotte (2000) found that auditory cues are likely to be important for discriminating between hard objects, and Shore and Simic (2005) focused on forms of audio-visual integration that could not be affected by top-down influences in visual tactile integration stimuli. No differences were found between modalities (visual and tactile) when subjects discriminated between the degree of roughness of different sandpaper stimuli (Rexroad and White, 1987, Jones and O'Neil, 1985) and fabric stimuli (Guest, 2003). Moreover,Bergmann Tiest (2007) found that people can discriminate roughness better through tactile than visual recognition. Henson and Lillford (2010) investigated people's affective responses to visual and tactile stimuli using a weighted average integration model. This experiment did not detect any evidence of interaction between visual and tactile stimuli for any of the words used except for 'natural'. The conclusion that can be drawn from this experiment is that people's affective responses to visual textures do not depend on tactile textures.

Numerous pieces of research have found that the performance of tasks is affected by two sensory modalities, but that performance has a one-way bias (Guest, 2003, Kitagawa et al., 2002, Kitagawa and Ichihara, 2002, Recanzone, 2003). Guest and Spence explained that the discrimination of roughness seems to affect touch in the visual perception. Ernst and Bulthoff (2004) reported that a unique coherent percept was generated by integrating the different modalities in the central system. However, Ernst and Banks (2002) found that the variability of estimates appears to be small, and that their reliability seems to increase when there are two signals rather than just one.

Other researchers contend that vision may be a dominant modality, showing that the role of vision seems to be increased when dealing with daily life products. One study used self-report questionnaires to investigate this, with the results suggesting that the sense used most might depend on the task performed and the object itself (Schifferstein, 2006).

Another important study investigated the integration of visual and tactile signals, and their results suggested that they relate to a set of brain regions, with three areas (the premotor, posterior parietal, and subcortical) playing roles in integrating visual and tactile information in order to represent sensory signals in the hand (Gentile, 2011).

Bresciani et al. (2006) examined the influence of vision and touch on perceptions of the number of taps and flashes experienced by subjects respectively. They found that the reliability of estimations made through touch and vision are similar. their results showed that the variance of the combined estimate was reduced when two modalities rather than just one were used.

The conclusion that can be drawn here is that the integration of modalities appears to be important for designing new products or tactile displays when one needs to know how many of them to take into account. Visual, tactile and auditory ways of processing information might need to be taken into account when using tactile displays. However, visual and auditory senses have a limited capacity for enabling users to interact with tactile displays, whilst the ability of touch enables users to interact with and manipulate objects in tactile displays more fully. Given this conclusion, this research will focus on tactile displays alone.

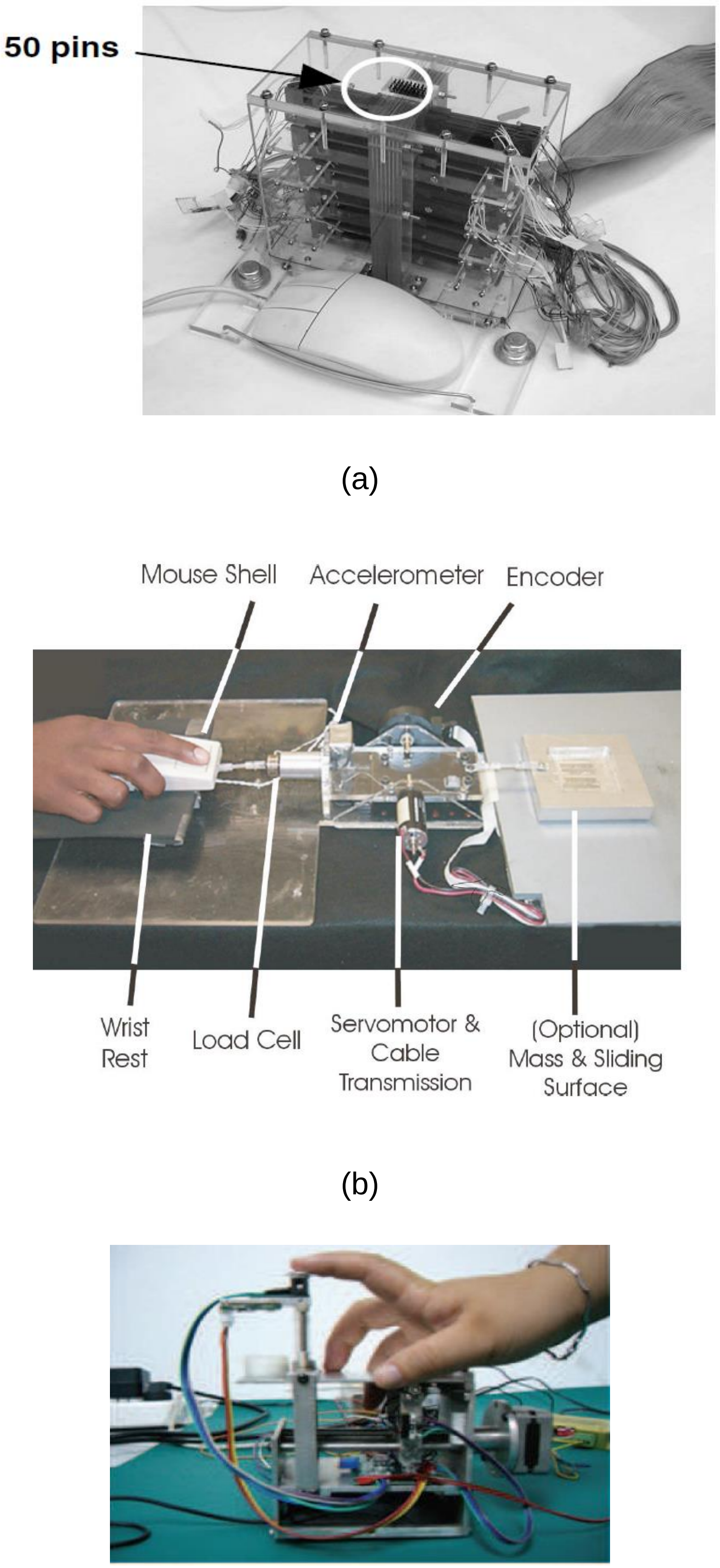
2.5 Feeling Softness through Tactile Displays

2.5.1 Tactile displays

A tactile display "is a human-computer interface that can reproduce as closely as possible the tactile parameters of an object, such as shape, surface texture, roughness or temperature" (Chouvardas et al., 2008). Tactile displays are used to convert sensor signals in order to produce physical sensations for human operators (Eltaib and Hewit, 2003). Examples of haptic displays include texture displays, friction displays, shape displays, softness displays and temperature displays (Song et al., 2008) (Figure 2.2).

Tactile displays thus present information about texture, local shape and local compliance to the user. Those that are used for tele-manipulation and remote palpation during minimally invasive surgery include technologies such as shape memory alloys, piezoelectrics and electrostatics, and tactile feedback can also be added into virtual environments (Eltaib and Hewit, 2003).

Tactile displays can be designed to produce physical sensations;for example, electrorheological devices for conveying compliance, ultrasonic friction and rotating disk for creating slip sensations. In these cases, the display is designed to make contact between the manipulator and the surgeon’s fingers. The artificial tactile sensing needs tactile feedback or a display to generate the sensation of contact with an object. In addition, tactile displays could be used for artificial sensing in surgery and medicine, with minimally invasive surgery possibly being the fastest developing area of their application. It is both exciting and difficult to design tactile displays that can deal with all the different forms of tactile experience, such as detection of texture, slippage and softness (Dargahi and Najarian, 2004).



(a)

(b)

(c)

Figure 2.2 (a) Texture Display (Ikei et al., 2001), (b) Friction Display (Richard and Cutkosky, 2002) and (c) Softness Display (Song et al., 2008).

The challenge of designing tactile displays for use in surgery consists in developing ones that can easily produce tactile data. The tactile display has to be incorporated into the laparoscopic instrument to enable the surgeon to recognise tissue properties. A number of research groups have produced tactile displays in this area. For example, one display gave the sensation of touching a soft object through controlling the ratio between the contact area of the finger and the palpation force. It would be desirable to produce tactile displays for lightweight laparoscopic instruments. To this end, it is useful to compare tactile displays in a variety of different surgical applications (Schostek et al., 2009).

A “tactile display is a device built to convey small scale spatial information about objects that cannot be directly manipulated by the user”,(Ottermo, 2008). Surgical tactile displays have been developed in response to the lack of tactile feedback that presents for some procedures, as this can limit the surgeon’s ability to feel the shape or hardness of the tissue under investigation. Moy et al. (2000) designed a compliant tactile display using an array of simulators in contact with the skin, with the contact with the finger being constant at all times and the tactile display using a compliant pneumatic actuator. A psychophysics experiment was conducted to examine the effectiveness of the tactile display. Two of the parts in this experiment (the contact interface and the pneumatic valve array) were designed to have a tactile display, and the contact interface was moulded from silicon rubber in a one-step mould. The contact between all the tactors and the finger was provided by the flexibility of the contact interface, which was connected to the pneumatic valve array in order to control the pressure. A psychophysics experiment utilising simulated gratings with a 5 mm period as stimuli was conducted to test the performance of the tactile display. After comparing the experimental results with the results from contacts with real gratings, it was found that the tactile display had sufficient amplitude resolution to match human perceptual limits. Compared with other pneumatically actuated tactile displays, the compliant tactile display had certain advantages, such as being comfortable to use, having no leakage and negligible pin friction. It thus seems advisable to conduct more psychophysics studies to test the performance of tactile displays and to apply these displays to real situations (Moy et al., 2000).

Maeno et al. (2006) developed a tactile display for surface texture using amplitude modulation of ultrasonic vibrations. When moving the finger with the vibrator, which varied in both waveform and velocity, the tactile stimuli created a realistic feeling for various surfaces. Maeno et al. used selected waves to display softness and wetness sensations.

Konyo et al. (2005) used a tactile synthesis method for controlling the feeling of roughness, softness and friction. Several texture feels and natural contact feelings could also be presented via this display. Various parameters can be used to produce the full range of tactile sensations (roughness, compliance and friction). The sensation of roughness can be produced by changing the frequency of the hand movement of the subject in relation to the physical properties of roughness and the amplitude. The sensation of softness could be produced by varying the amount of pressure sensation in the contact finger, and surface and friction sensations could be produced by altering the amount of this subjective sensation. This study thus showed that the sensation of roughness can be clearly presented when it has a short wavelength and small standard deviations. However, the longer wavelengths and larger standard deviations did not create a noticeable feeling of roughness because such roughness is perceived differently. Frequencies of less than 100Hz could be detected as pressure sensations using SAI mechanoreceptor.

Another important study of tactile display designs for minimally invasive surgery has been provided by (Ottermo, 2008). The tactile display was designed to be used by fingertips and to fit the handle of laparoscopic instrument, the display being 27mm × 20mm × 18mm. The display was tested to evaluate its performance with respect to positioning accuracy, force and bandwidth, and stiffness. Ottermo (2008) suggested that tactile displays that are designed to be small and lightweight can also facilitate accurate positioning of the pins and high stiffness. The principles of this design were thus informative for the development of the tactile display for this current research, especially in term of the size and weight of designs.

Yamamoto et al. (2006) developed a master-slave system that transfers the vibrations that are detected by a tactile sensor running on material surfaces into texture information. The vibration sensation can be obtained by moving the finger together across the slider film. For applied voltages, the additional friction is generated between the slider and stator and is transferred to the finger, which feels the texture sensation. The texture sensation can feel different when the voltage waveform is controlled using a simple tactile sensor. Table 2.2 shows the summary of types of tactile display.

Table 2.2 types of tactile display

Type of display	Description
Texture display	It consists vibratory pins that evoke a virtual touch sensation of textured seduces contacted to the user's fingerpad. It presents texture surface (Ikei et al., 2001).
Shape display	It consists actuator pin force and accuracy, pin resolution and mechanical bandwidth (Kammermeier et al., 2000).
Softness display	The softness display have different types of design: based on electro-rheological fluids; the fingertip contact area control; pneumatic arrays or elastic bodies (Song, 2008).
Thermal display	Protective gloves was designed with temperature sensors on the outside and two-vibrator tactile display inside the gloves to feel temperatures (Walters et al., 2010).

2.5.2 Softness displays

Song et al. (2008) cites a number of research projects that have proposed softness displays, but none with a wide stiffness range have thus far been proposed. In the small amount of current research on designing softness display devices, four types of design have been seen: softness haptic display devices based on electro-rheological fluids, softness haptic display devices based on the fingertip contact area control, softness haptic display devices based on pneumatic arrays, and softness haptic display devices based on elastic bodies.

Kajimoto et al. (1999) defined tactile feeling as “a sensation produced in your skin when you touch or rub something”. A softness display seems to be important for use in technology involving virtual reality and teleoperation in order to help to discriminate between different objects. If tactile feeling could be effectively generated in virtual reality, a more realistic feeling of presence could be elicited, and more difficult tasks could be performed therein (Kajimoto et al., 1999). This means that tactile feeling plays a role to discriminate between different softness.

The important elements for haptic display techniques are haptic perceptions and the display of softness (Liu, 2010). The softness of objects can be displayed by the fingertip contact area that reaches the target level, and feelings of softness can be displayed by reproducing a contact area or a contact width on a finger. Moreover, the pressure distribution over the area should also be controlled in order to produce different sensations of softness, as the surfaces that need to be rendered are not plain and uniform (Bicchi et al., 2000, Fujita and Ohmori, 2000, Yokota et al., 2007, Scilingo et al., 2010, Kimura and Yamamoto, 2012). The contact area is larger when a soft object is being touched than a hard one with the same force is applied to objects and the increase in the contact area depend on an increase in the contact force. When the target level of the contact area is reached, humans seem to perceive object softness, and contact area information affects the perception of softness in relation to the (variation in the) size of the contact area (Tsuchimi et al., 2012). Consequently, in spite of the fact that contact area and pressure distribution over this area affect pereceived softness, other factors might affect the perception of softness such as surface texture and material properties.

As a result of this finding, some researchers have studied the relationship between contact area and the display of softness. Fujita and Ohmori (2000) , for instance, investigated the hypothesis that the softness display is better when the contact area is dynamically controlled by a person using their finger to touch the display. In their experiment, the softness display system consisted of a softness display device with a load cell, a servo controlled pump, a DC servo controller and contact area control software. The property between contact force and contact area was measured by touching the material installed on the load cell, with an increase in the contact area representing softness. In this case, the pressure distribution appears to be constant with the intervention of the fluid. The comparison between the cognitive rate (rate of correct answers during comparison of real objects with displayed softness) of the original material and the softness display device reveals that softer materials are displayed better in display devices.

The technique proposed by (Fujita and Ohmori, 2000) was modified by (Yokota et al., 2007) to integrate the presentation of softness within the electrostatic display. To control the change of the contact width between the fingertip and the film, the height of the rods that support the corners of the slider film were altered. Yokota et al. (2007) found that people perceived softness to be harder by a log-log power low of 0.8 than the intended softness as a result of the control of the contact width.

Kimura and Yamamoto (2012) modified the softness display used by (Yokota et al., 2007) by controlling contact pressure distribution. They used photoelastic phenomenon to indirectly visualise the different pressure distribution and given evidence for the contact area and pressure distribution control of the feeling of softness. The pressure distribution was estimated through internal stress distribution, which was evaluated using two types of sponges of different thickness (4mm and 8mm). The sponges were pressed and information converted into contour images, which showed that the thinner sponge has more stress distribution than the thick one, even though the two sponges contact areas were similar. In order to produce differences in contact pressure distribution, Yokota et al. (2007) developed a display with a new mechanism for controlling the tension of the sheet. Three voice coil motors were used to modify the contact area and contact pressure distribution using Hertzian contact theory, according to which the contact area and contact pressure distribution are known to render a virtual soft object.

Tsuchimi et al. (2012) investigated the relationship between tactile softness and the variation in the size of the contact area through two experiments. In the first, a pressure sensor was used, with ink blots on the blocks for measuring and calculating the contact force and size of the contact area respectively. This experiment required participants to push their forefingers into silicone blocks with ink, and the results showed that the size of the contact area decreased with increases in Young’s modulus. The second experiment was used to evaluate the variation in the size of the contact area between a finger and an object. Two kinds of sensory tests and four silicone object tests were used for this experiment, which also used four different Young’s modulus values, which were made dissimilar to avoid burdening the participants. Scheffe’s paired comparison method was used for six combinations that were applied to evaluate softness between objects, and the results showed that the higher the Young’s modulus of an object, the harder an object was evaluated as being. The same participants evaluated tactile softness using a cylinder piston device that consisted of a piston and a stage. The two contact areas of the device were 5mm and 10mm square respectively, with the first area being smaller than the one between the subjects’ forefingers and the objects in the first experiment. The device was used to push objects, with the area of contact being constant, and the participants forcing the object without influencing the contact area. Scheffe (1952) used the paired comparison method, asking participants to appraise the difficulty of two tests. 97.2% of subjects evaluated the object to be harder when the Young’s modulus was higher in the first experiment and 86.1% did so in the second, and thus the evaluation of tactile softness was higher in the first set of sensory tests than in the second. This means that humans can distinguish between different softness whether real objects or simulated softness.

A tactile display system was constructed by (Shiokawa et al., 2008b, Shiokawa et al., 2008a) to display different sensations (roughness, softness and friction) through ultrasonic vibrators and force displays. In order to display these sensations, mechanical stimuli patterns—vibration patterns, pressure distribution patterns and friction force patterns—were reproduced. An ultrasonic vibrator was used to create a maximum amplitude of 20µm, which presents different friction characteristics at the vibrator’s surface, and two sensors—a PZT amplitude sensor and a normal force sensor—were used, the first to control the vibration amplitude and the second to measure the normal force applied by a finger to the vibrator. Variable component waves for mediating the amplitude of ultrasonic vibrations generally generate a sense of roughness, whilst a sense of softness is more likely to be produced by a steady component wave for the amplitude mediation of ultrasonic vibrations. A sense of softness can be combined with a sense of roughness in controlling the steady component (Shiokawa et al., 2008a, Shiokawa et al., 2008b). Hence, producing different sensations seems to depend on different ways of controlling vibrations.

Bianchi et al. (2010) designed a bi-elastic fabric-based display and graphical user interface. The display was designed to convey both cutaneous and kinaesthetic information, and the user interface was used to change the softness parameters. A set of psychophysical tests were used to evaluate the performance of the display, and to compare its performance with that of a CASR display.

A novel softness device based on the deformable length of elastic control elements is presented by (Liu and Song, 2007). Meanwhile, Wu et al. (2006) have designed and constructed a novel haptic display system that controls the deformable length of an elastic element in order to realise the stiffness display of a virtual environment (Figure 2.3). Their display consists of a thin elastic beam, a feed screw, a carriage with a nut, and a motor. The virtual object's proxy was designed to have an equivalent stiffness to the virtual one. Controlling the deformable length of the thin beam can change the stiffness feeling, and the deformable length can be changed by altering the position of the carriage. Wu et al. (2006) found that the participants reported the perception of a sensation of touch for various objects with a large range of different stiffnesses. This suggests that stiffness can be quickly and accurately replicated by this system.

Liu (2010) designed and developed a small-scale softness display that can rapidly control an elastic beam's changes in stiffness by adjusting the beam's effective length so that the operator can perceive the stiffness of the virtual object in real-time and correctly identify its physical properties and classifications. The deformable length—which is determined by controlling the position of the carriage using a motor, a feed screw and a nut—can change the stiffness. The device was designed to feel as if the user was touching the actual soft environment, which can be displayed in the stiffness range of 25N/m to 1500N/m. The device can be easily assembled, with a computer mouse at the bottom. A stepper motor, a Hall Effect position sensor and a touch force sensor were used to measure the position of the carriage, the displacement of the touch cap and the force applied by a human fingertip on a touch cap. The system was validated through simulation experiments. Thus, the simulated softness could be generated by controlling stiffness instead of Young's modulus. It means the stiffness and Young's modulus play an important role for producing softness feeling through tactile displays.

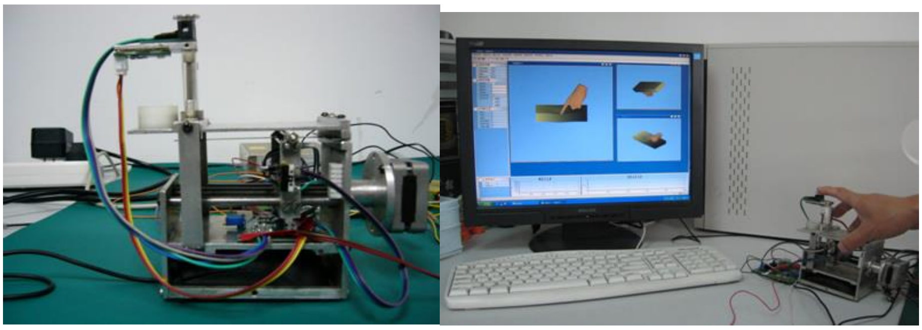


Figure 2.3 A tactile display (Liu, 2010)

A tele-presentation system for tactile softness was proposed by (Kimura et al., 2009, Kimura et al., 2010) focused on cutaneous perceptions regarding softness (with softness being represented by changes in contact width). The first work (2009) improved the softness display that was developed by Fujita (2000) by adding plastic force on both sides of a rubber sheet to control its height, which changes the contact width. The contact area was measured using the optical principle utilising an optical contact sensor attached to a glass hemisphere with a camera. Kimura et al. (2009) ran the programme at around 30Hz, and when they evaluated the system they found that giving remote objects different degrees of softness could be useful. The same group modified the system using a 2-DOF controlled softness display, which uses two DC motors to control the contact width. The functional design characteristics of the sensor in this design are the same as those of a real human finger, but do not have the same dimensions and physical parameters as a human finger. In analysing their results, they recommended improving the characteristics of the device to be as close to a real human finger as possible and adding a motor to control complicated of contact condition. Hence, the ideal tactile display seems to have characteristics like the human finger for indirect touch tasks.

Other work to integrate kinaesthetic and cutaneous information has been undertaken by Kimura et al. (2009; 2010), in both cases being related to perceived softness. They designed a haptic device to control kinaesthetic and cutaneous information, and conducted psychophysical experiments to verify the performance of the display and to compare subjective perceptions of softness with the perception of softness produced by directly touching physical objects. They combined their softness display (a pneumatic device comprising a set of cylinders of different radii which apply pressure when the cylinder is pushed down) with haptic device. The height of the cylinders in the softness display was used to control the contact area, with the pressure correlating to perceived force. A latex sleeve was used to cover the cylinders in order to control the pressure distribution and to reduce the edge effect. The experiments were undertaken in order to evaluate whether the haptic display rendered a perception of softness.

Three sessions of experiments were carried out, utilising direct touch with silicone stimuli using the haptic display in both sets of experiments. Different subjects were used for each experiment. The subjects were blindfolded and their ears were plugged so that they could not receive any sensory cues or diversions. The participants, who could move their wrists or fingers, were allowed to use their dominant hands to feel the silicone stimuli. These stimuli were constructed with varying percentages of softener, and there were three classes of stimuli in the first session: five stimuli with softener percentages of 0, 10, 20, 35, and 45%; five rigid cylinders with silicone cylinders that had the same percentage of softeners as class one; and five pairs, also having the same percentage of softeners as class one. In the second session, artificial stimuli were used to render different force-displacement and force-area curves through the haptic display. They used three different modes: the integrated display, the kinaesthetic display and the softness display. Pairwise discrimination and ranking tasks were used for both direct touch and rendered touch, with three different sources of information being used in these experiments;integrated tactile information, kinaesthetic information and cutaneous information.

Kimura et al. (2009, 2010) found that the most accurate source of information for comparing stimuli that are closer to the reference stimuli with the physical stimuli is integrated tactile information. However, when comparing between two stimuli that are farther away from each other, more information can be provided by cutaneous than kinaesthetic information. In ranking physical stimuli, the most appropriate display to use was the integrated one. When comparing rendered stimuli, the best performance was seen in relation to the integrated condition. Other than this, in ranking rendered stimuli, the same conclusion was found as that for ranking physical stimuli (Scilingo et al., 2010). Accordingly, simulated softness could depend on integrated kinaesthetic and cutaneous information. The softness could be more accurate when comparing between two close softnesses.

In conclusion, the design of softness displays can be based on the principles of contact area, electro-rheological, pneumatic arrays and elastic body. The softness display based on contact area is most popular softness display.

2.6 Definitions of psychophysical and physical properties

There are different physical properties which affect human touch perception such as compliance, adhesion and thermal conductivity. Furthermore, different perceptual cues may interact to affect perception (Table 2.3). In this research, the perception of softness and compliance are the most important psychophysical and physical properties because they are used to compare between healthy and unhealthy tissues during surgery.

Table 2.3 Psychophysical and physical properties affecting human perception.

	unit	Quantities	Definitions
softness	-	psychophysical	Is subjective impression of the progressive change in conformation of surface to the contours of the fingers that accompanies changes in contact force ((Hollins et al., 2000)
stickiness	-	psychophysical	Is perception of adhesion. The stickiness is defined as the feeling when fingertip feels glue, tape or rubber (Zigler, 1923, Yamaoka et al., 2008)
Roughness	-	psychophysical	is related to the spatial density of the features on the surface (Lederman, 1986).
roughness	µm	physical	Is related to the height differences on the surface of the material and can be perceived statically. It also depends on the fineness (Bergmann Tiest, 2010).
compliance	mm/N	physical	Is property of a material of undergoing elastic deformation when a subject applies force. It is also related to material's elasticity and it is a way to express the compliance: young's modulus (Bergmann Tiest, 2010).
Stiffness	N/mm	physical	is a measure of the resistance offered by an elastic body to deformation and it is inverse of compliance(Baumgart, 2000).
coldness	°C/sec	physical	Is related to the material's heat capacity and thermal conductivity and it is perceived statically (Bergmann Tiest, 2010).
slipperiness	mm/N	physical	Is related to the friction between stimulus and fingertip and it is dynamically perceived (Bergmann Tiest, 2010).
Adhesion	mN	physical	Is the physical phenomenon by which two materials are sticking together, or how fingertip and stimulus surface are sticking together (Lacombe, 2006)

2.7 Objectives and Research questions

The aim of this research is to investigate how adhesion and roughness influence human perception of softness, and how this can be applied to present softness feelings through a tactile display. This will be achieved through the following objectives:

1. Investigation of the effect of roughness on the perception of softness.
2. Investigation of the effect of stickiness on the perception of softness.
3. Determining whether there are interactions between the physical properties which effect the subjective perception.
4. Investigation of whether softness can be represented through a tactile display and whether people can distinguish between different compliances through display as they can distinguish real materials.

In order to achieve the objectives of this research, the following research questions are defined as a guideline for the research effort:

- How do physical material properties affect perception of softness?
- How do rough surfaces affect the perception of softness?
- How does stickiness affect the perception of softness?
- How does the interaction of material properties affect the perception of softness?
- How can softness feeling be represented through tactile display?

2.8 Summary

This chapter has discussed the literature relating to tactile perception, compliance discrimination, the multisensory integration of perception and the perception of softness through tactile displays. The literature review showed that tactile displays can convey compliance, and revealed the existence of multisensory integration. Multisensory integration seems to be important for designing tactile displays and we need to know how many of them to take into account. To find the reasons for this, it is necessary to investigate which properties can be integrated by emulating them through tactile displays.

There are different senses that could affect the perception such as visual, auditory and touch. For example, visual feedback combines with tactile feedback to discriminate softness. However, touch is the dominant modality for many tasks to get information about compliance and texture. In this thesis, we focus on the tactile feedback first, and then in future we can add other senses and investigate whether they affect the discrimination of compliance through tactile displays. For this reason, my research will take only touch in account. Experiments examining this will be discussed in Chapters 3 and 4, which look at how active touch perception can shed light on how these sensory perceptions can relate to each other.

To see whether this integration of sensory perceptions can be emulated through tactile displays, Chapter 5 describes the assessment of a tactile display that conveyed the impression of softness.

Chapter 3
An Investigation of the Influence of Texture Roughness on Perception of Softness

3.1 Introduction

The relationships between perception of softness and material properties are important for feeling softness and in the design of tactile displays. These relationships were investigated by other researches as explained in Section 1.3. The researches in this field (Section 2.2) reported that perception of softness or hardness is influenced by physical properties and the mode of interactions (Bergmann Tiest and Kappers, 2006, Shao et al., 2010, Koçak et al., 2011, Harper and Stevens, 1964, Srinivasan and LaMotte, 1995). Barnes et al. (2004) evaluated that tactile feelings are affected by surface roughness.

This experiment aims to determine the influence of surface roughness on perception of softness. To accomplish this goal, the experiment used research which was done by (Shao et al., 2010). Their research investigated the relationship between material properties and touch perception. From their results, they built a regression model for these relationships. Our work has assessed these regression models, but our experiment has been done by an improved experimental design and by controlling physical properties as much as possible. The experiment design is a general factorial design with counterbalanced design to avoid any affects from other factors as explained in Section 3.5. Controlling physical properties independently was attempted by making stimuli with controlled compliance and roughness. This differs from Shao's work which used packaging materials.

3.2 Method

The aim of this study is to determine the effect of surface roughness on perception of softness. To achieve this aim, magnitude estimation was used to determine people's ratings of softness of materials. Magnitude estimation is a scaling technique that is used in psychophysics to determine how much of a given sensation a person experiences and is explained more fully in Section 3.6. This method is more suitable for obtaining ratings than using Likert or semantic differential scales, but is more difficult and less intuitive for participants to use.

In this experiment, participants were asked to rate 8 textures compared to a reference sample. Participants were asked to press and slide their fingers over textures with their dominant hand. Once the participants had touched the reference texture and then touched the test texture, they assigned a value which was a positive, non-zero, non-decimal or non-fraction, compared with 20 for the reference texture. The stimuli were presented in a random order, and each pair of stimuli was presented three times to each participant in both the sliding and pressing conditions. Participants' responses were normalized. The normalization procedure used to normalization magnitude estimation values is geometric averaging (McGee, 2003).

The two-way repeated measure ANOVA test was conducted to explore relations between the human tactile perception and interaction between surface roughness and compliance, taken from magnitude estimation data. Also, it was used to determine whether there is interaction between two factors. ANOVA is a parametric test. The parametric statistical test can be used when the parametric assumptions are reasonably met. These are when there is homogeneity of variance amongst the data and the data follows a normal distribution. These tests were carried out. For the ANOVA, an assumption which needed to be tested was sphericity as it was assumed that the relationship between one pair of conditions was similar to the relationship between a different pair of conditions.

Further analysis was carried out to determine whether, for each surface roughness, participants appeared to distinguish between the compliance of the stimuli using the Chi-Square test. In order to examine the relationship between physical measurements and softness perception, a Pearson correlation coefficient was computed to assess the relationship between the physical properties with perceived softness for both conditions.

Also, a regression analysis was used to draw this relationship between perceived softness and physical properties. This means that the perceived softness can be predicted by compliance. SPSS statistical 21 software is used for all these analyses.

3.3 Participants

Twenty four participants took part in this study (7 female and 17 male). They were financially compensated for their participation. The average age was 33 years for females and 31.5 years for males, although the ages covered a wide range (20-49). Almost all of the participants were students at the University of Leeds except two of them who were undergraduate students from Leeds Metropolitan University. In the experiment, a handedness inventory questionnaire was used that had been adapted from the handedness questionnaire by Briggs and Nebes (1975). Participants were asked to tick a suitable choice on the handedness questionnaire from a five point scale. The score was used to identify which hand was the dominant hand. Participants took a few minutes to complete the handedness questionnaire (Appendix A.1), to determine their dominant hand.

Table 3.1 shows scores for the scale point and total scores, and which total scores were interpreted to measure the strength of handedness for each participant.

The experiment was performed according to ethical guidelines. All participants signed a consent form at the beginning of the experiments but were free to withdraw at any point. This form was approved by the MEEC Faculty Research Ethics Committee at the University of Leeds (Ethics reference MEEC 10-016). Participants were asked to press or slide the sample, dependent on the instruction given by the researcher, using the index finger of their dominant hand to assess the compliance of samples as shown in Appendix A.1. The participants could not see the stimulus to remove any influence from the shape and surface differences between the stimuli.

Table 3.1 scores for the scale point for determining dominant hand

Score point	**Score**
Always right	+2
Usually right	+1
No preference	0
Always right	-2
Usually right	-1

Total Scores	**Dominate hand**
-24 to -9	Left handed
-8 to +8	No preference
+24 to +9	Right handed

3.4 Stimuli

Nine stimuli with three different levels of compliance and three different levels of roughness in all combinations were made. Stimuli were produced in dimensions of 100mm × 100mm × 10mm. These were made from thermoplastic polyurethane material of different compliances (Figure 3.1).

Figure 3.1: Sample of stimuli made of thermoplastic polyurethane

Stimuli were made using a hot pressing process. The process produced stimuli from thermoplastic polyurethane material with different hardness (IROGRAN A 60 E 4902, PS455-203, PS440-200). The process used was to melt thermoplastic polyurethane at high pressure and high temperature so the performing polymer induced sintering. Three textured aluminium sheets with different surface roughness were used to imprint different surface roughnesses on the stimuli. The full details of this process can be found in Section 3.4.1. Full factorial stimuli and an arrangement of the experiment and the stimuli during touching are shown Figure 3.2(a, b).

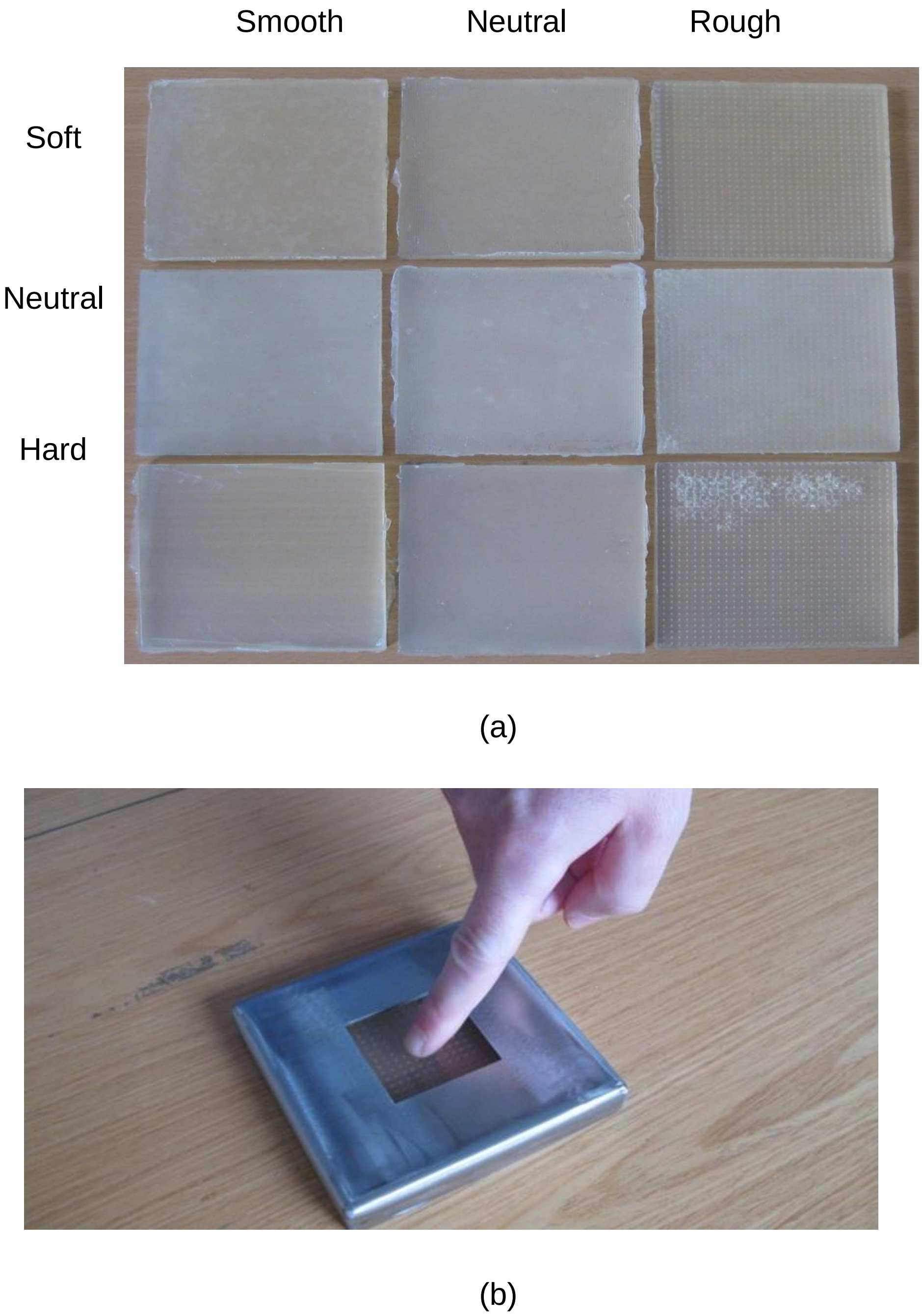


Figure 3.2: (a) Stimuli full factorial arrangements used in this experiment, made from polyurethane (b) Stimulus during touching

3.4.1 Describing the process

Stimuli were made using a hot pressing process in the Physics Laboratory. The process used thermoplastic polyurethane materials with different hardness (IROGRAN A 60 E 4902, PS455-203, PS440-200). The process used was to melt thermoplastic polyurethane at high pressure and high temperature so the performing polymer induced sintering; each grade of thermoplastic polyurethane had a processing temperature which can be found on the product data sheet.

The process comprised the following steps. First the thermoplastic polyurethane was weighed dependent on the area of the die and the grade of thermoplastic polyurethane. Prior to that, the temperature of the hot press was adjusted to a suitable temperature which differed for each grade of polyurethane. Next, the top part of the die was placed on an aluminium plate and the textured aluminium sheet was inserted inside it. The weighed thermoplastic polyurethane was poured on the die and the bottom part of die was put together. Next, the die was inserted between two platens, and then the platens were pressed onto the die and kept there until the temperature reached the required temperature. Next, the platens were pressed manually until the parts of die fit and closed and the pressure of the top platen decreased. Following that, the platens were pressed until the pressure of the bottom platen rose to 10 MPa. Then, the die was cooled until the temperature of bottom platen was 20ºC or less, and until the temperature of the top platen went down to 40ºC for safety purposes. Finally, it was necessary to ensure that the die was warm to remove the stimulus from the die. This procedure was repeated until all stimuli had been made.

3.5 Design

There were 18 conditions, corresponding to the combinations of two independent variables: compliance (soft, neutral and hard) and roughness (smooth, neutral and rough) and the pressing and sliding conditions. The order of stimuli was randomized for each participant. The pressing and sliding conditions were counterbalanced.

The experimental approach used was to develop a general full factorial design (3×3). In this approach, two factors were used: compliance and roughness. Each factor had three levels; the reason for using this approach was because a general full factorial design was used when there were several factors (< 5) that have multiple levels. There were three replications at each factor setting, making a total of 24 runs, because one stimulus was used as the reference stimulus which was used for comparison with other stimuli. Minitab 16 statistical software was used to design a general full factorial design. From that, spreadsheets were compiled to calculate the results for each participant. In order to avoid any effects from the behaviour of the participants on treatments, the counterbalanced design was used in this experiment. The experiment had two conditions (A = pressing with softness and B = sliding with softness), these conditions required two orders (Beierholm et al., 2007) in which these can occur. Participants were divided into two groups, each having an equal number of participants, which meant 12 participants were in each group. It meant all participants were treated with a different order of conditions (with pressing first, followed by sliding and sliding first followed by pressing) (Field, 2010).

3.6 Procedure

Each participant was given a brief outline of what the experiment would involve. An instruction sheet was presented to each participant, which explained how the experiment should be performed to ensure participants understood what they should do.

Participants took part in this study individually, so they did not influence each other in their responses. Twenty four runs were used during the experiment for each participant. The magnitude estimation procedure and an active touch were chosen as the most appropriate method under two experimental conditions pressing and sliding to evaluate the perception of softness. All participants during their experiment were provided with a reference stimulus that had a compliance of 2.4 mm/3N. This stimulus acted as a reference and was assigned a value of 20 by the experimenter and it had a middle value for compliance.

Before starting the experiment, in order to help participants understand magnitude estimation, they were given an explanatory sheet (Appendix A.4). This sheet, which was developed to allow participants to understand the concept of magnitude scaling, was based on an example exercise described by Lodge (1981). In this exercise, participants were asked to assign a value which was a positive, non-zero integer, decimal, or fraction of first “reference line”. Participants were asked to assign how much longer or shorter the remaining lines were compared to the reference line. The longer a line seemed to be, the larger the number they should assign it. The shorter a line seemed to be, the smaller the number they should assign it compared with the reference line. All participants were asked if they understand exercise and their answers were checked to make sure they were acceptable. None of participants had to withdraw because they could not understand the procedure.

A pilot experiment was carried out to ensure that instructions were understandable and clear. This pilot experiment was conducted by the researcher and one of her supervisors. After the pilot experiment, slight adjustments were made to the instructions so that they would be more understandable.

The participant was seated in front of a curtain on one side of a table and the researcher was on the other side of the table. The participant was asked to rate 24 stimuli compared to a reference stimulus. To avoid the participants from seeing the stimuli, a curtain was dropped half way across the breadth of the table. The stimuli were placed behind the curtain in the same place. The participant was presented with the test and reference stimuli which were placed in front of the participant, the reference stimuli was placed on the participant’s left hand side while the texture the participants were asked to evaluate was placed on their right hand side. Stimuli were placed on two blocks, enclosed in steel cases which have a window on the top surface through which participants were able to touch them. Participants were asked to press the textures; then they were asked to slide their fingers over the surface, or vice versa. They were instructed to use the same index finger in both cases. The participants had to rate one surface at a time. Furthermore, it was important to limit the time that a participant evaluated each stimulus because of loss of fingertip sensitivity and overtiring. A signal light system was used to indicate when the stimuli were in place. When the light turned green, the participant put their hand through the curtain to touch the test stimulus and reference , and they can go back to indicate how many times softer the test stimulus on their right compared to reference stimulus by assigning a proportional value to the test stimulus. They wrote down this value in a box labelled “test stimulus” on a sheet. The softer they thought the stimulus on the right was, the smaller the value they should assign to it compared to the value of the reference stimulus. The less soft they thought it was, the greater the value they should assign it. So, for example, if they thought a test stimulus is twice as soft as the reference one, they would assign it a value that is twice as small as (10) value of reference stimulus, while should they have felt that the stimulus is half as soft as the reference one, they would give it a value twice as great as the value of the reference (40). Each participant could go back between test and reference stimuli as often as desired. After they recorded the value of the test stimulus, the light switched to red when their hand was withdrawn. The next stimulus was put in place to have its value assigned compared with the reference, and the procedure was repeated until all test stimuli had been given a value compared with reference stimulus.

Before starting, each participant wiped his or her fingertips with hand hygiene wipes to clean off any sebum or dust. The stimuli set were also cleaned with a mild surface cleaner (non-bleach, no taint and no odour) to ensure constant stimuli intensity. Participants were allowed to rest at any point during the experiment if necessary. After each condition, each participant was allowed to rest for as long as they needed: rest times ranged from 0-5 minutes. The experiment lasted for approximately 40- 45 minutes (mean = 42 minutes and standard deviation = 1.85) and the full study was performed within 6 weeks.

3.7 Material Properties Measurement

During the measurement phase, two different pieces of apparatus were used to measure different material properties. One of them was a tribometer which is an apparatus using to measure tribological quantities between two surfaces in contact (compliance, adhesion, friction and thermal conductivity). The tribometer consists of a two-axis load cell [MiniDyn multicomponent dynamometer type 9256C2, Kistler], an X–Y motion table (series 1000 cross roller, motion link), an artificial fingertip, a controller, and a personal computer (PC) (Shao et al., 2009, Shao et al., 2010) as shown in Figure 3.3. The other apparatus was a Talysurf machine (Talysurf 120L; Rank Taylor Hobson).

For friction measurement, the artificial fingertip was secured to the mounting plate and the stimulus was placed on the force table using double-sided tape. Pre-programmed commands were downloaded from the WSDK program to the controller. The artificial fingertip was positioned relative to the top of stimulus using manual commands. The artificial finger was moved against each sample material while the forces F_y, F_x respectively were recorded against time by LabVIEW program. The force-time curves generated and average curves were obtained. The force applied to each sample was 0.5N (Shao et al., 2010). The friction coefficient was obtained by taking the average of $F_x = \mu F_y$ during the mid-section of the data where the fingertip was in contact with the stimuli.

For the compliance measurement, the artificial fingertip was replaced by a steel ball of 10 mm diameter which was placed on the mounting plate. The stimulus was fixed on top of the force table using double-slide tape. The ball was moved in the vertical direction against the stimulus. Pre-programmed commands were downloaded from the movement control program (WSDK) to the controller. The force measurement was taken from the Kistler charge amplifiers by a LabView measurement program. The ball was pressed into the surface of each compliant stimulus in a controlled displacement cycle, and the load was recorded against time. The normal force (Fy) should reach 3N and force (F_x) should remain approximately zero.

The speed of the displacement of the steel ball was 0.5mm/s. The data was sorted in an Excel file, and then the compliance was calculated. An average curve for the compliance measurement was obtained. The measure of compliance was taken to be the distance the ball travelled in 3N as used in previous work (Shao et al., 2010) (mm/3N). The distance can be calculated by multiplying the time period (from the first time the ball contacted the surface to the peak at 3N) by speed.

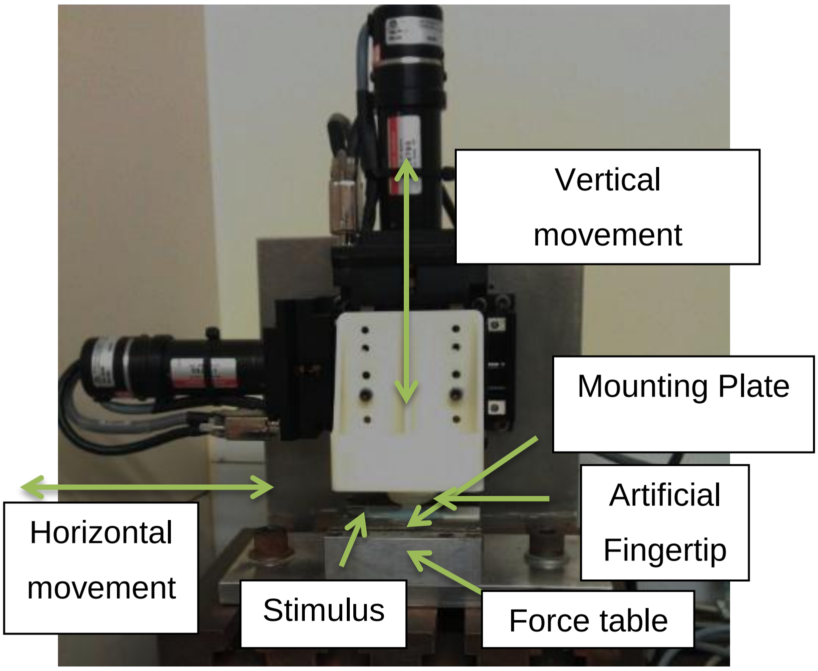


Figure 3.3: Tribometer.

The heat transfer measurement was measured using the tribometer. The artificial fingertip was replaced by heated rubber fingertip. The fingertip was contacted to the mounting plate and connected to a 5V power supply. The stimulus was placed on the top of the force table. Pre-programmed commands were downloaded from the WSDK program to the controller. The fingertip was moved to raise 3mm away from the stimulus surface using manual commands. The room temperature was recorded. The fingertip temperature was set up to be room temperature +10ºC. If the temperature was lower, the voltage supply was increased to reach a fingertip temperature equal to room temperature +10ºC. If the fingertip temperature was higher than room temperature +10ºC, then the voltage supply was decreased. After setting the temperature, the fingertip was lowered until the force applied was 1N (typical static human fingertip load) to make fingertip contact with the stimulus as shown in (Shao et al., 2010). The data for temperature and force was stored in Excel. The rate of temperature change was calculated using the equation dT/dt = $\frac{T_n - T_{n-1}}{t_n - t_{n-1}}$ and maximum value of dT/dt was used to represent heat transfer.

The R_a roughness (µm) of the stimuli was measured by contact surface profilometry, using a Talysurf machine using a long-wavelength 0.8mm cut-off.

For all measurements, each measurement was repeated three times at different points across the stimulus and averages obtained. The compliance and material properties of each stimulus is shown in Table 3.2.

To check how surface roughness affected the perception of softness, a parametric statistical test was employed to carry out the analysis.

Table 3.2 Material properties for stimuli

Sample code	**Stimulus**		**Compliance (mm/3N)**	**Roughness (µm)**	**Friction Coefficient (µ)**	**Heat Transfer (ºC/sec)**
Irogran PS440-200	Hard	A	1.95	1.74	2.05	0.34
Irogran PS440-200		B	2.00	48.43	1.32	0.38
Irogran PS440-200		C	2.20	8.35	1.41	0.34
Irogran PS455-203	Neutral	D	2.30	1.71	2.71	0.35
Irogran PS455-203		E	2.40	52.15	1.39	0.38
Irogran PS455-203		F	2.50	8.35	1.42	0.42
Irogran A 60 E 4902	Soft	G	4.30	1.70	1.85	0.37
Irogran A 60 E 4902		H	4.50	50.75	1.74	0.35
Irogran A 60 E 4902		I	5.20	8.24	1.41	0.33

3.8 Results

None of the participants reported any individual inquiries or any information. None of the participants had any impairment to their sense of touch. Analysis of data collected from the participants did not show any cause for concern.

The handedness questionnaires were completed at the laboratory and all participants except one were found to be right handed. The left handed participant was a male in his twenties. None of the subjects reported any neurological or physical injury that affected sensitivity of the index fingers on either hand.

It was discovered that there is homogeneity of variance amongst the data and normal distribution presented in these data. Figure 3.4 and 3.5 show the raw data. The x-axis and y-axis represent the compliance level and perception of softness respectively for different roughness levels for pressing and sliding conditions.

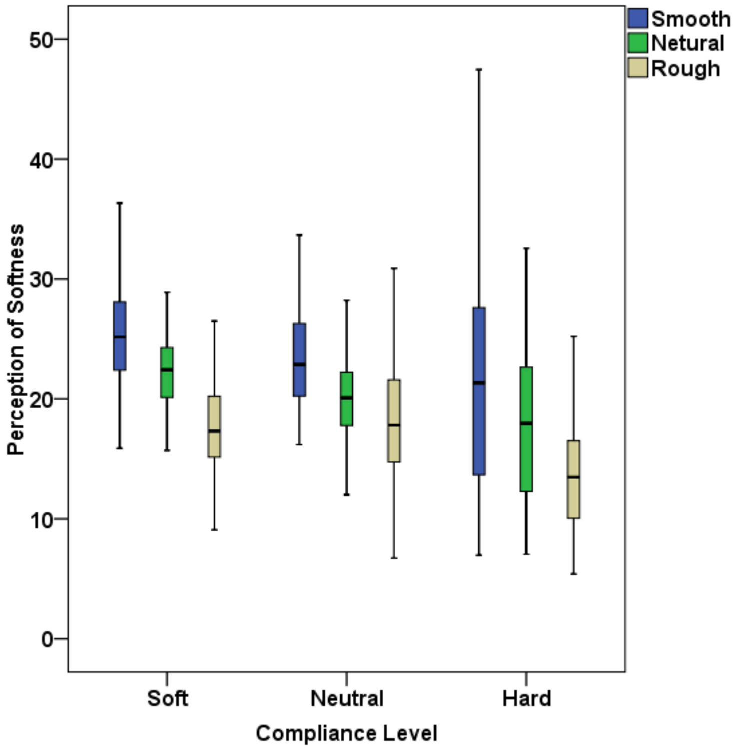


Figure 3.4 The clustered boxplot for data (pressing condition)

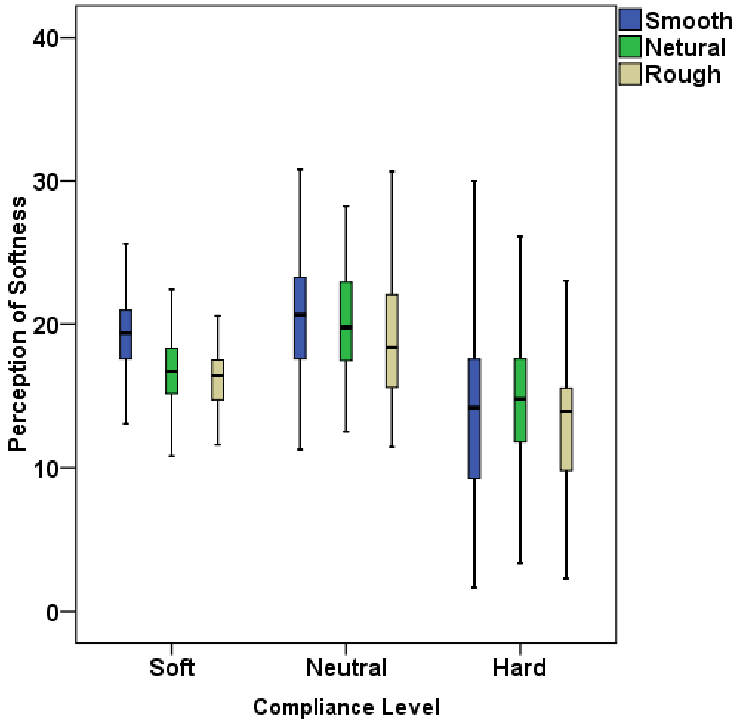


Figure 3.5 The clustered boxplot for data (sliding condition)

3.8.1 Pressing Condition

A two-way repeated measures analysis of variance was carried out with the normalized magnitude estimates of perceived softness as the dependent variable, and compliance and roughness as independent variables. Mauchly’s test indicated that the assumption of sphericity is met for the main effects of compliance, X^2 (2) = 41.62, p (0.0001) <0.05, roughness, X^2 (2) = 43.20; p (0.0001)<0.05 and interactions between compliance and roughness, X^2 (9) = 20.67; p (0.014)<0.05 and so correction of the F-ratio was required for the main effect of compliance, roughness and the interactions. Therefore, the degree of freedom was corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.69 for the main effect of compliance, 0.69 for the main effect of roughness and 0.88 for main effect of interaction between compliance and roughness).

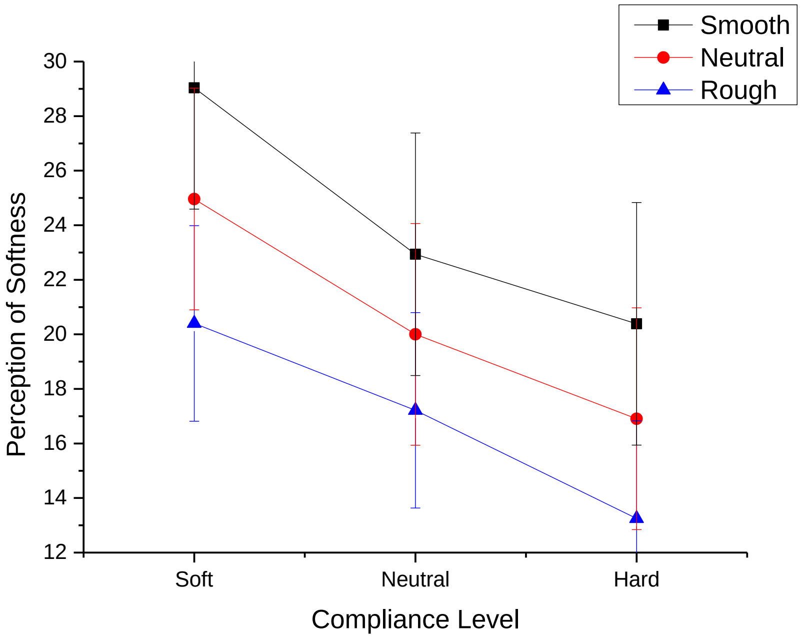


Figure 3.6: Perceived softness vs compliance at different levels of roughness through pressing condition

All effects are reported as significant at p<0.05. There was a significant main effect of compliance on the perception of softness, F (1.38, 98.05) = 39.39, p (0.0001) <0.05. This indicated that when the roughness level was ignored, the perception of softness was significantly different according to the compliance levels. There was a significant main effect of level of roughness on the perception of softness, F (1.37, 97.23) = 26.11; p (0.0001)<0.05. There was no significant interaction effect between the level of compliance and the level of roughness used, F (3.53, 250.50) = 2.45, p (= 0.054)>0.05. Figure 3.6shows the geometric means for reported perception of softness as a function of compliance in the pressing condition, and how this varied with the different roughness conditions. This figure compares the perception of softness for different compliance in different surface roughness. The rating of softness increases with increasing compliance level and decreasing surface roughness. The line in this figure is drawn between the data points to determine whether they are parallel to indicate independence of effects. Table 3.3 shows the geometric mean and standard deviation for perception of softness under pressing conditions.

Table 3.3 Geometric means and standard deviation for perception of softness through pressing condition

Stimulus	Geometric Mean	Standard Deviation
A	20.40	8.83
B	17.21	5.74
C	13.25	6.19
D	24.96	8.61
E	19.99	3.99
F	16.91	6.69
G	29.04	10.18
H	22.94	4.72
I	20.39	11.34

3.8.2 Sliding Condition

Mauchly’s test indicated that the assumption of sphericity had been violated for the main effects of compliance, χ^2 (2) = 9.37, p (0.009) <0.05. Moreover, it had been violated for the main effects of roughness, χ^2 (2) = 12.40, p (0.002) <0.05; also for the main effects of interactions between compliance and roughness, χ^2 (9) = 43.89, p (0.0001) <0.05. So correction of the F-ratio was required for all the effects of compliance, roughness and the interaction. Therefore, the degree of freedom was corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.89 for the main effect of compliance, 0.86 for the main effect of roughness and 0.76 for the main effect of interaction between compliance and roughness).

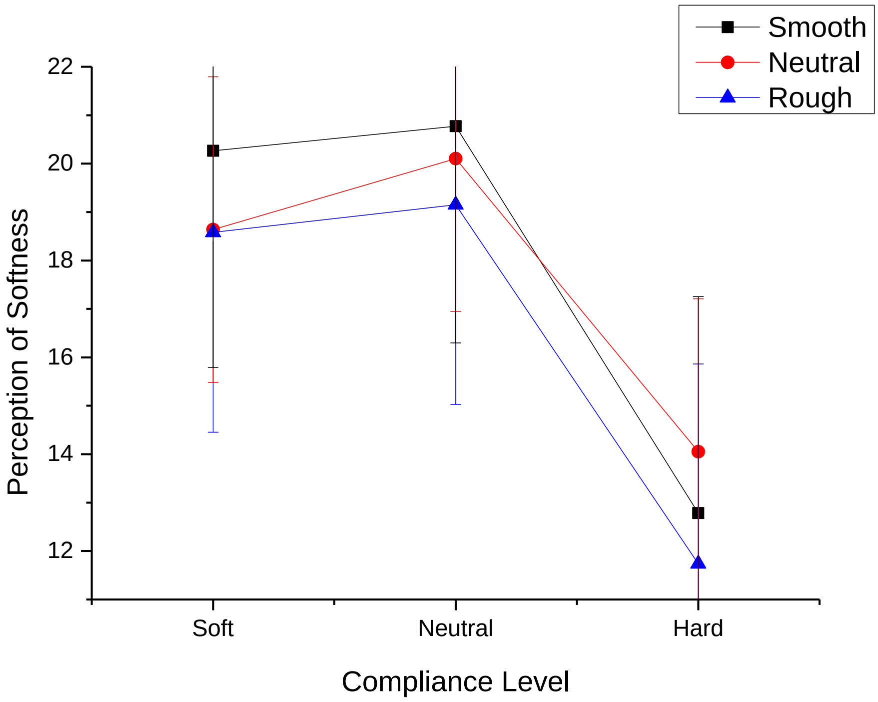


Figure 3.7: Perceived softness vs compliance at different levels of roughness through sliding condition

From the tests of subject effects, there was a significant main effect of compliance on the perception of softness, F (1.78, 126.19) = 11.57, p (0.0001) <0.05. There was also a significant main effect of level of roughness on the perception of softness, F (1.72, 122.17) = 22.15, p (0.0001) <0.05. There was no significant interaction between the level of compliance and the level of roughness used, F (3.05, 216.33) = 1.84, p (0.140) >0.05. Figure 3.7shows the geometric means for reported compliance as a function of compliance in the sliding condition, and how this varied with the different roughness conditions. This figure compares the perception of softness for different compliances in different surface roughnesses. The curve show that perception of softness decreases with decrease of compliance level and increase of surface roughness.

Means and standard deviation for perception of softness through sliding conditions are shown in Table 3.4. In short, the above analysis demonstrates that the interaction between compliance and roughness do not significantly affect the perceived softness for both conditions. Figure 3.8shows perceived softness against compliance for both conditions.

Table 3.4 Mean and standard deviation for perception of softness through sliding task

Stimulus	Geometric Mean	Standard Deviation
A	18.58	8.19
B	19.15	5.47
C	11.74	5.07
D	18.64	8.46
E	20.10	4.99
F	14.05	5.06
G	20.26	6.85
H	20.77	5.07
I	12.78	6.65

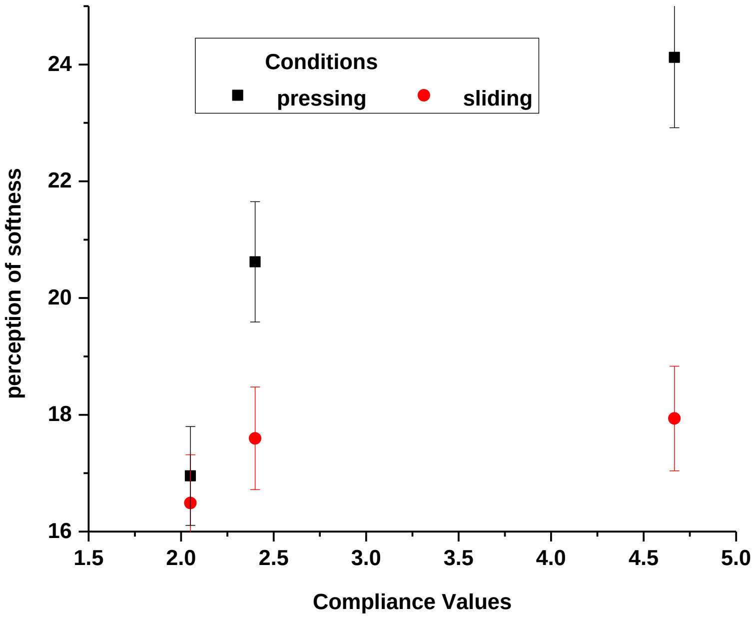


Figure 3.8: Perceived softness vs compliance

There is a significant difference between the levels of compliance. This means that participants could distinguish between different compliances for all surface roughness. Table 3.5 shows the results of the Chi-square test.

Table 3.5 Chi-square results

	Pearson Chi-Square value	**P Value**
Compare between feeling softness at smooth surface	263.83	0.00001
Compare between feeling softness at natural surface	156.1	0.00001
Compare between feeling softness at rough surface	212.35	0.00001

The results of correlation test and regression test are shown in Table 3.6 and 3.7 respectively.

Table 3.6 Correlations between physical properties and perceived softness during both conditions

	Compliance (mm/3N)	**Averaged of measured Roughness (R_a) µm**	**Friction coefficient (µ)**	**Heat transfer (°C/sec.)**
Perceived softness (pressing condition)	0.750*	-0.083	-0.458	0.07
Perceived softness (sliding condition)	0.300	0.618	-0.74	0.181

* Correlation is significant at the 0.05 level

Table 3.7 Beta coefficients of regression of perceived softness during pressing

Model	**Perceived softness (pressing)**	**Model**	**Perceived softness (sliding)**
	Standardized Coefficients		**Standardized Coefficients**
Measured compliance	0.750	Friction coefficient	-0.736

A Pearson correlation coefficient was computed to assess the relationship between the physical properties with each other. There were no correlations between two different variables and Table 3.8 summarizes the results. Overall, there seem to be no statistically significant correlations between physical properties.

Table 3.8 Correlations between physical properties

	Compliance	**Averaged of measured Roughness (R_a) µm**	**Friction coefficient (µ)**	**Heat transfer**
Compliance (mm/3N)	1	-.01	-.17	-.29
Averaged of measured Roughness (Ra) µm	-.01	1	-.45	.22
Friction coefficient (µ)	-.17	-.45	1	-.32
Heat transfer (^{o}C/sec.)	-.29	.22	-.32	1

Correlation is significant at the 0.05 level

3.9 Discussion and Conclusions

The aim of this experiment was to establish whether the interaction between surface roughness and compliance could influence perception of softness. Across the two conditions tested (pressing and sliding), there was a strong outcome that interaction between roughness and compliance does not affect perception of softness. In this section the main findings are summarized and their implications discussed.

The main result of this experiment was that the compliance × roughness interaction had no significant effect on perceived softness; this was true for both pressing and sliding conditions. There was no evidence that interaction between compliance and roughness affected perceived softness. This may be because of frictional forces between the finger tips and the stimulus or because of small differences between compliance levels of samples. The amount of deformation that fingers undergo during pressing may be one reason, because it depends on the contact force and how stiff the material is compared to a finger. Nevertheless as this experiment shows, participants were able to distinguish between the compliance for each roughness level. This is in agreement with a previous study on the perception of softness (Srinivasan and LaMotte, 1995), which showed that perception of softness might depend on the objective compliance of the stimuli and people could discriminate softness easily through active touch. Our results are in agreement, since the compliance was largely determined by the influence of other material properties. The comparison of these results with previous findings shows very similar judgements on the relationship between perceived softness and physical hardness, as well as no significant effect between perception of softness and interaction between compliance and roughness surface.

The results showed that perception of softness was affected by compliance for the pressing condition. This finding is in agreement with previous studies (Shirado and Maeno, 2005, Bergmann Tiest and Kappers, 2006).

The present findings seem to be consistent with other research (Petrie et al., 2004) which found that the relationship between the perception of smoothness of a surface and the physical hardness of the samples was not significant, and the interactions with other variables (such as surface shape) were also not significant. Moreover, the present finding is also in agreement with Shirado and Maeno (2005) who showed the influence of elasticity for different materials on the tactile sense.

However, these results differ from some published studies (Bergmann Tiest and Kappers, 2006, Shao et al., 2009, Chen et al., 2009b), which found that the perception of softness relates to other material properties such as compliance.

It is difficult to explain this result, but it might be related to the deformation of the material and the finger caused by the magnitude of friction forces when pressing and sliding on the surface. These friction forces have an important role in the perception of softness. Moreover, the stiffness of the material compared to a finger and the contact force with material affects the deformation of the material. Another explanation is that perceived softness depends on the force used for pressing the stimuli. The study by Friedman et al. (2008) found that participants press a hard object with more force than a soft object.

Further analysis is required to investigate how perception of softness is related to physical material properties. Linear regression analysis was used to explore the relationship between perception of softness and physical material properties. The data shows that there is a correlation ($r = 0.75$, <0.05) between the perceived softness and the measured physical compliance during the pressing condition. This seems to be consistent with the results by Shao et al. (2009). Perception of softness and compliance values seems to have a strong relationship (Petrie et al., 2004). However, there is only a weak effect ($r = 0.30$, $p>0.05$) between the perceived softness and measured compliance during the sliding condition. Roughness and softness seem to be perceived differently. Roughness can be tracked by running the finger across the surface (sliding) and softness tracking by pressing the finger onto the surface. For this reason, the tactile display was built. As can be seen from the analysis, the mean of perceived softness was high in cases of high roughness. Perceived softness depends on the way stimuli are touched, how the contact area increases with contact force, the pressure over the contact area, and the force used to press the stimuli (Bergmann Tiest, 2010, Johnson et al., 2000, Friedman et al., 2008).

In addition, the data indicated that there is a correlation ($r = -0.74$, $p<0.05$) between the perceived softness and the friction coefficient during sliding conditions. In reviewing the literature, data were found on the association between perceived softness and friction coefficient (Chen et al., 2009c). However, the findings of the current study are inconsistent with those of Shao et al. (2010) who found that soft perception was related to compliance and thermal conductivity. Perhaps we did not find a correlation between softness perception and thermal conductivity because we controlled that condition, for example, dT/dt was made to be the same in every case.

Across the friction coefficients tested, there was no correlation ($r = -45$, $p>0.05$) between the friction coefficient and measured roughness during both conditions, which shows that this finding is in agreement with results by Shao et al. (2009), (Shao et al., 2010). They reported that rough was related to the roughness of a surface. However, it appears to be different from results found by Skedung et al. (2011). Roughness and friction are inverse correlated. This means that perceived coarseness is less when the friction is high.

Unlike most previous work which studied relations between subjective and objective properties separately, Chen et al. (2009a) examined the combination of physical properties in relation to touch perception. This study included consideration of a range of material properties interacting to influence perception of material softness.

My findings from the analysis respond to the study’s research question and help to achieve its goals, which are to investigate whether roughness and compliance could affect the perception of softness. These findings have significant implications for the design of the tactile display, particularly for the purpose of presenting softness. The results obtained in this experiment may help developers to decide how to generate tactile sensations and how this information can be delivered to surgeons' fingertips.

3.9.1 Summary

An experiment was conducted to explore whether perception of softness was affected by interaction between compliance and surface roughness. There were 24 participants involved in this experiment. Their task was to evaluate how many times the stimulus is softer than a reference stimulus using the magnitude estimation method for two different conditions (pressing and sliding). An analysis using two-way repeated measures ANOVA demonstrates that interaction between compliance and roughness appear to not significantly affect perceived softness for both conditions, indicating that both compliance and roughness had the same effect on participants' ratings depending on which task was being employed. Results of correlation analysis confirm that the compliance appears to be related to perceived softness. A tactility test for softness should involve pressing and does not need to take account of a surface's roughness. The tactile display was designed taking these findings into account. The tactile display was designed to reproduce the sensation of softness using compliance in the pressing condition. This analysis will be extended in Section 6.2.

Chapter 4
Effect of Adhesion and Compliance on Perception of Softness

4.1 Introduction

Tactile perception is related to the material's physical properties (Shao et al., 2010). Some researchers have examined the relationships between physical properties with different tactile feelings such as perception of softness (as explained in Sections 1.3 and 2.2). Shirado and Maeno (2005) showed that tactile feelings were affected by material properties. Also, softness perception seems to be affected by more than one physical property (Bergmann Tiest and Kappers, 2006).

The experiment described in this chapter aimed to characterize the influence of adhesion on the perception of softness. To achieve this aim, the experiment used the same experiment design as the previous experiment (Chapter 3) but, instead of varying roughness and compliance, varied the levels of adhesion and compliance of each sample. Zigler (1923) defined sticky as the sensation that comes when the skin is released from the stimulus. The release gives the sensation of stickiness because the finger breaks away in patches. In this chapter, participants were asked to evaluate the stickiness as well as softness. This is important in the context of laparoscopic surgery, for example, because bleeding tissue becomes sticky (Shopf and Olano, 2006).

4.2 Method

This experiment aims to characterize how surface adhesion and compliance affect the perception of softness. To accomplish this aim, there are several methods that could be used, but the method applied is magnitude estimation, which is fully explained in Section 3.6 and Appendix A.4. The stimuli were presented to participants in randomized order. Each stimulus was presented three times to each participant for evaluation during four conditions, which are explained in Section4.5. The method applied in this experiment follows the same method as in Chapter 3 (Section 3.2).

Participants were asked to rate nine samples compared to a reference sample. Participants were asked to touch samples with their dominant hand and they were also asked to slide their fingers over the surface of each stimulus. Once the participants had touched the reference sample and then touched the test sample, they gave a number (should be a positive, non-zero whole number) for the test sample compared to 25 which had been assigned to the reference sample. The procedure used to normalization magnitude estimation values is geometric averaging (McGee, 2003).

Two-way repeated measures ANOVA was performed to determine the relationships between the human tactile perception and interaction between adhesion and compliance, taken from the magnitude estimation data. It was used to find out whether there is interaction between the two factors. Further analysis was carried out to determine whether, for each surface level of Adhesion, participants appeared to be able to distinguish between the compliance of the stimuli using the Chi-Square test. Regression and correlation analysis was carried out to examine the relationship between physical measurements and softness perception.

4.3 Participants

There were 24 participants in the experiment made up of undergraduate and postgraduate students and staff at the University of Leeds. Their age ranged between 20 and 49 years. Eleven were female and 13 were male. The average age was 31.8 years for females and 33 years for males. The participants performed the experiment one at a time. All were found to be right handed, which was determined through a handedness inventory questionnaire as was explained in Section 3.3. None of the subjects were reported as having any neurological or physical injury that affected sensitivity of the index figures on both hands. This experiment was approved by the MEEC Faculty Research Ethics Committee at the University of Leeds (MEEC 11-022). Each subject gave their informed consent. The participants could not see the stimulus, as in the first experiment, in order to remove any influence of visual cues.

4.4 Stimuli

Nine stimuli representing all combinations of three levels of compliance and three levels of adhesion were created for each participant. Compliances of stimuli were varied by mixing Platsil gel 10, parts A and B with different amounts of a plasticizer. Plasticizer was added to Platsil Gel 10 with different ratios used to lower the hardness from a 10 Shore A to a soft gel consistency. Adhesion of stimuli were varied by air-brushing a mixture of silicone, plasticizer and toluene with different ratios of plasticizer and toluene onto the blocks, to give a surface layer of different adhesion on the surface of the compliant blocks. A full description of the process is in Appendix B.1. Figure 4.1 shows the stimuli. The mould used to make stimuli was circular with a diameter of 40 mm and a thickness of 10mm as shown in Appendix B.1 (Figure B.1). Initially, this experiment was conducted using a set of stimuli with the same dimensions as those in Section 3.4. However, it was found that the sticky layer began to wear off after two or three sessions, making it impossible to control the level of stickiness. To address this, a new set of stimuli had to be made for each participant, and were discarded after the experiment. Due to the limited material available, these had to be made in a smaller size to ensure there was sufficient material to make a new set for each participant.

(a)

(b)

Figure 4.1: (a) the stimuli, (b) Stimulus during touching

4.5 Design

The experimental approach used was to develop a 3×3 randomized complete block factorial design. In this approach, two factors were used: compliance and adhesion. The Minitab 16 statistical software was used to design a randomized complete block factorial design. In order to avoid the order of treatment or other factors influencing the results, a counterbalanced design was used in this experiment. The experiment was to have four conditions (A = rating softness through pressing, B = rating stickiness through pressing, C = rating softness through sliding and D = rating stickiness through sliding), these conditions required 24 orders (4*3*2*1) in which they can occur. The orders are given in Appendix B.2. Participants were divided into 24 groups to have an equal number of participants in each group (group have all experiment conditions); meaning one participant was in each group (Field and Hole, 2010).

4.6 Procedure

Each participant was given a brief outline of what the experiment would involve. An instruction sheet was presented to each participant, as well as an explanation as to how the experiment would be performed to ensure participants understood what was going to happen.

Before starting the experiment, the subjects were presented with an explanatory sheet (Appendix A.3) of magnitude estimation as explained in Chapter 3.

Each of the experimental stimuli was presented twice (18 trials in total). During the experiment, participants touched the stimulus under four touch conditions: rating softness through pressing, rating stickiness through pressing, rating softness through sliding and rating stickiness through sliding. The conditions were presented randomly using a counterbalanced design for each participant. After each condition, the participants were allowed to rest for a different time dependent on the participant. The time ranged between 0-6 minutes. Participants were also allowed to rest at any point during the experiment if necessary. The total experimental time per participant was between approximately 18 to 58 minutes (mean = 35 minutes and standard deviation = 9.7) and the full study was performed within 8 days. The full procedure is explained in Appendix B.3.

4.7 Material Properties Measurement

During the measurement phase, a Tribometer (Figure 3.3) was used to measure different material properties such as compliance, adhesion, friction coefficient and thermal conductivity of each stimulus.

The compliance was measured using the same procedure which has been explained in Section 3.7, except the load used. In this case, the load applied for the measurement of compliance was 1N instead of 3N. This change was necessary because of the greater compliance of the silicone blocks. The compliance was measured at three different positions and the average was calculated.

In order to measure the adhesion of the stimuli, a stimulus was placed on top of the force table. The artificial fingertip was replaced by an aluminium disc (10mm in diameter) which was connected to the mounting plate. The aluminium disc was moved in the vertical direction. In the WSDK program, adhesion pre-programmed commands were downloaded to the controller. Manual commands were used to position the aluminium disc and adjust the movement speed. The normal force (Fy) was 1N maximum downward contact force with the stimulus with a speed of 10 mm/s (normal force and speed would be natural human contact values (Shao et al, 2010)). The normal forces (Fy) were noted against time using a LabVIEW programme, which generated a force-time curve for the force acting at the interface between the aluminium disc and stimulus. Figure 4 shows a typical force-time curve. Average curves were obtained using Excel. The force was zero until the disc and stimulus are in contact. When the disc contacts the stimulus, the normal force will increase until it reaches 1N. At this point the motion of the driving unit is reversed to release the load. The adhesion force is the value between zero load and the maximum value reached at negative load. When the adhesion force is overcome, the surfaces are released and the separating force returns to zero. The surfaces are fully separated when the load becomes zero.

For friction measurement, the artificial finger was moved against each sample material while the forces Fy, Fx were recorded against time on a LabVIEW programme as explained in Section 3.7. The force applied to the sample was 0.5N. The friction coefficient was obtained by taking the average of Fx/Fy during the mid-section of the data where the fingertip contacted the stimuli.

For heat transfer measurement, a heated rubber finger was used to measure the thermal conductivity of the stimuli. The room temperature was recorded as explained in Section 3.7. The rate of temperature change of the finger was calculated using the equation dT/dt and maximum values from this equation were taken as a measure of thermal conductivity.

Three measurements per stimulus per physical property were made at different points across the stimulus and the averages obtained. The compliance and material properties of each stimulus are shown in Table 4.1

Table 4.1 Material properties for stimuli

Stimulus		**Compliance (mm/1N)**	**Adhesion (mN)**	**Friction Coefficient (μ)**	**Heat Transfer (^{o}C/sec)**
A	Hard	1.60	200.96	2.45	0.41
B		1.76	429.61	2.56	0.45
C		1.78	1484.38	2.24	0.43
D	Neutral	5.36	165.96	1.60	0.37
E		5.66	465.93	1.33	0.42
F		5.27	1056.23	2.25	0.36
G	Soft	7.57	177.95	1.50	0.35
H		8.97	427.56	1.82	0.27
I		8.04	1054.42	1.93	0.32

4.8 Results

A two-way repeated measure ANOVA with independent measures on both variables was conducted on these data to explore the relations between the perception of softness and stickiness. The two-way repeated measures analysis of variance was carried out with the magnitude estimates of perceived softness as dependent variables and independent variables which were compliance levels and adhesion levels.

The geometric mean scores and standard deviation for perceived softness or stickiness with different surface adhesion for four conditions is presented in Table 4.2. Figures 4.2, 4.3, 4.4 and 4.5 show the raw data, the x-axis and y-axis represent the compliance level and perception of softness and stickiness respectively for different adhesion levels for four conditions.

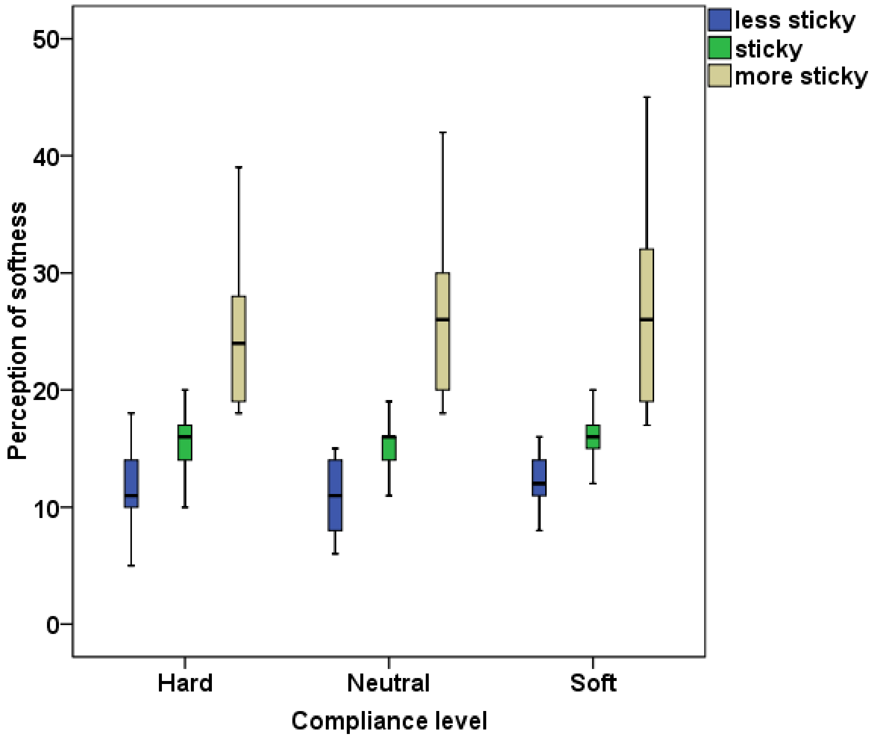


Figure 4.2 The clustered boxplot for rating softness through pressing condition

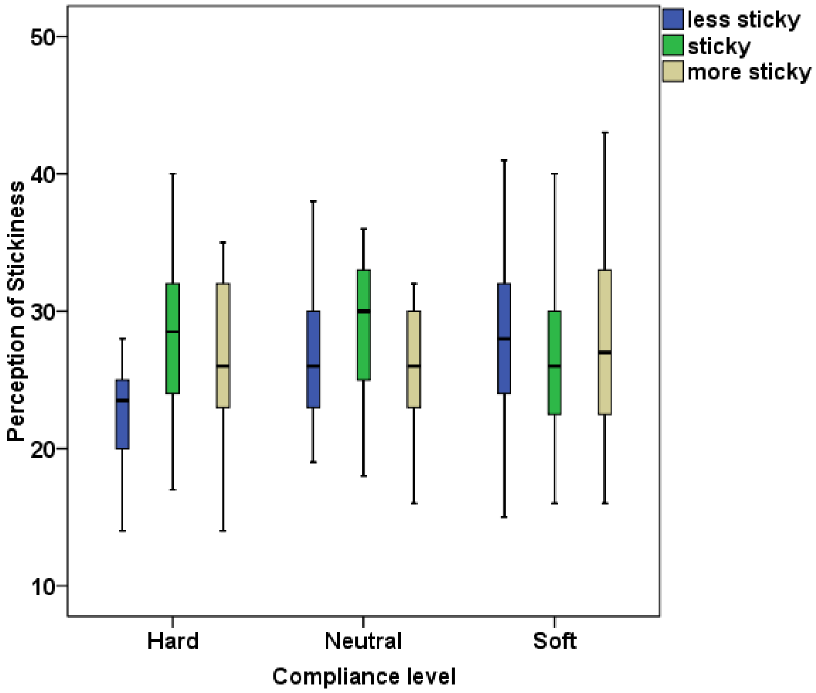


Figure 4.3 The clustered boxplot for rating stickiness through pressing condition

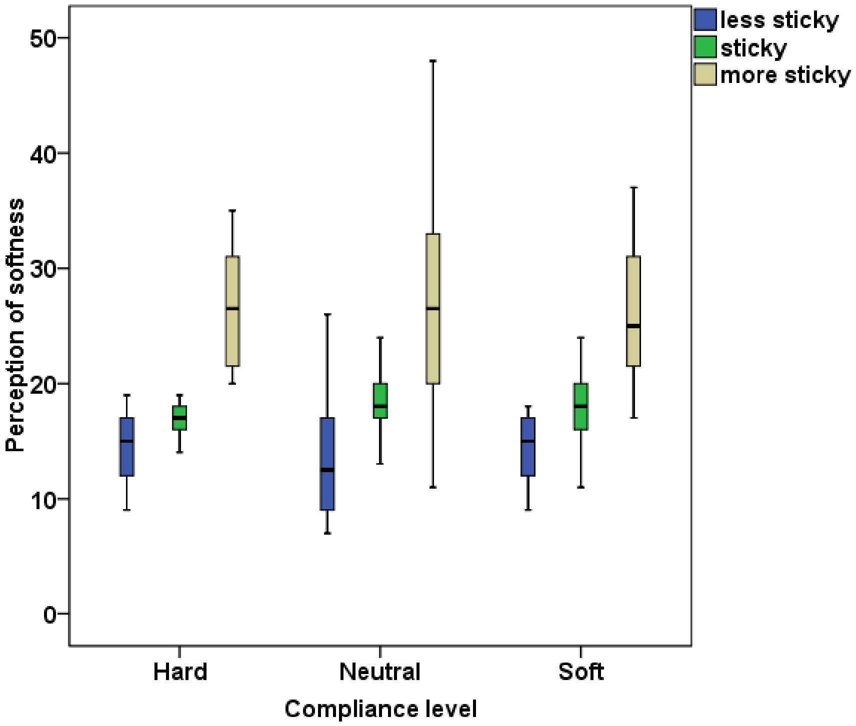


Figure 4.4 The clustered boxplot for rating softness through sliding condition

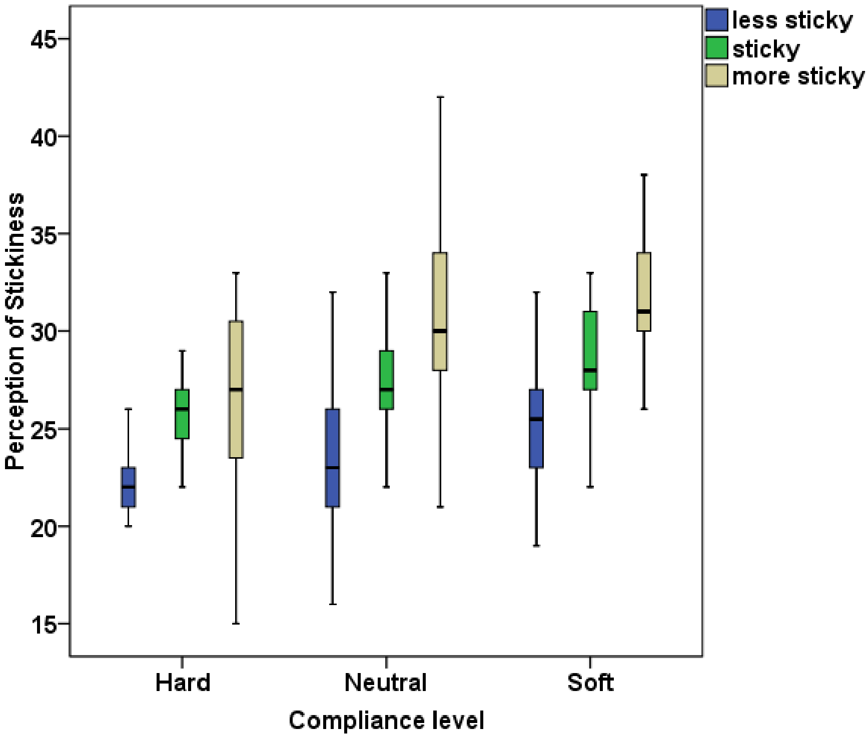


Figure 4.5 The clustered boxplot for rating stickiness through sliding condition

4.8.1 Perception of Softness (through pressing task)

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of compliance, χ^2 (2) = 69.41, p (0.0001)<0.05, adhesion χ^2 (2) = 7.08, p (0.029)<0.05; and interactions between compliance and adhesion, χ^2 (9)= 47.91, p(0.0001)<0.05. So correction of the F-ratio was required for the main effect of compliance, adhesion and the interactions between compliance and adhesion. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.56 for the main effect of compliance, 0.88 for the main effect of adhesion and 0.66 for the main effect of interaction between compliance and adhesion).

All effects are reported as significant at $p<0.05$. There was a significant main effect of compliance on the perception of softness, F (1.12, 25.86) = 107.32, p=0.0001. This indicated that when the adhesion level was ignored, the perception of softness was significantly different according to the compliance levels. There was no significant main effect of level of adhesion on the perception of softness, F (1.75, 40.29) = 0.56, p=0.55. There was no significant interaction effect between the level of compliance and the level of adhesion used, F (2.65, 60.88) = 2.57, p=0.065.

Figure 4.6 shows the geometric means for reporting softness as a function of compliance with the pressing condition, standard deviation error bar and how this varied with the different adhesion conditions. This figure compares the perception of softness for different compliance levels in different adhesion levels. The perception of softness increases with increasing compliance level. Contrasts with this interaction term revealed that when the difference in the perception of softness between levels of compliance was compared with adhesion levels there were no significant differences, as shown in Table (B.3) in Appendix B.4.

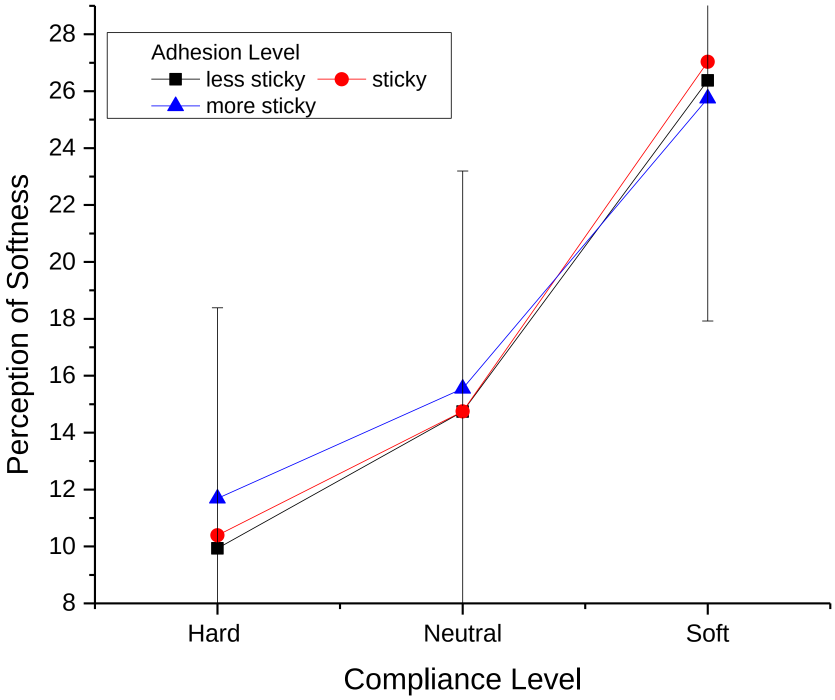


Figure 4.6: Perceived softness vs compliance at different levels of adhesion during pressing conditions

4.8.2 Perception of Stickiness (through the pressing task)

Mauchly's test indicated that the assumption of sphericity was met for the main effects of compliance, χ^2 (2)= 2.02, p>0.05, but the assumption had been violated for the adhesion, χ^2 (2)= 10.13, p<0.05 and interactions between compliance and adhesion, χ^2 (9) = 14.33, p>0.05 and so it was necessary to correct the F-ratio for these effects. Therefore, degree of freedom was corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.0.84 for the main effect of adhesion and 0.86 for the main effect of interaction between compliance and stickiness).

From the tests of subjects' effects, there was no significant main effect of compliance on the perception of stickiness, F (1.92, 90.13) = 2.82, p=0.067. There was also a non-significant main effect of the level of adhesion on the perception of stickiness, F (1.67, 78.49) = 2.38, p=0.108. To conclude, there was a no significant effect of adhesion on the perception of stickiness.

There was no significant interaction between the level of compliance and the level of adhesion used, F (3.46, 162.37) = 1.58, p=0.191. The geometric means for reporting softness as a function of compliance with the pressing conditions with standard deviation error bar and how this varied with the different adhesion conditions are shown in Figure 4.7. This figure compares the perception of stickiness for different compliance levels in different adhesion levels. Contrasts on this interaction term revealed that when the difference in the perception of stickiness between different levels of adhesion was compared with different levels of compliance there were no significant differences, as shown in Table (B.4) in Appendix B.4.

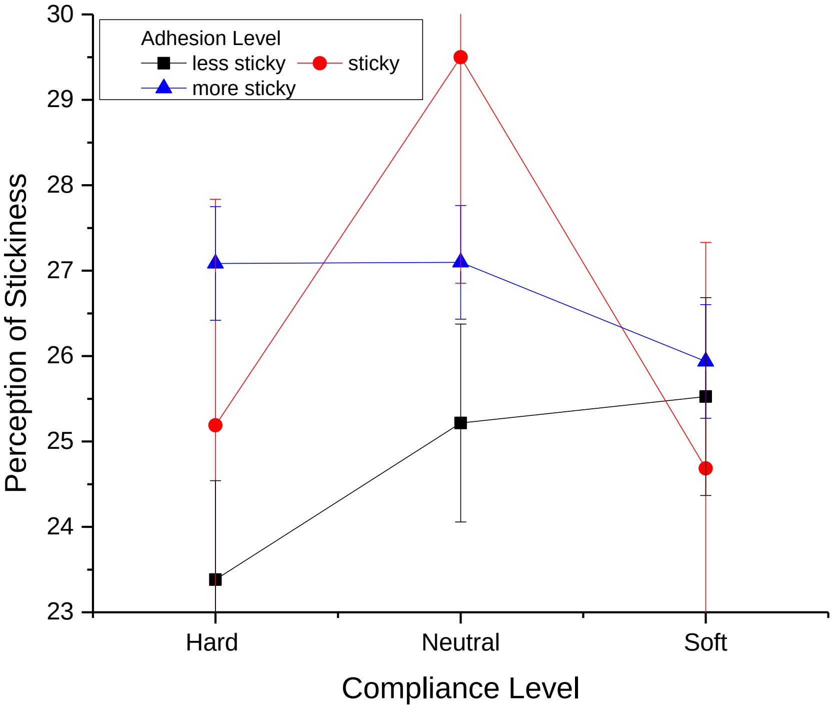


Figure 4.7: Perceived stickiness vs compliance at different levels of adhesion during pressing conditions.

4.8.3 Perception of Softness (through the sliding task)

In this condition, Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of compliance, χ^2 (2) = 59.73, $p<0.05$ and the interaction between compliance and adhesion, χ^2 (9) = 62.14, $p<0.05$. Therefore, the degrees of freedom was corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.58$ for the main effect of compliance and 0.61 for the main effect of interaction between compliance and adhesion).

The results show that there was a non-significant interaction effect between the level of compliance and the level of adhesion used, F (2.42, 113.65) = 0.64, p= 0.558, indicating that both compliance and adhesion had the same effect on participants' ratings. To sum up, there was no significant interaction between the levels of adhesion and level of compliance for perceiving softness. Contrasts on this interaction term revealed that when the difference in the perception of softness between different levels of adhesion was compared with different levels of compliance there were no significant differences, as shown in Table (B.5) in Appendix B.4.

Simple main effects analysis showed that there was a significant main effect of compliance on the perception of softness, F (1.16, 54.43) = 65.58, p= 0.0001. This effect revealed whether the different levels of adhesion were ignored, perception of softness of different levels of compliance were different.

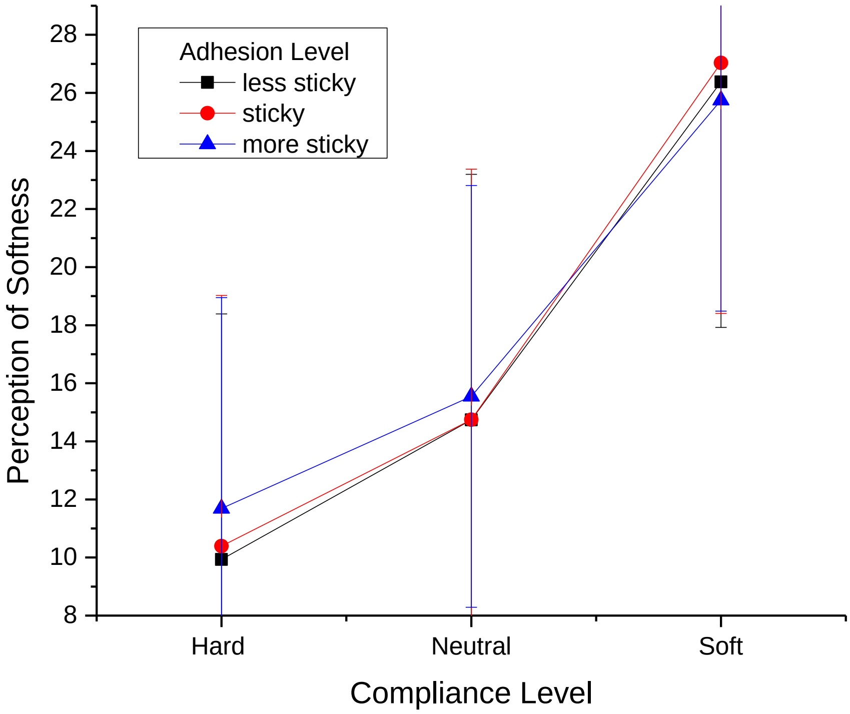


Figure 4.8: Perceived softness vs compliance at different levels of adhesion during sliding conditions.

There was a significant main effect of the level of adhesion on the perception of softness, F (1.84, 86.59) = 3.62, p= 0.034 with adhesion level. To conclude, adhesion affects the perception of softness significantly.

Figure 4.8 shows the geometric mean for perception of softness along with different compliance levels and different adhesion levels when participants made a sliding touch of the stimuli with standard deviation error bar and how this varied with the different adhesion conditions. This figure compares the perception of softness for different compliance levels in different adhesion levels. The perception of softness increases with increasing compliance level.

4.8.4 Perception of Stickiness (through the sliding task)

In the fourth condition, Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of compliance, χ^2 (9) =

25.48, p<0.05, the main effects of adhesion, χ^2 (9) = 54.20, p<0.05 and interactions between compliance and adhesion, χ^2 (9) = 45.51, p<0.05. Therefore, the degrees of freedom was corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.70 for the main effect of compliance, 0.54 for the main effect of adhesion and 0.74 for the main effect of interaction between compliance and adhesion).

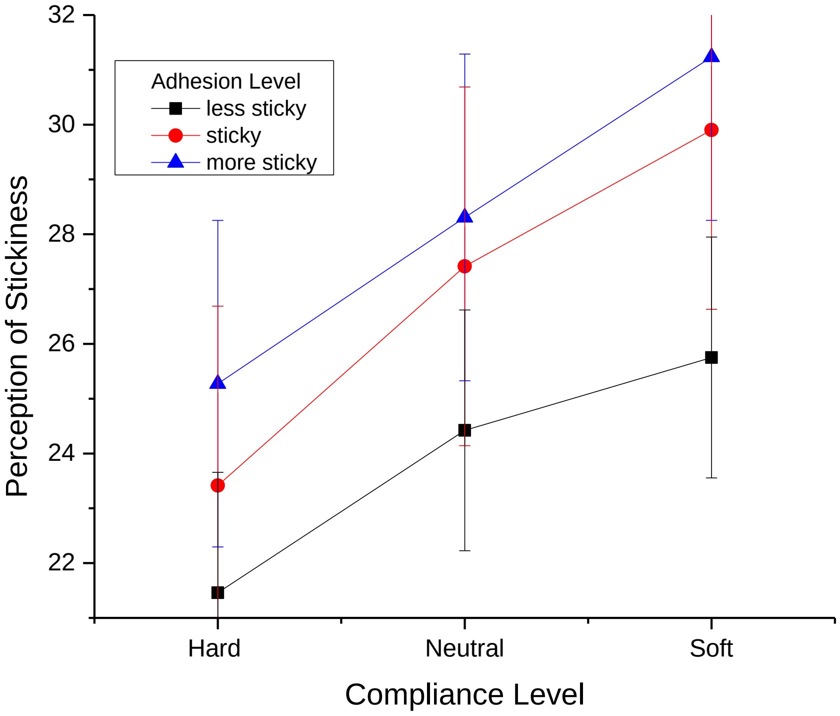


Figure 4.9: Perceived stickiness vs compliance at different levels of adhesion during sliding conditions.

Table 4.2 Mean and standard deviation for perception of softness through four conditions

Compliance level* adhesion level*	Rating softness through pressing		Rating stickiness through pressing		Rating softness through sliding		Rating stickiness through sliding	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
A	10.46	3.44	27.25	7.60	27.96	9.83	25.79	4.49
B	10.83	3.24	25.25	6.90	26.83	8.02	30.21	4.99
C	11.92	2.50	26.67	7.28	27.75	7.04	31.50	4.054
D	15.63	2.37	28.46	9.11	18.96	4.52	24.42	4.09
E	15.13	3.71	30.88	8.88	18.08	2.90	27.75	3.07
F	15.42	4.71	27.50	9.85	18.08	4.61	28.92	4.54
G	27.75	8.29	28.42	7.99	14.04	4.39	21.67	3.46
H	28.54	8.86	26.50	7.96	13.42	4.61	24.08	4.46
I	27.13	8.1	24.38	7.64	14.25	4.59	25.86	4.62

The results show that there was no significant interaction between the level of compliance and the level of adhesion used, F (2.96, 139.18) = 1.60, indicating that at a given level of compliance, the perception of stickiness does not change reliably for all levels of adhesion. These interactions between compliance and adhesion are shown in Figure 4.9 due to the interaction of the three lines. To sum up, there was a non-significant interaction between the levels of adhesion and level of compliance for perceiving stickiness. The perception of stickiness due to levels of compliance compared to levels of adhesion is not affected by whether stimuli are soft or hard. Contrasts on this interaction term revealed that when the difference in the perception of stickiness between levels of adhesion was compared with compliance levels there were no significant differences, this is shown in Table (B.6) in Appendix B.4.

Simple main effects analysis showed that there was a significant main effect of compliance on the perception of stickiness, F (1.40, 65.95) = 36.39. This effect reports that the different levels of compliance used had a different effect on the perception of stickiness when the levels of adhesion were ignored.

There was also a significant main effect of level of adhesion on the perception of stickiness, F (1.18, 55.55) = 27.99. To conclude, this effect revealed if the different levels of compliance were ignored, perception of stickiness of different levels of compliance was different according to different levels of adhesion (Figure 4.10). This figure compares the perception of adhesion for different compliance in different stickiness with standard error.

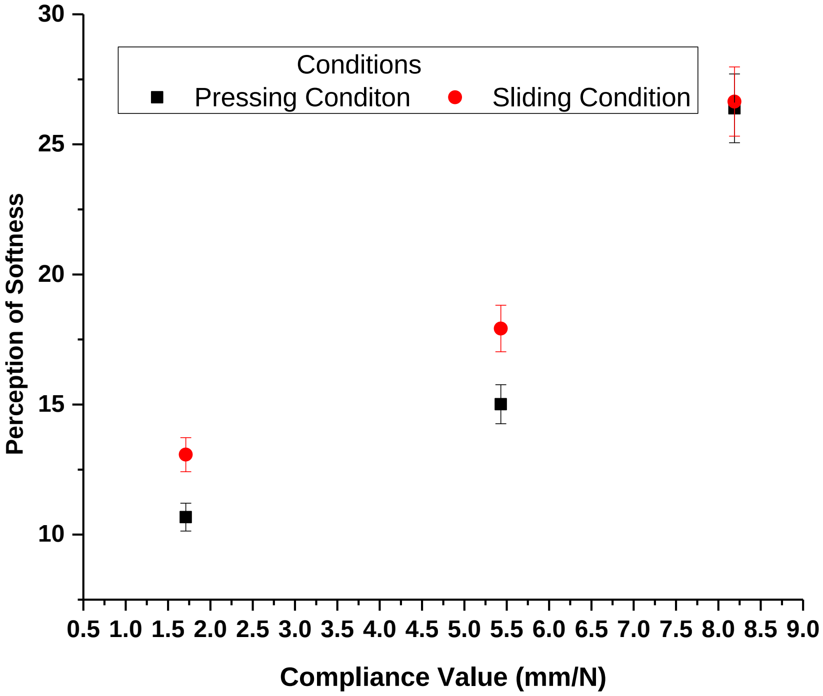


Figure 4.10: Perceived softness vs compliance

The results of the one way ANOVA show the perception of softness was significantly affected by compliance for all levels of adhesion. The values of the F test and p value are shown in Table 4.3 for pressing and sliding conditions.

From the analysis, perception of softness correlated with compliance, friction coefficient and thermal conductivity during the pressing and sliding conditions. Perception of stickiness correlated with compliance and thermal conductivity during sliding conditions ($r = .763$, $p = 0.02$; $r = .691$, $p = 0.039$).

Table 4.3 One-way ANOVA analysis to distinguish between the compliance of the stimuli through pressing and sliding conditions.

Level of compliance	**Pressing condition**		**Sliding condition**	
	F(2,71)	**P value**	**F(2,71)**	**P value**
adhesion level 1 compare different level of compliance	38.43	0.00	26.31	0.00
adhesion level 2 compare different level of compliance	59.83	0.00	35.55	0.00
adhesion level 3 compare different level of compliance	55.58	0.00	37.93	0.00

In order to examine the relationships between physical measurements and softness perception, a Pearson correlation coefficient was computed, as shown in Table 4.4.

A regression analysis was used to examine the relationship between physical measurements and softness perception (Table 4.5). The results showed that perception of softness or stickiness for both conditions was made up of more than one physical property as found in previous studies (Shirado and Maeno, 2005, Bergmann Tiest and Kappers, 2006). This means that the perceived softness or stickiness can be predicted by these physical properties.

A Pearson correlation coefficient was computed to assess the relationship between the physical properties. There were strong, negative correlations between the compliance and friction coefficient and between compliance and heat transfer and no correlations between other physical properties (Table 4.6).

Table 4.4 The statistical correlations between physical properties and perceived softness and stickiness for both conditions

	Compliance (mm/1N)	**Adhesion (mm/N)**	**Friction coefficient (μ)**	**Heat Transfer (^oC/sec)**
Perceived softness (pressing condition)	0.932*	-0.14	-0.51*	-0.89*
Perceived stickiness (pressing condition)	-0.01	-0.52	-0.44	0.28
Perceived softness (sliding condition)	0.94*	-0.09	-0.56*	-0.87*
Perceived stickiness (sliding condition)	0.77*	-0.69*	-0.75*	-0.65

* Correlation is significant at the 0.05 level.

Table 4.5 Coefficients of regression of perceived softness and stickiness during pressing and sliding

Model	**Perceived softness (pressing)**	**Perceived softness (sliding)**	**Perceived stickiness (sliding)**
	Standardized Coefficients	**Standardized Coefficients**	**Standardized Coefficients**
(Constant)	24.3	17.40	28.1
Measured compliance (mm/1N)	1.70	1.75	0.64
Adhesion (mm/N)	0	0	-0.004
Friction coefficient (μ)	0	0	-1.24
Heat transfer (^oC/sec)	-39.8	-17.00	0

Table 4.6 Correlations between physical properties

	Compliance (mm/N)	**Adhesion (mm/N)**	**Friction coefficient (μ)**	**Heat transfer (^{o}C/sec)**
Compliance	1	-.14	-.69*	-.89*
Adhesion	-.14	1	.31	.06
Friction coefficient	-.69*	.31	1	.38
Heat transfer	-.89*	.06	.38	1

∗ Correlation is significant at the 0.05 level.

4.9 Discussion and Conclusions

The main result of this experiment showed that interaction between compliance and adhesion do not significantly affect perceived softness and perceived stickiness during pressing or sliding touch. It means that both compliance and adhesion had the same effects on participant responses depending on which condition was being employed. There was no evidence that the interaction between compliance and adhesion affected perceived softness. A possible explanation for this might be the frictional force between the fingertips and the stimulus; those forces have an important role in perception of softness. When the compliance increased, the force decreased. It means the force varied dependent on the different compliances (Kaim and Drewing, 2009). The force differed from one participant to another. Another possible explanation for this is the surface deformation. It depends on the contact force and how stiff the material is compared to a finger, but in the present study all stimuli materials were less stiff than a finger. Also, another reason is the stimuli's dimensions which influence compliance but those are the same in the present work. Another possible explanation for this is that the contact area between the finger and the stimulus might affect the participants' perception of softness and stickiness. This result may be explained by the fact that the important factor which affects perception of softness is cutaneous sensation. The cutaneous information is located within the skin which provides tactile feedback. Moreover, the cutaneous information alone is sufficient to discriminate the compliance of objects with deformable surfaces (Srinivasan and LaMotte, 1995).

Referring to Figure 4.7, the results show that sticky stimuli were represented. These results were completely unexpected; given that it is possible that participants cannot distinguish the stickiness by pressing. A possible explanation might be that stickiness seems to be detected through dynamic touch rather than a static touch. Bergmann Tiest et al. (2012) pointed out that people could detect stickiness through dynamic touch.

However, participants were able to distinguish between the levels of softness for each adhesion level, in agreement with a previous study on perception of softness, (Yoshioka et al., 2007).

Our results are in agreement because the softness was largely influenced by other material properties. The results were compared with previous findings; these are the same in terms of the relationship between perceived softness and physical hardness. Moreover, the present findings seem to be consistent with other research which found that the influence of texture for the different materials and surface properties on the subjective ranking of compliance is uncertain (Shirado and Maeno, 2005).

Even though the findings of the current study support previous research (Shao et al., 2009, Chen et al., 2009b), they are consistent with those of touch perception being related to more than one physical property. They are consistent with the perception of stickiness being associated with compliance and friction, and with the perception of hardness being related to thermal properties and compliance of the stimulus.

It is difficult to explain this result. Sticky is a term not just related to friction but also related to more contact between a finger and a surface (Shao et al., 2009) and related to vibratory cues which contribute to perceiving stickiness (Bensmaïa and Hollins, 2005).

The linear regression analysis was used to explore the relationship between perception of softness and physical material properties in both conditions. Correlations between physical measurements of compliance and psychophysical perceptions of softness and stickiness are presented in Figure 4.8. From the results, there is a significant relationship between the perceived softness during pressing conditions and measured compliance which is highly correlated with each other and with heat transfer. Moreover, perceived softness during sliding conditions was significantly related to measured compliance and heat conductivity ($p<0.05$). In addition, there was a significant correlation between perceived stickiness, compliance, adhesion and friction coefficient during sliding conditions ($p<0.05$). However, perceived stickiness during pressing conditions was not significantly correlated with any physical properties. The results seem to be consistent with findings by Shao et al. (2009).

In order to examine the relationship between physical measurements and softness perception, a regression analysis was used. A feeling of softness depends on compliance and thermal conductivity, which are consistent with relationships identified by Shao et al. (2009). Their finding was that hardness perception was correlated with compliance and thermal conductivity. It seems this is because the properties depend on the material of stimuli or the condition used to manipulate the stimuli (Shao et al., 2009).

A feeling of stickiness depends on compliance, adhesion and friction which differs from the relationships identified by Shao et al. (2009) that sticky perception was correlated with friction and compliance. It also differs from the findings of Hollins and Risner (2000) which state that sticky perception depended only on friction. It seems this was because of the task applied or the material used. However, all relations appear to be in agreement with research done by Shirado and Maeno (2005) which draw together the relations between physical properties and people’s perception. They found that perception of softness is related to modulus of elasticity and heat transfer property.

Regardless of the method of contacting the stimulus, by pressing or sliding, the subjective softness felt by a typical participant was very similar to the objective compliance. This means that softness correlates with compliance; it is the same as the results found by Shao et al. (2009). They reported that there was a correlation of thermal and compliance properties dependent on the materials of the stimuli. Perception of softness and Shore hardness values seems to have a strong relationship (Petrie et al., 2004).

An implication of this is the possibility that softness feelings could be presented through a tactile display using compliance of material. This finding may help us to understand how to design an ideal tactile display which presents realistic softness feelings to the surgeon's fingertip.

4.9.1 Summary

The analysis demonstrates that interaction between compliance and adhesion do not significantly affect perceived softness for all conditions, indicating that both compliance and adhesion had the same effect on participants' ratings depending on whether the task of pressing or sliding was being employed.

These experiments found that perception of softness appears to depend on the compliance of the materials. However, Young's modulus is a valid way to represent softness to people through the Leeds's tactile display, because the design structure depends on previous work by (Kimura and Yamamoto, 2012). So, a tactile display was built to test how well people can make a comparison between different simulated softnesses (as explained in Chapter 5).

In this experiment, we examined the effect of interaction between compliance and adhesion on perception of softness. From the result, there is no significant effect interaction between compliance and adhesion on perception of softness. The perception of softness is correlated with the compliance of the material and thermal conductivity in the pressing condition. The findings from this experiment show that softness feeling depends on compliance, which is used to present softness through the tactile display.

Also, the findings show the softness can be perceived through the pressing condition.

Chapter 5
Evaluation of Softness Feeling Through Tactile Display

5.1 Introduction

Softness feelings can be displayed by controlling the contact area, or contact width and pressure distribution between the finger and the surface being touched. The reason for that is because realistic surfaces are not plain and uniform (Bicchi et al., 2000); (Fujita and Ohmori, 2000); (Yokota et al., 2007); (Scilingo et al., 2010) and (Kimura and Yamamoto, 2012). The feeling of softness or hardness depends on the size of the contact area during touching. To produce a feeling of softness from a soft object, the contact area is larger than the one used to sense a feeling of hardness. The perception of softness seems to be affected by the variation of the size of the contact area (Tsuchimi et al., 2012).

As explained in Chapter 2, sensations of softness can be reproduced when the contact area is dynamically controlled, as in the case of touching by human fingertips (Fujita and Ohmori, 2000). This idea of controlling the contact area for sensing softness was proposed in early research carried out by Fujita and Ohmori, (2000) which continued the research done by Kimura and Yamamoto (2012) with control pressure distribution over the contact area. Research by Bichchi et al. (2000) and Porquis et al. (2011) pointed out that pressure distribution and contact area varies from soft surfaces (more compliant compared to the fingertip) to the hard surfaces (less compliant compared to the fingertip). When pressing the soft surfaces compared with hard surfaces, in soft surfaces, the pressure distribution was non-uniform. The surface adapted to the finger’s shape. The concept of contact area spreading and pressure distribution was considered to be a important factor in softness sensation.

The aim of this study was to evaluate the tactile display by determining whether people can distinguish simulated softnesses as they would distinguish the softness of real materials. As discussed in Section 1.1, a tactile display would be important for helping surgeons to discriminate between healthy and unhealthy tissues during laparoscopic surgery. The tactile display is dependent on controlling the contact area to present different softnesses to participants. Therefore, the tactile display was constructed and tested to determine whether it could present the softness feeling to people. A realised system would have a tactile sensor and tactile display as shown in Figure 1.1. The tactile sensor measures the compliance of tissue by contacting with tissues, and a tactile display would provide tactile data to surgeons. In this chapter, the focus is on testing a tactile display designed to present a realistic feeling of softness.

To determine the requirements of a tactile display for laparoscopic surgery, a tactile display has been built to display softness through control of contact area by five students at the University of Leeds in their fourth year of study of an undergraduate programme in the School of Mechanical Engineering. Two separate sessions were conducted to build a psychometric function for the display and evaluate how well humans perceive softness through the tactile display. Three different experiments were conducted during these two sessions to achieve the aim of this chapter. These experiments were done to examine the tactile display for laparoscopic surgery. The aim of the first experiment was to determine how well people distinguish between the softness of real materials compared to a simulated reference softness. The aim of the second experiment was to determine how well participants could distinguish between a range of simulated softnesses and a simulated reference softness. And the aim of the third experiment was to determine how well participants could distinguish between a range of simulated softnesses and the softness of a real, reference material. The first and the third experiments were done in the same session and used the same participants, same procedure and same design.

The ability of people to distinguish between the softness stimuli is displayed as a psychometric function. The psychometric function is central to the theory and practice of psychophysics. In our experiments, the psychometric function could estimate the ability of people discriminate between different displayed softness. The reason for using the psychometric function is that it can provide information about the reliability of psychophysical threshold estimates (Zchaluk and Foster, 2009, Guilford, 1954, Wichmann and Hill, 2001a, Wichmann and Hill, 2001b, Gescheider, 1997, Kingdom and Prins, 2010). The following sections outline the methodology, results and discussion of the three experiments.

5.2 Methods

The experiments were conducted in two separate sessions. In the first session, participants compared the softness of a test real material with a simulated reference softness displayed through the device. In the first session, they also compared different test simulated, displayed softnesses with the softness of a real, reference material. In the second session, participants were asked to compare a range of different test simulated, displayed softnesses with a test real stimulus reference. Participants were asked to compare 44 pairs of displayed softness in each session and indicate which was softer. The two-alternative forced choice (2AFC) procedure was used for each session, as explained in Appendix C.1. MATLAB was used to draw the psychometric function for all sessions.

5.3 Participants

The 24 participants in the experiment were compensated for their participation. They were undergraduate students, postgraduate students and staff at the University of Leeds. There were 12 participants in the first session, which consisted of six males and six females ranging in age from 20 to 39 years. Almost all of the participants in this session were right-handed according to the results of a handedness questionnaire (Briggs and Nebes, 1975), except two who were left handed. There were 12 participants in the second session, which consisted of six males and six females ranging in age from 20 to 39. They completed the handedness inventory questionnaire (Briggs and Nebes, 1975) and all of them were right-handed.

None of the subjects reported any neurological or physical injury that affected sensitivity of the index fingers of both hands.

These experiments were approved by the MEEC Faculty Research Ethics Committee at University of Leeds (MEEC 12-031). Each subject gave informed consent.

In order to have only tactile cues, the participants could not see the device and real materials so as to remove any influence from the shape surface differences between the stimuli. Pink noise was presented through headphones to the participants to prevent noise cues from the tactile display.

All participants in all three experiments performed each experiment one at a time. All participants were naïve with respect to the study's predictions. None of them had any experience with the softness display.

5.4 Equipment

The design of the tactile display was based on that presented by (Kimura and Yamamoto, 2012). The device was constructed (Figure 5.1) from flexible sheet (polyimide film) providing contact pressure to a user's fingertip. The sheet is pressed against a force sensor mounted on the aluminium part of the base frame. A thick base is made from aluminium in order to prevent the device from transferring vibrations from the ground. A voice coil motor VCM1 (AVM40-20) was used for lifting up the sheet to control the contact area. Two other voice coil motors of smaller capabilities VCM2, 3 (AVM20-10) are placed on the sides of the top frame. They are connected to the polyimide sheet which is placed on the top of the frame. These two motors adjust the tension of the film to control the pressure distribution. The height of the top frame alters the contact area. To reduce the friction forces between the film and the top frame, the edges of the top frame are curved and the grains of the ABS material were used to reduce the friction force between the film and the frame. A laser displacement sensor is used to measure the height of the top frame. The Hall Effect sensors measure the tension of the film (Figure 5.2).

In contrast to the original Japanese design of the display, the Leeds device was built to display both softness and wetness. The goal of these developments was to provide a tactile display to aid laparoscopic surgery.

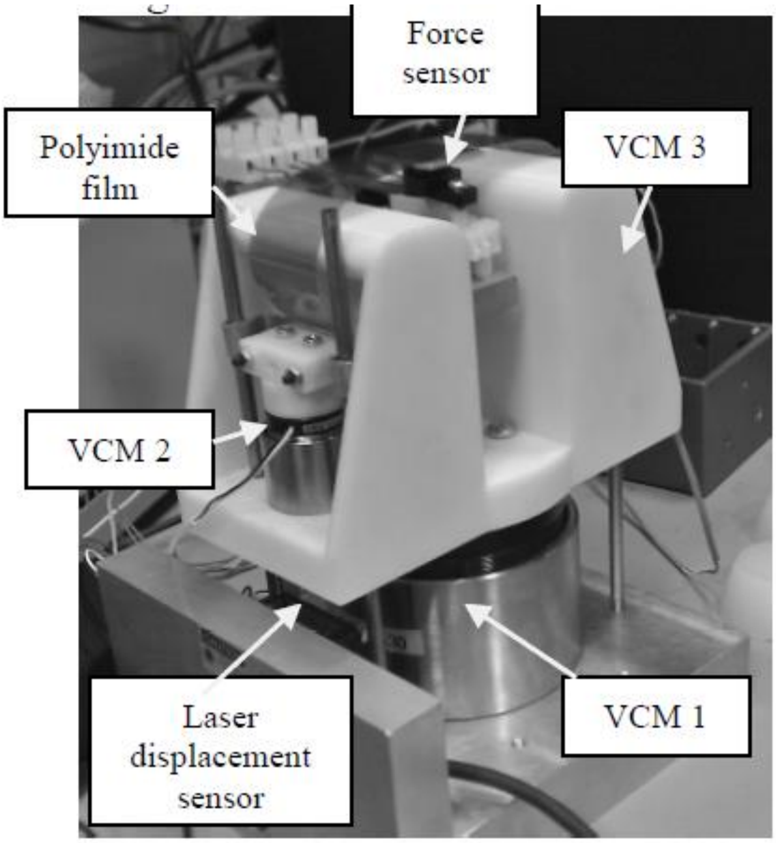


Figure 5.1: Leeds' softness display

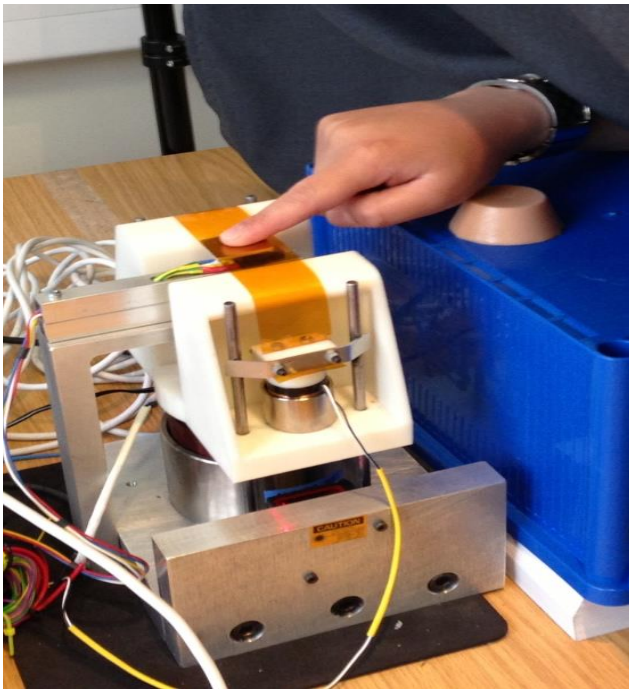


Figure 5.2: Softness display during touching

5.5 Setup of the device

Before the experiment started, the device was set up to display different feelings of softness. The instructions for display are explained in Appendix C.2. The participants were asked to press the device and feel the softness and compare it with another displayed softness or with a real material dependent on the experiment.

5.6 Psychometric function

The relationship between the level of stimuli and a particular response of participants (or a participant’s ability to detect contrast or probability of success on a certain number of trials at stimulus level) is described by a psychometric function. This function can be described by a specific parametric model and parameters. Figure 5.3 shows an example of a psychometric function. It can be described as predictions of performance at other stimuli levels. The psychometric function fits to some functions such as the logistic and Weibull functions. Numerous researchers (Grassi and Soranzo, 2009, Ulrich and Miller, 2004, Zchaluk and Foster, 2009) have proposed psychometric functions dependent on reference stimuli ≤ or ≥ test stimuli. This means that the test stimulus is changed from trial to trial, sometimes greater than, less than and equal to the reference stimulus. The stimuli are presented in a random sequence paired several times (Gescheider, 1985).

The two-alternative forced choice (2AFC) procedure was conducted for the experiment. This method is a common methodology for estimating the properties of psychometric functions and their thresholds (Ulrich and Miller, 2004). Two stimuli are presented for participants in each trial (Linschoten et al., 2001, Klein, 2001, Kingdom and Prins, 2010). Previous research examined and found that the 2AFC procedure minimizes the response biases and maximized the performance level (Gescheider et al., 2005, Ulrich and Miller, 2004). In this procedure, the correct responses usually range from 50% to 100% and the threshold is at 75% of the correct response. In my research, the range is between 0% to 100% of proportion of rating the stimulus as softer. Then the threshold is a value at 50% of proportion of rating stimulus as softer (Figure 5.3).

In this experiment, the threshold and parameters were estimated using Matlab. The threshold value was 50% rating the stimulus as softer. A more detailed explanation is in Section 5.7.3 to Section 5.10.

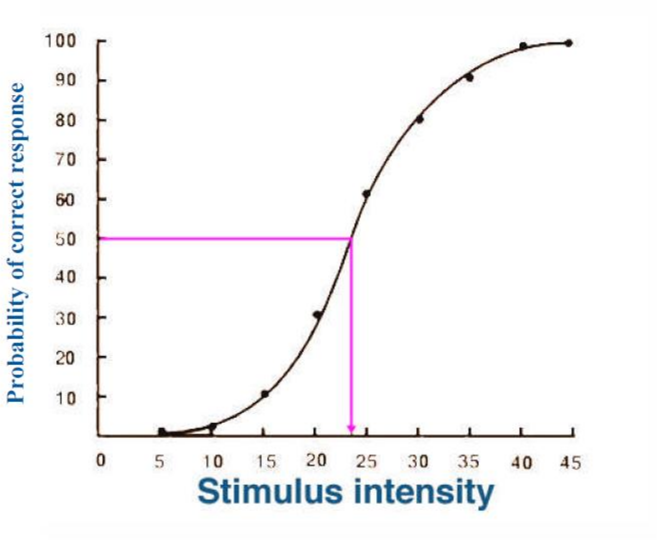


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Figure 5.3: Psychometric function model

5.7 Comparison of different real material stimuli with displayed softness as reference

The aim of the first experiment was to evaluate the tactile display by determining how well people distinguish between the softness of real materials compared to a simulated, displayed softness as the reference.

5.7.1 Design

The method of 2AFC was used. Participants were asked to indicate whether the real material or the simulated, display softness was softer.

Table 5.1 shows the Young's modulus for each stimulus which was compared in a random sequence with the reference sample. The reference sample was located in the centre of the range of Young's modulus values of the stimuli. The reference Young's modulus was 1.95GPa of simulated softness.

The stimuli were eleven real samples made from silicone as explained in Section 4.4 and Appendix B.1. The stimuli were made using the same procedures as the stimuli in Section 4.4 and Appendix B.1 except that the final surface layer, which previously varied the stickiness, was not applied. Figure 5.4 shows the stimuli. The difference between the stimuli was their Young’s modulus. Each stimulus was circular with a diameter of 40mm and a thickness of 10mm. The Young’s modulus of each stimulus was estimated from force displacement data obtained from a TETRA Modular Universal Surface Tester (Compass Instruments). The force applied was constant at 500mN for all samples by measuring the displacement of indenter on the surface tester, ΔL, Young’s modulus can be calculated using Equation 5.1.

$$E \equiv \frac{\text{tensile stress}}{\text{extensional strain}} = \frac{\sigma}{\varepsilon} = \frac{F/A_0}{\Delta L/L_0} = \frac{FL_0}{A_0 \Delta L} \tag{5.1}$$

where

E is the Young's modulus (modulus of elasticity)

F is the force exerted on an object under tension;

A0 is the original cross-sectional area through which the force is applied;

ΔL is the amount by which the length of the object changes;

L0 is the original length of the object.

Figure 5.4 Stimuli

For each participant, the real stimulus was presented 10 times resulting in a total of 110 trials. The order of the reference and test stimuli was randomized across trials. The order of trials was selected for each participant according to true random number service (True random number service, 2000) The displayed softness reference was presented first and test stimulus second on half the trials, and the order reversed on the other half of the trials to control the effect of time errors. Time errors were caused by presenting stimuli at different times.

Table 5.1 Young's modulus of real stimuli for both sessions

Sample Number	**Young's Modulus (N/m^2)**
1	2.35×10^9
2	2.25×10^9
3	2.06×10^9
4	2.01×10^9
5	2×10^9
6	1.95×10^9
7	1.78×10^9
8	1.74×10^9
9	1.68×10^9
10	1.51×10^9
11	1.41×10^9

5.7.2 Procedure

An instruction sheet was presented to each participant which explained how the experiment should be performed and to ensure participants understood what they should do. Participants took part in this study individually, so they did not influence each other in their responses. 110 pairs of stimuli were used during the experiment for each participant. The order of the trials was a random sequence using the experimental design described in Section 5.7.1. Each of the experimental trials was presented ten times (110 trials in total for each participant). The order of these trials was generated by Excel. All participants were provided with a simulated, displayed reference that had a middle value for softness during their experiments compared to the real materials they were touching (1.95GPa).

A pilot experiment was conducted to ensure that the instructions were understandable and that the displayed softnesses were chosen appropriately. This pilot experiment was conducted by the researcher and one of her supervisors.

Before starting the experiment, participants had to understand the concept involved in the experiment, so an experimenter prepared a short training session for participants. Participants were asked to evaluate the real stimuli and displayed softness through the touch display. Also, each participant wiped his or her fingertip with hand hygiene wipes to clean off the sebum and dust.

All participants completed the session using the index finger of their dominant hand. Their fingers were placed at the centre of the film on the device or in the middle of the real stimulus. They were allowed to press the film or real stimulus without sliding the finger over the surface to make a single continued contact with displayed softness or real stimulus.

To avoid the participants from seeing the device or real stimuli, a curtain was stretched across the breadth of the table. Each participant was presented with the real stimulus and reference displayed softness without seeing them. The device and real stimuli were placed behind the curtain and participants touched first the real stimulus and then the second displayed softness reference, or touched the displayed softness reference and then real stimulus. The participant was immediately asked to state which was softer. Each participant could go back and forth between the test and reference stimuli as often as desired. There were time restrictions made on subjects during both sessions. This procedure was repeated until they had evaluated all of the pairs. They touched the first stimulus for 30 seconds and then 30 seconds for the second one and a rest between trials of 30 seconds if they did not ask for a break.

After certain trials, the participants were allowed to rest for different ranges of time depending on the participant. The time ranged between 0-7 minutes. Also participants were also allowed to rest at any point during the experiment if necessary. There was a 30 seconds pause between the presentations of each trial. The total experimental time per participant was between approximately 50 minutes to 81 minutes (mean = 70.6 minutes and standard deviation = 9.0).

5.7.3 Results

The boxplot (Figure 5.5) shows the raw data. The x-axis and y-axis represent the Young's modulus and proportion of correct responses respectively.

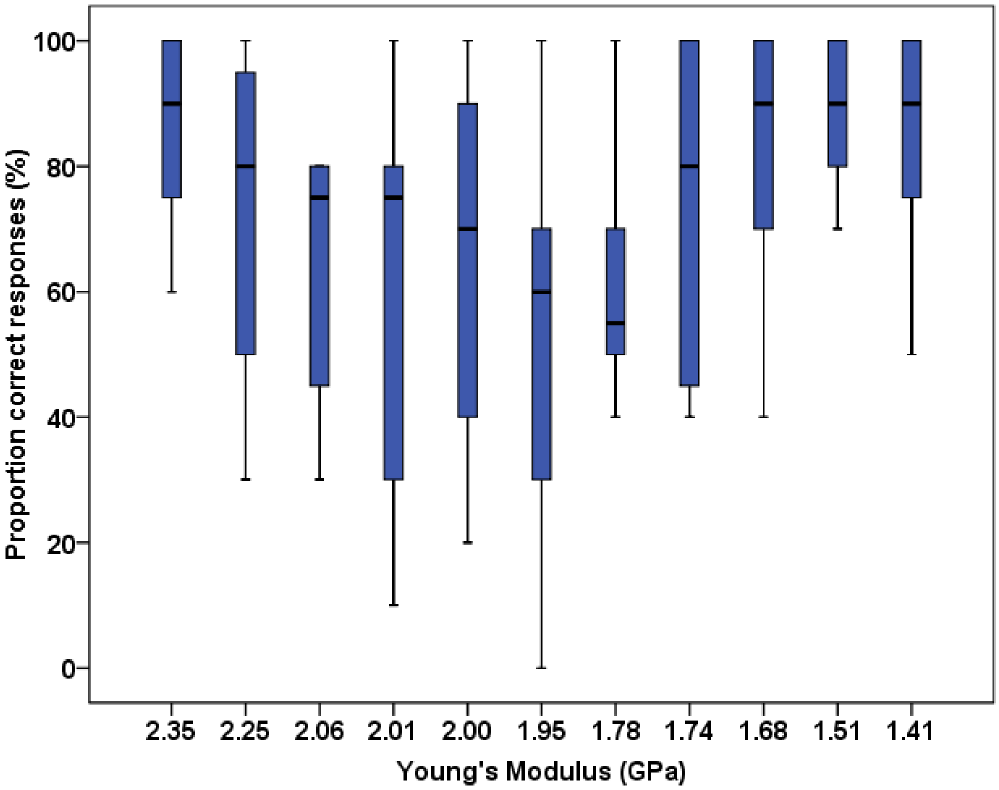

Figure 5.5: Boxplot for correct responses for a range of real materials compared to a simulated, displayed reference.

A psychometric function was drawn using MATLAB and the Palamedes toolbox (Prins and Kingdom, 2009) (Figure 5.6). This figure shows the curve for softness of real stimuli compared with simulated softness. The vertical axes represent the proportion rating the stimulus as softer for all participants. The S-shape fitting curve was derived by the cumulative normal distribution function as explained in Appendix C.1. The point of subjective equality (PSE) represents the value of 0.50 of correct responses. The percentage of subjects rating the stimulus as softer decreased as the Young's modulus increased. Softer objects were more easily identified. The lower the Young's modulus was, the better the participants' ability to discriminate.

The estimated parameters (α, β) depend on the function. The values of these parameters and for parameters (γ, λ) are shown in Table 5.2 for cumulative normal. The parameters are defined as α: a location parameter of psychometric function on the stimulus axis, β: a parameter that determines how steeply the psychometric function rises (parameter determines the slope or gradient of the curve), γ: the lower asymptote, λ: the upper asymptote (Guilford, 1954, Garcia-Perez and Alcala-Quintana, 2005, Kingdom and Prins, 2010, Wichmann and Hill, 2001a, Zchaluk and Foster, 2009). The results of other parameters of other functions are shown in Appendix C.3.

Table 5.2 Parameters values for the psychometric function of people's discrimination between real, soft materials and a simulated, displayed reference.

		Cumulative Normal
Free parameters	α	1.65
	β	-4.51
Fixed parameters	γ	0.00
	λ	0.00
LL		-897.23

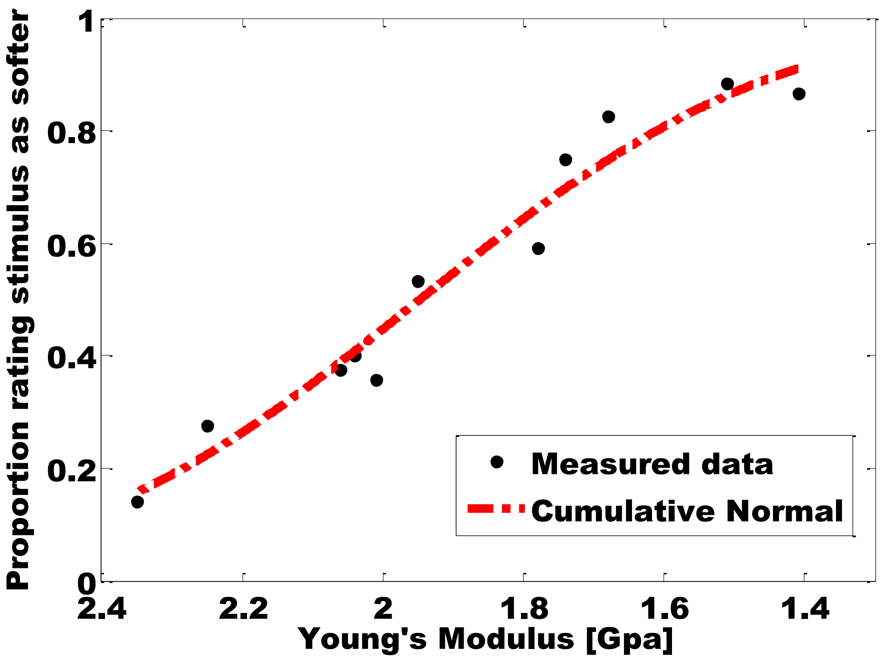

Figure 5.6: Psychometric function representing cumulative normal fits to the data for a range of real materials compared to a simulated, displayed reference.

After comparing between different functions, the cumulative normal function seems to be the best function to fit the data according to the likelihood, standard error and pDev. The threshold is defined as the lowest level of stimulus which participant can detect (Perez et al., 2010). In this case, the threshold was the value of Young's modulus at 0.50 of proportion rating stimulus a softer was (1.93 GPa). This value deviates from Young's modulus reference (1.95GPa). The results show that the curve was as expected and the threshold value is close to the reference value. It means that participants could discriminate between the stimuli.

5.8 Comparing different simulated, displayed softnesses with a simulated, displayed softness reference

The aim of the second experiment was to evaluate the tactile display determining how well participants could distinguish between ranges of simulated softnesses compared with simulated reference softness.

5.8.1 Design

In this session, the 2AFC method was used to find out whether participants could distinguish the softness of simulated softnesses displayed on the tactile display and a simulated, displayed reference. The two samples were presented in each trial and one chosen as the softer one. One was called the ‘reference’, and the other was called the ‘test’. The reference stimulus remained fixed, while the other stimulus was varied with a range of different stiffnesses. Each set was presented 10 times resulting in a total of 110 trials for each comparison.

5.8.2 Procedure

In this session, participants were asked to indicate which of two displayed softnesses was softer.

Before starting the experiment, each participant wiped his or her fingertip clean of sebum and dust which also helped them revive their fingers. All participants completed the session using the index finger of their dominant hand. Their fingers were placed at the centre of the film on the tactile display. They were allowed to press the film without sliding over the surface to make a single continued contact with each displayed softness.

Participants were presented with a series of displayed softnesses. These were intended to replicate the Young’s moduli of the real stimuli used in the experiment described in Section 5.7. Thus the Young’s modulus ranged between 1.41GPa to 2.35GPa (Table 5.1). Participants were presented with each displayed softness and a corresponding displayed, reference softness, and they were asked which one was the softer of the two. The device was placed centrally behind the curtain and participants reached beneath the curtain to touch the display. This procedure was repeated until all the pairs had been evaluated. In this session, displayed softness tests changed and were compared with a reference of displayed softness (1.95GPa) which remained the same. The participant was asked to state which was softer. Each participant could go back and forth between the test and reference stimulus as often as desired. This procedure was repeated until all the pairs had been evaluated.

After collecting the data, the correct percentages were calculated. There were time restrictions made on subjects during both sessions. They touched the first stimulus for 30 seconds and then 30 seconds for the second one and a rest between trials of 30 seconds if they did not ask for a break.

The participants were allowed to rest for different time intervals dependent on the participant. When a participant did take a rest period, the time ranged between 0 - 8 minutes. Participants were allowed to rest at any point during the experiment if necessary. All participants took a 30 second rest between trials. Participants could not see the stimuli at any point of the test or rest periods. The total experimental time per participant was between 39 minutes to 61 minutes (mean = 51 minutes and standard deviation = 6.8). The full study was performed within 18 days.

5.8.3 Results

All participants finished the experiment successfully. None of the participants reported any individual inquiries or any information; none of the participants had any impairment of their sense of touch. Figure 5.7 presents the boxplot which represents the proportion of correct responses in y-axis and Young’s modulus in x-axis. The psychometric function, with the proportion of softer responses plotted against Young’s modulus of the test stimulus is shown as Figure 5.8. This figure shows percentile curve for simulated softness. The vertical axes represent the proportion of rating stimulus as softer for all participants. The S-shape fitting curve was derived by cumulative normal distribution function as explained in Appendix C.1. The PSE represents the value of 0.50 of correct response. The percentage of subjects correctly responding increased as Young’s modulus of test stimuli decreased, meaning the softer objects were more easily identified. The greater the Young’s modulus is, the better the participants’ ability to discriminate.

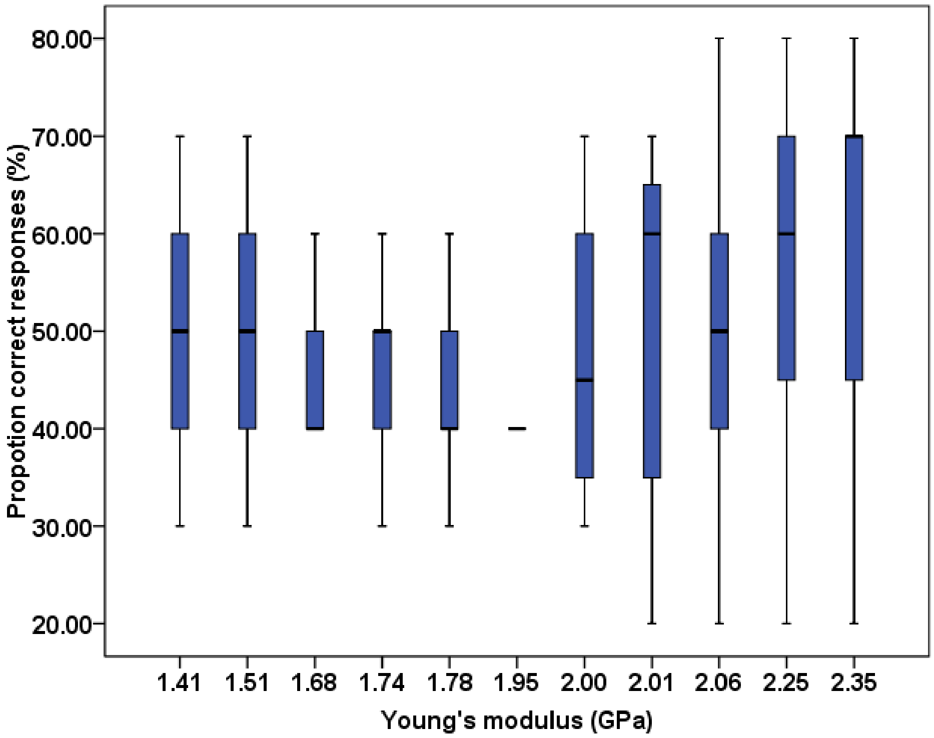

Figure 5.7 Boxplot for correct responses for simulated softness compared with a simulated reference.

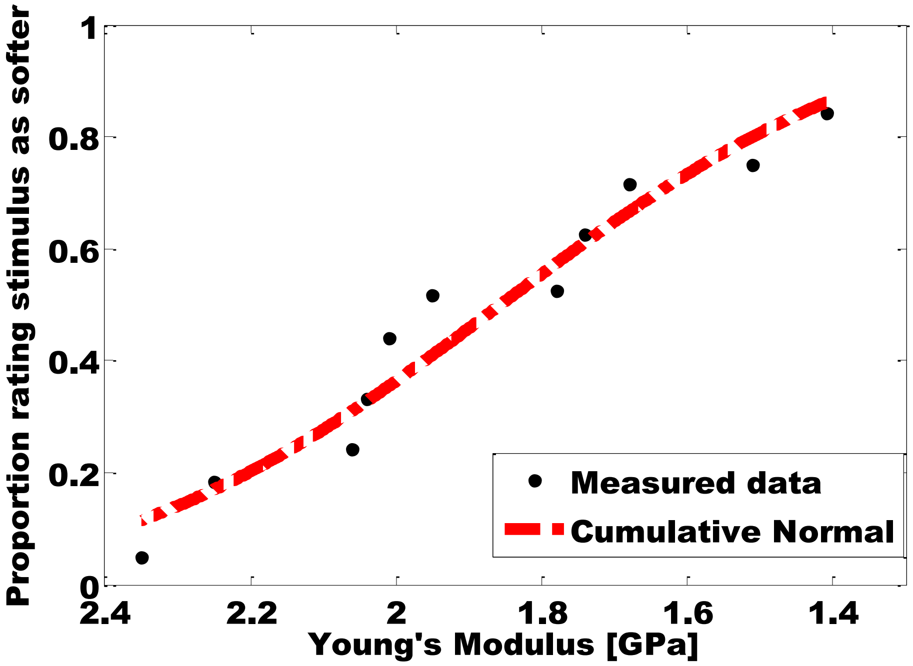

Figure 5.8: Psychometric function represents cumulative normal fits to the data for simulated softness compared with a simulated reference.

As explained in Appendix C.1.1, the estimated parameters (α, β) depend on the function. The values of these parameters and for parameters (γ, λ) are shown in Table 5.3. After comparing the different functions, the cumulative normal function seems to be the best function to fit the data. The comparison depends on three methods which were explained in Appendix C.1.1; choosing the best fit is when there is minimum standard error, maximum likelihood or maximum pDev occur compared with other values of other functions. The results of other parameters of other functions are shown in Appendix C.3.

Table 5.3 Parameter values for the psychometric function of people's discrimination between simulated, displayed softness

		Cumulative Normal
Free parameters	α	1.86
	β	-2.43
Fixed parameters	γ	0.00
	λ	0.00
Likelihood		-754.73

The threshold was estimated from this function. It was the value of Young's modulus at a value of 0.50 of proportion rating stimulus as softer. The value of the threshold was 1.86 GPa which differs from Young's modulus reference (1.95 GPa). The results show that the curve was as expected and the threshold value is close to the reference value. It means that participants could discriminate between the stimuli.

5.9 Comparison of different displayed softnesses with real stimuli as reference

The aim of this experiment was to evaluate the tactile display by determining how well participants could distinguish between a range of simulated softnesses and the softness of a real material.

5.9.1 Design

The design of this experiment is the same as the one in Section 5.7.1 because, as explained in Section 5.1, the first and third experiments were done in the same session by the same participants and using the same procedure. In this third experiment, however, the participants compared a range of different simulated, displayed softnesses with a real reference stimulus. The different displayed softnesses were the different Young's modulus programmed in LabView which was used to control the contact area and pressure distribution over the area of the fingertip. These were intended to replicate the Young's moduli of the real stimuli used in the experiment described in Section 5.7. Thus the Young's modulus ranged between 1.41GPa to 2.35GPa (Table 5.1).These were used to present softnesses to participants.

5.9.2 Procedure

The procedure of this experiment was the same as the one described in Section 5.7.2.

5.9.3 Results

Figure 5.9 presents the average number of correct responses for each displayed softness. A psychometric function was drawn using MATLAB and a cumulative normal function was fitted to the psychometric data. The result of fitting the function is shown in Figure 5.10. This figure shows the percentile curve for simulated softness compared with the real sample. The vertical axes represent the proportion rating the stimulus as softer than the reference for all participants. The S-shape fitting curve was derived by the cumulative normal distribution function as explained in Appendix C.1. The PSE represents the value of 0.50 of proportion of participants rating the reference stimulus as softer. The proportion decreased as the Young's modulus of the stimulus increased. Less soft objects were more easily identified.

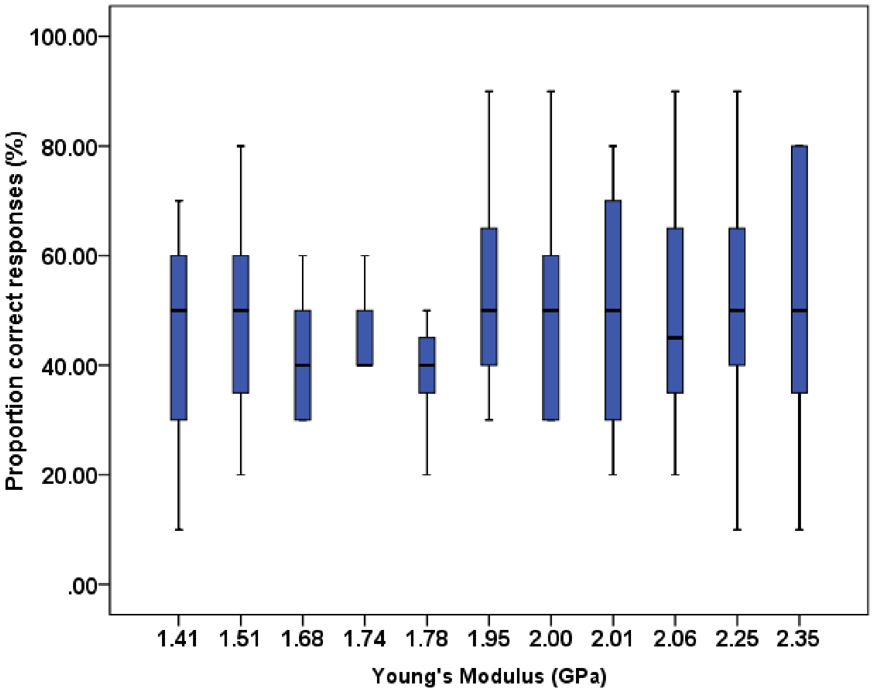

Figure 5.9 Boxplot for correct responses for different displayed softnesses with real stimuli as reference.

As explained in Appendix C.1.1, the estimated parameters (α, β) depend on the function. The values of these parameters and for parameters (γ, λ) are shown in Table 5.4.

The data fit cumulative normal after comparing with different functions because of maximum likelihood, minimum standard error and maximum pDev compared with other functions. This comparison is explained in Appendix C.3.

Table 5.4 Parameter values for the psychometric function for a range of simulated, displayed softness compared with a real reference.

		Cumulative Normal
Free parameters	Α	2.18
	Β	0.52
Fixed parameters	γ	0.00
	λ	0.00
LL		-897.23

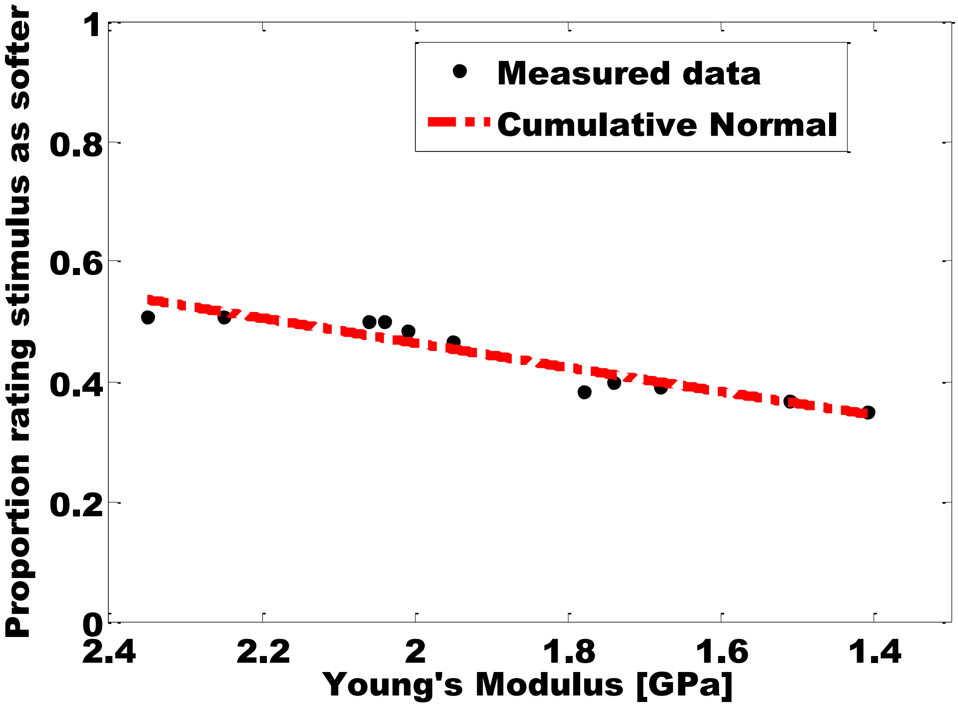

Figure 5.10: Psychometric function representing cumulative normal fits to the data for a range of simulated, displayed softness compared with a real reference.

The value of the Young's modulus at the threshold of 0.5 was 1.95GPa. This value is exactly the same as the value of the Young's modulus of the reference, but the psychometric function is not as expected. It is different from those in Figure 5.6 and Figure 5.8.

5.10 Discussion and Conclusions

The aim of these experiments was to evaluate the tactile display by finding out whether people can distinguish the simulated softness of tactile display in the same way as they distinguish the softness of real materials. Two sessions were conducted to achieve the aim of these experiments. In this section, the main findings are summarized and their implications discussed.

Bergmann Tiest and Kappers (2011) highlighted a value of point of subjective equality (PSE). At this point, the reference and test stimuli have the same value (in this case of Young’s Modulus) and participants should not be able to reliable differentiate them, leading to about 50% rating each as softer, since they will have to guess one way or the other (due to the 2AFC approach). They observe that in practice, this is not always the case, and highlight that there is a point of subjective equality (PSE) at which 50% percent of actually rate of each of the test and reference stimuli as softer. Suggesting they cannot reliably discriminate the difference in perceived softness, even though objectively, the Young’s moduli of test and reference stimuli are different.

In the first experiment, which determined the psychometric function for softness of a range of real test materials compared to a simulated, displayed reference, the threshold (Figure 5.6) at 50% of proportion rating stimulus as softer was 1.93GPa. This value is close to the reference (1.95 GPa). This means that the participants are able to distinguish between real materials when comparing them with a displayed softness.

In the second experiment determined the psychometric function for softness of a range of simulated test softnesses compared with a simulated reference (Figure 5.8). The threshold at 50% of proportion rating simulated test as softer was 1.86GPa. The values have a small deviation from the reference (1.95 GPa). This means that the participants are able to distinguish between simulated test softness when comparing with a displayed softness.

However, the threshold of the psychometric function for softness for a range of test simulated, displayed softness compared with a real reference (Figure 5.10) was totally different for other curves, the participants were not able to distinguish between reference and test stimuli. They made few correct answers; they might have had difficulties in feeling the difference between the stimuli.

The results shown in Figures 5.6 and 5.8; are similar, and the threshold seems to be much the same in both cases. It gives us evidence that the tactile display seems to display different softnesses. The results confirmed that the displayed softness can be controlled in these experiments.

However, the results shown in Figure 5.10; appeared to show that it is difficult for participants to distinguish displayed softness when compared with a real stimulus. This experiment did not confirm that the displayed softness could be controlled, because the proportions rating the stimulus as softer were so low for all values of Young's modulus. The proportions were between 40% to 58%. These results were surprising; participants had difficulties when they compared between simulated softness and real material. There could be many possible causes including that the aluminium plate at the bottom of the flexible sheet feels hard.

It is clear the deviation of PSE from the reference could be due to various reasons. One of them is that discrimination between stimulus and simulated softness might be difficult because Young's modulus might not be a good presentation of softness. Possibly it might be because of the presence of other factors such as stickiness, roughness and wetness.

Another reason may be that the learning time might not be enough for participants to feel the differences between displayed softnesses through the device. The time for training during the experiment was 10 minutes which was restricted for all participants. However, we can make it longer but it may affect the total time of each session and we wished to avoid fatigue bias.

The third reason might be the participants themselves; meaning that the participant could not easily distinguish all displayed softnesses correctly, especially for the same displayed softness. Moreover, the abilities of participants seem to be another factor that could have influenced the results. It means that participants rank a stimulus as softer than another one without true feeling. Sensitivity and variation of fingertip between participants could lead to this division and bias the results.

Another reason is likely to be the device itself; to be more exact, whether the tension derives from the aluminium support block or the flexible sheet. When participants press the sheet, their tension seems to be small or large dependent on the force they applied and it produces two regions of contact area. If the tension is small, the contact area is large and then they receive pressure from the support block, but if it is large they seem to receive pressure from the sheet. From other work done by (Kimura and Yamamoto, 2013, Kimura and Yamamoto, 2012), it appears that the participant can feel the softness through the device from large sheet tension and periodic sheet vibration. In our experiment, there were different vibrations between different trials for the same participant and between participants.

This appears to be a good explanation for having bias in the results. Moreover, the time between displaying softnesses might also affect participants' responses. When the time gap is large, the participants might have been confused in distinguishing between the displayed softnesses, and their responses were not clear and correct. However, if the time between displaying softness is small, the participants may be able to detect between the displayed softness.

Finally, the participants have different responses to softness perception. This contradiction occurs even when they compare between real stimuli (for example between two silicone samples). This is likely to be difficult to control between all participants.

Three methods were used to compare between the functions to choose the best fit as explained in Sections 5.7.3, 5.8.3 and 5.9.3. As explained from previous work, three functions have been successfully used to describe the data; the functions are Weibull; logistic and cumulative normal. The results showed in Figures 5.6, 5.8 and 5.10 that the function which was the best fit for the data for all sessions was the cumulative normal function. There are three methods which play a role in choosing the best function; the methods are Likelihood, standard error and pDev. The best function is the function which has maximum likelihood, minimum standard error and maximum pDev. Choosing an unacceptable function may affect the value of the threshold.

The present findings seems to be consistent with other research (Kimura and Yamamoto, 2013), which tested their improved tactile display. They modified their pervious device (Kimura and Yamamoto, 2012) by taking the size of rendered lumps in account. The reason for this is that lump sensations were felt from the softness display. The pressure of the real soft object was expected to be not uniformly distributed. They reported that the lump sensations seem to be produced by controlling the tension of flexible sheet. The distribution will be uniform in cases when the tension is large and the sheet lifts up from the support block. Their modification rendered lumps by applying a large tension but not exceeding the tension which lifts up fingertip. They examined this theory using psychophysical experiments and psychometric functions. The experiment compared the control softness display based on this model with real soft samples that contain different hard lumps. From their results, they found that the size of lumps seems to be controlled. Therefore, they evaluated that participants could feel lump sensations and softness through tactile display.

5.10.1 Summary

A tactile display has been constructed at the University of Leeds modelled on ideas from researchers at the University of Tokyo, Japan (Kimura and Yamamoto, 2012). Psychophysical experiments were conducted to evaluate the tactile display and evaluate how well humans could distinguish between different displayed and real softnesses.

Twenty four participants performed two sessions, 12 participants for each experiment. They were presented with and compared two displayed softnesses in each trial and real materials, and displayed softness through the tactile display for the first and second sessions respectively. The two alternative forced choice approach was used to present real and display softness for both sessions. The results of the psychometric functions showed that the best fitting for data was cumulative normal. The best fit was found by using three methods to compare different functions, the methods were the standard error; the likelihood and deviance (Dev) and pDev value. The thresholds for all sessions differed from the value when the correct response was 75%.

The results confirmed that tactile display could successfully produce softness sensations using the contact area and pressure distribution over the area. However, the results from last experiment, which compared a range of test simulated softnesses with a real reference (Section 5.9.3), did not confirm that tactile display produces the softness sensation.

Surgeons manipulate the tissues and compare between tissues but they do not compare between tissue and sample tissue. I have tried to identify the requirements of tactile display. I suggest that tactile display could be used in cases of comparing between tissues inside the body, but not between the tissue and sample. This is because of the invalidity in the procedure of comparing between simulated softness and a real reference. I also suggest that softness can be presented purely as a compliance, without needing to take into account other material properties according to my previous experiments in Chapters 3 and 4.

Chapter 6 Discussion and Conclusion

6.1 General Discussion

In order to present the information about texture, shape and compliance and to present tactile feedback in laparoscopic surgery, a tactile display could be used. It seems to be difficult to design an ideal tactile display because of the many unanswered questions about human perception, and because the requirements of tactile displays have not been identified. The design of tactile displays needs to take into account how we can control the contact area between a surface and a finger to simulate softness. Tactile displays have drawbacks, the principal ones of which are size and weight (Ottermo, 2008).

This Thesis presents regression models for how the perception of softness relates to material properties. The relationships between the perception of softness and the material properties of roughness, compliance, adhesion, and thermal conductivity have been characterized in the form of regression models. These material properties were considered in this study because other researchers have reported that these materials are the perceptual bases for softness (Hollins et al (2000)) (Yamauchi et al., 2010).

Two different psychophysical experiments were conducted to determine the relationships between the perception of softness and material properties. The first experiment used a 3×3 factorial design, with stimuli made with three levels of roughness and three levels of compliance. The results of the first experiments found that the interactions between perception of softness and material properties was not significant. In other words, the perception of softness was not affected by interaction between roughness and compliance. The second experiment used a 3×3 factorial design, with stimuli made with three levels of adhesion and three levels of compliance. This experiment demonstrated that the perception of softness was not affected by the interaction between adhesion and compliance through the conditions of pressing and sliding.

It is worth considering possible reasons why an interaction between roughness and compliance, and adhesion and compliance, was not observed, if such interactions actually exist, despite this research having not observed them: there seems to be frictional forces between the finger tips and stimulus; deformation of fingers during the pressing condition might depend on contact force and how stiff material is compared to finger, so the softness of the stimuli compared to the finger could have affected results.

A possible explanation for the results of first two experiments, which identified the effects of roughness and adhesion on people's perception of softness, might be because of the magnitude of the friction forces, which is an important aspect in the perception of softness. These forces cause the deformation of the finger and the material of stimuli. Moreover, the perception of softness seems to be related to the differences between stiffness of material compared to stiffness of finger. Also, the magnitude of the forces applied in pressing appear to affect the perceived softness ((Friedman et al., 2008)). However, perceived stickiness is related to the contact area between a finger and surface of the stimulus and vibratory cues (Shao et al., 2009, Bensmaïa and Hollins, 2005).

A strong relationship was found between the perception of softness and the compliance of stimuli for the pressing condition, as had been predicted in the experiment looking at the effect of roughness on perception of softness. It was surprising no relationships between perceived softness and compliance was indicated for the sliding condition. This finding might have been affected by other factors such as the way that stimulus was touched. During the sliding condition, the perceived softness was related to the friction coefficient. It seems to be inconsistent with previous researches which suggest that the perceived softness is related to compliance and thermal conductivity. In the second experiment looking at the effects of adhesion on perception of softness, very strong relationships between the perceived softness, and compliance and thermal conductivity was found for both the pressing and sliding conditions. The second experiment also identified a weaker correlation between perception of softness and friction coefficient. This seems to be consistent with other researches. These relationships might depend on the conditions used or the material of the stimuli.

It is clear from analysis that stickiness perception can be related to compliance, friction coefficient and adhesion for the sliding condition. It differs from the models proposed by previous researches which found that the perceived stickiness relates to compliance and friction coefficient or with only friction. However, there is no relationship between the perceived stickiness and material properties during pressing condition.

Two experiments were conducted to evaluate how well the tactile display can present softness feelings compared to those in materials. In these experiments, the device simulated various compliances. It was found that by changing the tension and the contact area between the fingertip and the flexible sheet, the softness perceived by the participants can also be changed. In other words, there is a relationship between softness perception and the contact area and pressure distribution over the area as addressed in Chapter 5. As concluded from previous researches, three functions appear to fit data; Weibull, cumulative normal and logistic. In our work, it is found that cumulative normal seems to be the best function fitting for all the data discrimination.

In the experiments with the tactile display, the value of the point of objective equality (POE) (Bergmann Tiest and Kappers, 2011) and point of subjective equality (PSE) is determined to be a value at 50% of proportion rating test stimulus as softer. From the first experiment, in which participants evaluated real stimuli compared with a displayed reference, this value seems to be 1.93GPa at 50% which deviates from the reference (1.95 GPa). In addition, the value of PSE for the second experiment, comparing displayed samples with displayed softness as reference, was 1.86GPa. In the third experiment with the tactile display, in which participants compared simulated test softnesses with a real reference material, the participants' responses were different to those found for softness perception in the first two experiments. While the POE was 1.95 GPa, all averaged judgements were close to 50% rating the test stimulus as softer, suggesting that participants were guessing, and were unable to distinguish between the stimuli.

There are some reasons the PSE might deviate from the reference. The reasons were learning time, the device itself and the time gap between the display of each softness. The learning time or training time was 10 minutes for each participant in this study. It could not be longer because it would affect the total time of experiment. This time seems to be insufficient for all participants to become familiar with feeling softness through the device.

The PSE might deviate from the reference because of the presence of the aluminium support block under the flexible sheet of the display itself. The tension of the sheet controls softness sensations and affects participants’ abilities to give the correct response. If the tension is large enough, the sheet lifts the fingertip off the support block. However, if the tension is low, the sheet, and hence the finger, is in contact with the block. Therefore, participants feel the block and this could affect their responses. We noticed that participants had different responses in each trial because they applied different forces which changed the tension. This reason is in agreement with Kimura and Yamamoto (2012).

The time gap between displays of softness may have affected participants’ responses. If this gap is big, the participants could not easily compare between softnesses. In this experiment, the time between two softness displays was five seconds.

The results of the first two the experiments with the tactile display, comparing real test stimuli with a simulated reference, and comparing simulated test stimuli with a simulated reference, were approximately similar and the threshold seems to be similar. These results confirm that the tactile display seems to display different softnesses. While the results of comparing compliance from the tactile display with real material as a reference appear to show that it is difficult for participants to compare between them. This result suggests that the tactile display did not confirm that the displayed softness could be controlled, because the proportions rating stimulus as softer were so similar for all values of Young’s modulus. These results were surprising; the force used to press on the tactile display was an important contributor to these results. Another possible cause is that the aluminium plate under the flexible sheet might affect the softness feeling.

6.2 Conclusion

This research conducted experiments to explore whether the perception of softness is affected by interactions between compliance and surface roughness, and interactions between compliance and adhesion. The research then considered how to emulate these findings through a tactile display.

The research questions can be answered through the findings of the experiments. The following conclusions were derived.

1. **Investigation of the effect of roughness on the perception of softness.** As a result from our experiments, it was found that the interaction between compliance and surface roughness do not significantly affect perceived softness for sliding or pressing conditions, indicating that both compliance and surface roughness had the same effects on participants’ ratings.
2. **Investigation of the effect of stickiness on the perception of softness.** Interaction between compliance and adhesion does not significantly influence perceived softness for sliding and pressing conditions, indicating that both compliance and adhesion had the same effects on participants’ ratings.
3. **Determination of whether there are interactions between the physical properties which effect the perception of softness, and if there are any correlations between perceived softness and material properties.** Results from the first experiment, which used polyurethane stimuli to determine the effects of roughness and compliance on the perception of softness, confirm that perceived softness was related to compliance alone in the pressing condition, and friction coefficient alone in

the sliding condition. However, in the second experiment, which used silicone stimuli to determine the effects of adhesion and compliance on the perception of softness, the perception of softness correlated to compliance, thermal conductivity and friction coefficients for both the pressing and sliding conditions. An explanation for this result could be because it was not possible to control the physical properties of the silicone stimuli independently; both thermal conductivity and friction coefficient correlated with the materials' compliance. For the polyurethane stimuli, it was possible to control the physical properties independently. The difference in results could also be because the silicone stimuli were similar in compliance to the human finger, and the polyurethane stimuli were somewhat harder, and that perception of softness does indeed also depend on thermal and friction properties.

4. **Investigation of whether softness can be represented through a tactile display and whether people can distinguish between different compliances through the display as they can real materials.** The results confirmed that tactile display could successfully produce softness sensations when participants compared simulated materials with a simulated reference, and real materials with a simulated reference. However, participants were unable to distinguish between a range of simulated softnesses and a real, reference material.

This work is an essential step towards understanding interactions between compliance and other material properties which affect perception of softness and how this understanding can be applied to the medical field, especially laparoscopic surgery.

6.3 Requirement for tactile display

Requirements can be identified for tactile displays that allow humans to obtain information about compliance when pressing their fingers on the surface of the display.

From previous researches, an effective tactile display for softness is likely to be based on the principles of controlling contact area and pressure distribution over the fingertip. This research used a display based on flexible tape in tension, but other means of controlling contact area and pressure have been demonstrated by others. Further research is required to determine which schemes will make the most effective tactile displays.

Tactile displays require information about material properties which influence the perception of softness, to provide a realistic sensation when pressing the finger into the display. To characterize which material properties influence the perception of softness, the experiments (explained on Chapters 3 and 4) were performed to identify which material properties affect the perception of softness. Although there might be correlations between the perception of softness and friction and thermal properties, these do not affect people’s abilities to rate soft materials, so friction and thermal properties do not necessarily need to be displayed. Consequently, the most important property to be displayed is compliance.

Although the compliance is the principal property that needs to be controlled, there are different ways of measuring it; for example, Young’s modulus, mechanical stiffness, or contact area spread rate. In this research, because of the technical model underpinning the tactile display, Young’s modulus was used. However, further research is required to identify which measure, or combination of measures, would make the most effective tactile displays for softness.

6.4 Contribution

This research presented a number of contributions to the field of application of perception of softness and softness tactile display. These are as follows:

1. Characterized the interactions between compliance, roughness, and adhesion that, in the context of my experiments, affect the perception of softness.
2. Confirmed previous work that, in the context of my experiments, shows that compliance, friction and thermal conductivity can affect

perception of softness when the finger is sliding and pressing respectively.

3. Developed and demonstrated an approach to assessing the performance of a tactile display for softness.

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Appendix A
Compliance and Roughness Experiment

A.1 Handedness inventory

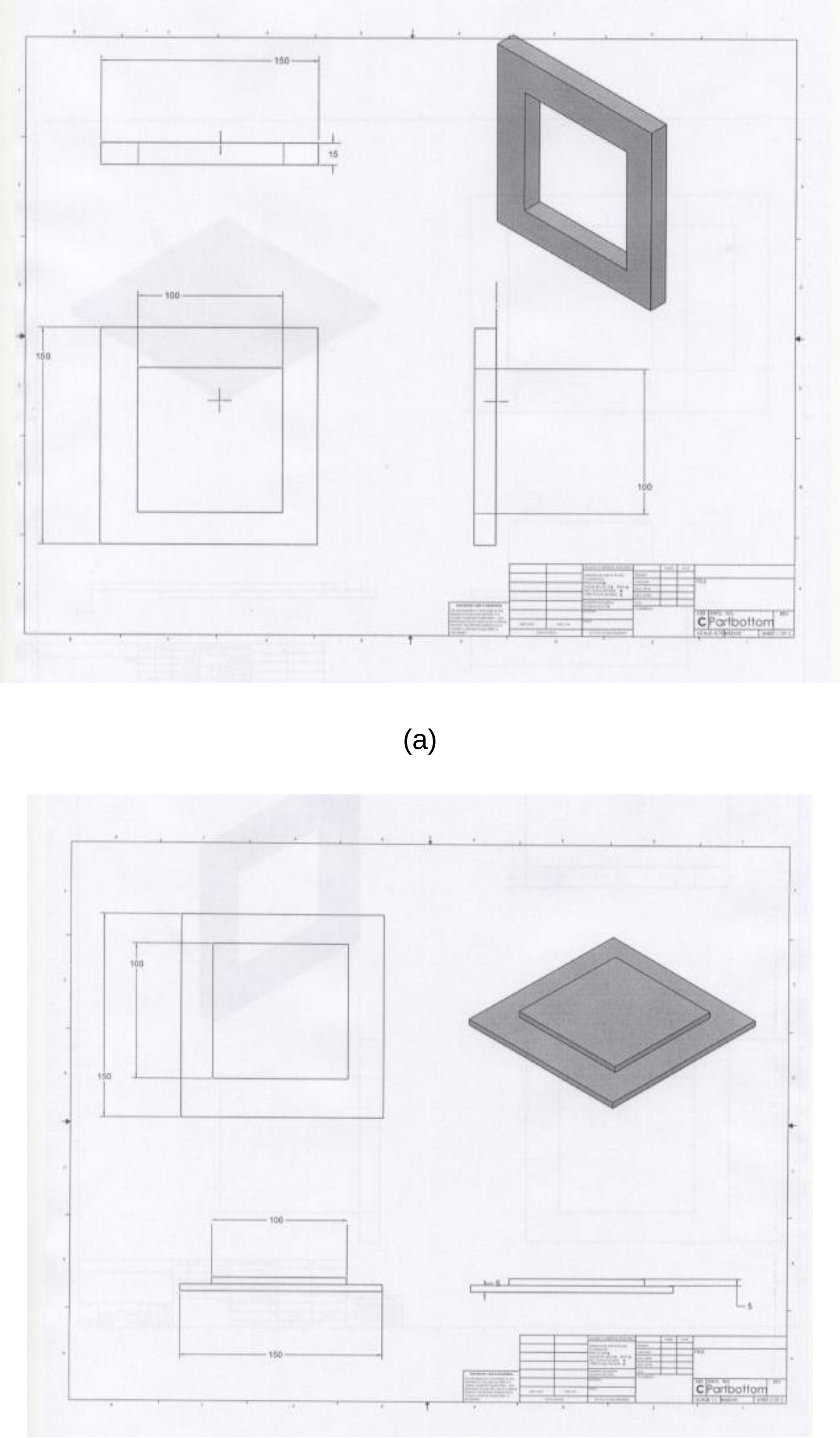
Please read each of the questions below. Decide which hand you use for each activity and then mark the answer that describes you the best. If you are unsure of any answer, try to act it out to see which hand you are using. Please indicate hand preference.......

	Always Left	Usually Left	No Preference	Usually Right	Always Right
To write a letter legibly					
To throw a ball to hit a target.					
To play a game requiring the use of a racquet.					
At top of broom to sweep dust from floor.					
At the top of a shovel to move sand.					
To hold a match when striking it.					
To hold scissors to cut paper.					
To hold thread to guide through eye of needle.					
To deal playing cards.					
To hammer a nail into wood.					
To hold a toothbrush while cleaning teeth.					
To unscrew the lid of a jar.					

Thank you for completing the handedness questionnaire.

A.2 Making the die

In order to make these stimuli, two steps were followed: making the die and manufacturing the stimuli. Engineering drawings were drawn using Microsoft Solid Works 2009 Sp4.0, for the stimuli the same shape of design was used (100mm ×100mm area and thickness 1 mm). The design consists of two parts, the shape die (Figure A.1a) and the top die (Figure A.1b). After design, the engineering drawings were submitted to the mechanical workshop who then manufactured the die (Figure A.2) which was made of aluminium. Two textured aluminium sheets with different surface roughness were ordered from Gooding Aluminium Limited (UK) to have different texture to the surface on top of stimuli. Two textured aluminium sheets were vertex: mill finish textured sheet (GA VXM21) and flat plain aluminium sheet: anodised finish sheet (GA B1412). Another sheet was made by the workshop in Mechanical Engineering using the shot blast method. Figure A.3 shows the textured surface plates.



(a)

(b)

Figure A.1: Engineering drawings (a) the shape die, (b) the top die

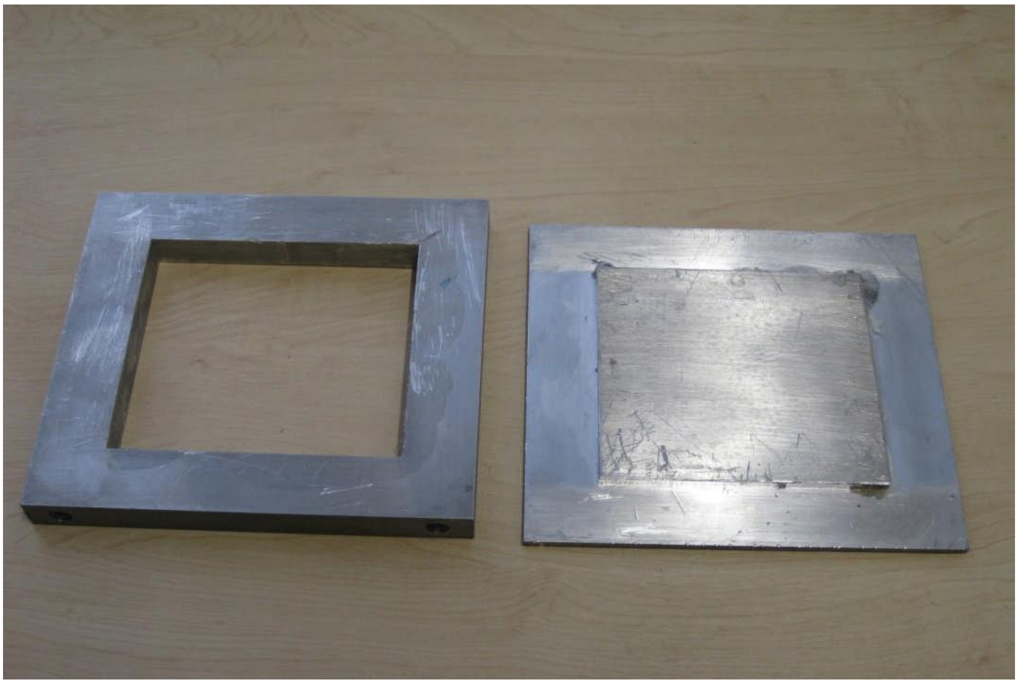
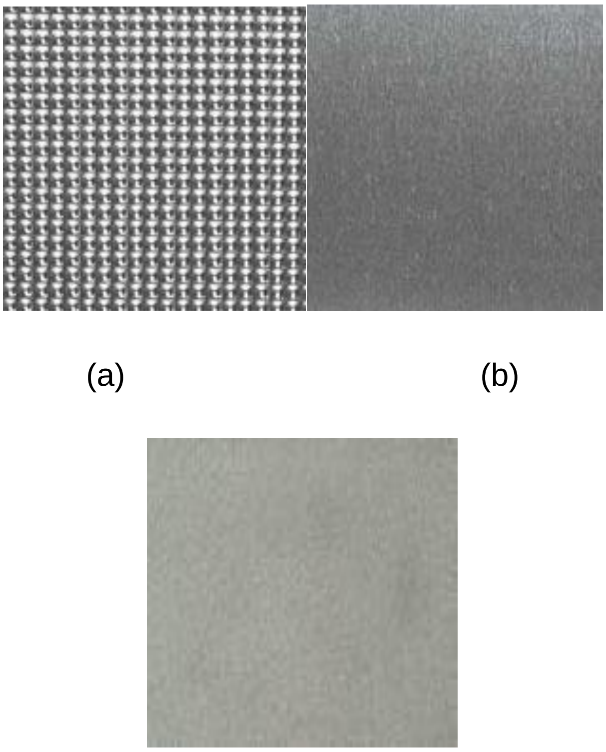


Figure A.2: The die made of aluminium

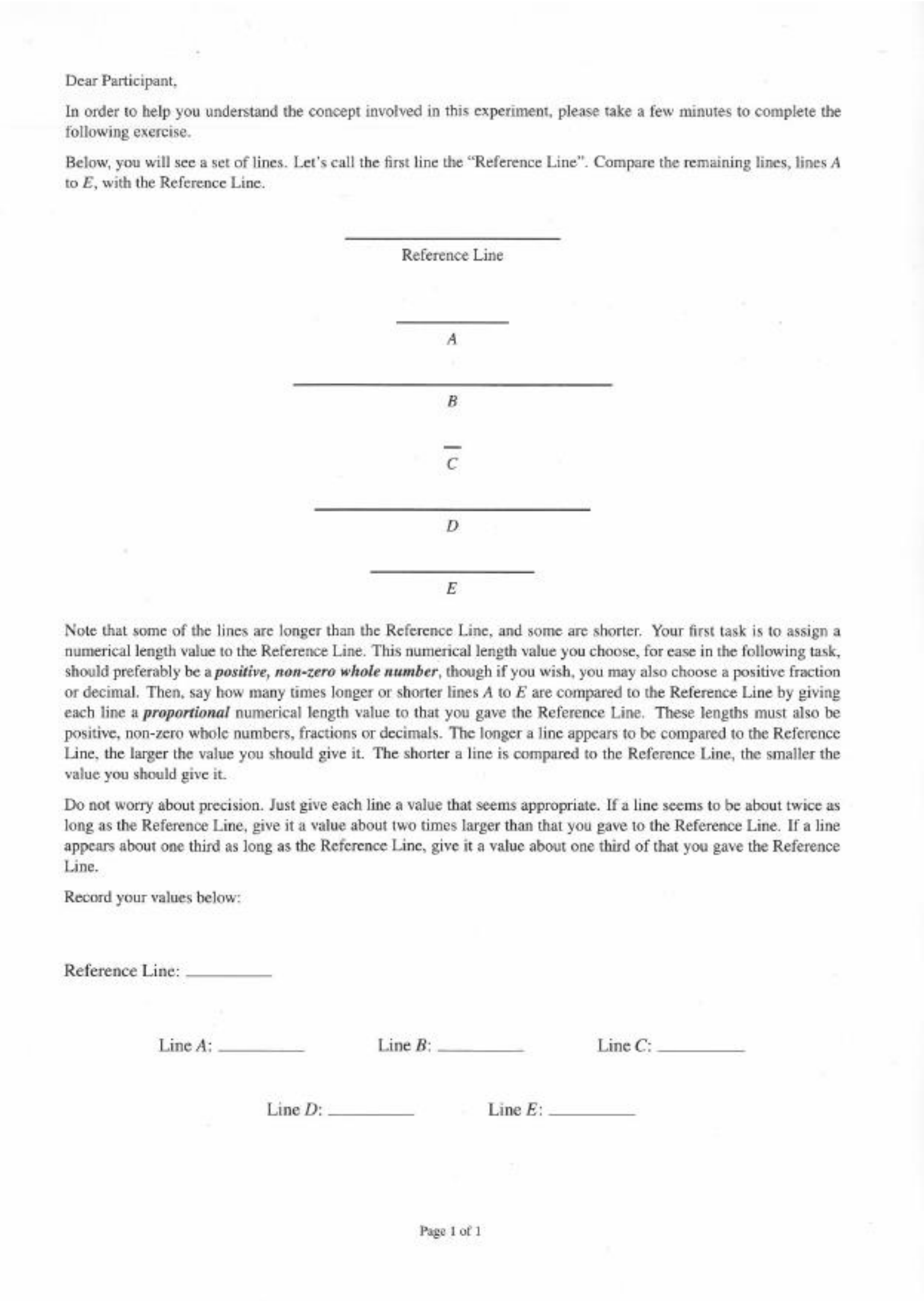


(a) (b)

(c)

Figure A.3: textured aluminium sheets (a) vertex: mill finish textured sheet, (b) flat plain aluminium sheet: anodised finish sheet and (c) sheet was made using the shot blast method.

A.3 Magnitude estimation practice sheet



Dear Participant,

In order to help you understand the concept involved in this experiment, please take a few minutes to complete the following exercise.

Below, you will see a set of lines. Let's call the first line the "Reference Line". Compare the remaining lines, lines *A* to *E*, with the Reference Line.

Reference Line

A

B

C

D

E

Note that some of the lines are longer than the Reference Line, and some are shorter. Your first task is to assign a numerical length value to the Reference Line. This numerical length value you choose, for ease in the following task, should preferably be a ***positive, non-zero whole number***, though if you wish, you may also choose a positive fraction or decimal. Then, say how many times longer or shorter lines *A* to *E* are compared to the Reference Line by giving each line a ***proportional*** numerical length value to that you gave the Reference Line. These lengths must also be positive, non-zero whole numbers, fractions or decimals. The longer a line appears to be compared to the Reference Line, the larger the value you should give it. The shorter a line is compared to the Reference Line, the smaller the value you should give it.

Do not worry about precision. Just give each line a value that seems appropriate. If a line seems to be about twice as long as the Reference Line, give it a value about two times larger than that you gave to the Reference Line. If a line appears about one third as long as the Reference Line, give it a value about one third of that you gave the Reference Line.

Record your values below:

Reference Line: _________

Line *A*: _________ Line *B*: _________ Line *C*: _________

Line *D*: _________ Line *E*: _________

Page 1 of 1

Appendix B

Compliance and adhesion Interaction (Experiment 2)

B.1 Describing the process of second experiment

All stimuli used in this experiment were circular blocks of silicone. Nine stimuli were made with different combinations of compliance and adhesion. Softness was separated on three levels, express levels as 1: hardest stimuli, 2: natural, 3: softest stimuli. Also, adhesion was split on three levels which can express as 1: least sticky, 2: natural, 3: most sticky. Stimuli were made using a casting process in the strength of material Laboratory, model making area and Formula Student area. The process used was to pour silicone with different percentages of plasticizer to have a different softness and mix silicone with other materials to have different adhesion as shown in Table B.1.

Table B.1 Components of each layer

Parts	**Components**			
	1	**2**	**3**	**4**
First layer	4 parts of acetone	One part of Encapsulator		
Circle block	20gr of each platsil gel 10 part A and part B	50%,100% and 150% (of the weight of the total mix A and B of platsil gel 10) of plasticizer		
Fine layer of adhesion	One spoon of each part of silicone	25%, 75% and 125% (of the weight of the total mix A and B of platsil gel 10) of plasticizer.	Three times (of volume of the total mix plasticizer and A and B of platsil gel 10) of toluene	Little of black colour

The process comprised the following steps. The steps divided to three parts: first part, capsulate layer was made; second part, circle blocks were made and third part, fine layer of stickiness was painted. First part, materials used was acetone and encapsulator and bald cap plastic. One part of encapsulator and bald cap plastic mixed with four parts of acetone by volume. This mixture sprayed 3-4 coats to the mould (Figure B.1) using airbrush, allowing up to 10 minutes between each coat. Second part, materials were used in this part platsil gel 10 part A and B and plasticizer. Firstly, simply mix the platsil gel 10 part A and B and plasticizer together by weight (Table B.1) at room temperature mixture creates a chemically stable gel with the look and feel you desire and different percentage of plasticizer was to have different softness. (For example mixing at proper ratio of 1 platsil gel 10 part A: 1 platsil gel 10 part B: 1 plasticizer by weight). Secondly, this mixture poured over first layer in the mould and top surface was checked to have flat surface. Thirdly, the mould was allowed to cure for one day. Finally, circle blocks were removed from the mould and ready to put final layer which use the same procedure for first part but with different materials. Last part, making stickiness layer, two parts of platisl gel-10, different percentage of plasticizer (25%, 75% and 125%), toluene and black colour is used to make the stickiness layer. The steps for make this layer was: first, platisl gel-10 part A and B, plasticizer and toluene were mix together with different ratio by volume and then black colour was added and mixed together. The ratio of these combinations depend on adhesion level: the ratios of adhesion level 1 was 1:1:0.5:7.5 by volume of platisl gel-10 part A and B, plasticizer and toluene respectively, the ratios of stickiness level 2 was 1:1:1.5:10.5 of the same material and the ratios of adhesion level 3 were 1:1:2.5:13.5 of the same material. Second, this mixture was sprayed several fine layers on the circle blocks using airbrush allowing overnight for drying this layer. Finally, circle blocks were ready to test perception of softness with stickiness. The total time to make all stimuli was 10 days.

Figure B.1: Silicone mould

B.2 Counterbalanced design

Table B.2 Counterbalanced design for second experiment

Participant no.	Order of conditions			
1	A	B	C	D
2	A	B	D	C
3	A	C	B	D
4	A	C	D	B
5	A	D	B	C
6	A	D	C	B
7	B	A	C	D
8	B	A	D	C
9	B	C	A	D
10	B	C	D	A
11	B	D	A	C
12	B	D	C	A
13	C	A	B	D
14	C	A	D	B
15	C	B	A	D
16	C	B	D	A
17	C	D	A	B
18	C	D	B	A
19	D	A	B	C
20	D	A	C	B
21	D	B	A	C
22	D	B	C	A
23	D	C	A	B
24	D	C	B	A

B.3 Procedure of second experiment

The experiment was carried out using a similar procedure to the previous experiment. Participants were seated on one side of table and on the other, the experimenter was stationed. A curtain, gray in colour, was dropped half way across the breadth of the table to avoid the participants from seeing stimuli. The stimuli were placed behind the curtain at the same place. Participant was presented with a test and a reference stimulus. These were placed in front of the participant, one in right side and other in left side. A traffic light system was used to indicate when the stimuli were in place. The light turned green, the participant put their hand through the curtain to slide the test stimulus and reference one, and they can go back to say how many times softer the silicone blocks on their right compared to reference block by assigning value to the test block and recorded this value of in box labelled on the sheet using the magnitude estimation process described above. Each participant could go back between test and reference stimulus as often as desired. After they recorded the value of test stimulus, the light switched to red when their hand was withdrawn. The next stimulus was put in place to assign value compared with reference and the procedure was repeated until all test stimuli had been given a value compared with reference stimulus.

B.4 The results of ANOVA test within subject contrasts

Full results the tests of within contrasts for second experiment were described in Table B.3, B.4, B.5 and B.6.

Table B.3 Tests of Within-Subjects Contrasts for perception of softness (Pressing condition)

Source		adhesion	df	F	Sig.
compliance	Level 1 vs. Level 3		1	61.61	.000
	Level 2 vs. Level 3		1	40.64	.000
Error(Softness)	Level 1 vs.Level 3		23		
	Level 2 vs. Level 3		23		
adhesion		Level 1 vs. Level 3	1	.41	.529
		Level 2 vs. Level 3	1	.28	.600
Error(adhesion)		Level 1 vs. Level 3	23		
		Level 2 vs. Level 3	23		
compliance * adhesion	Level 1 vs. Level 3	Level 1 vs. Level 3	1	6.66	.017
		Level 2 vs. Level 3	1	.14	.714
	Level 2 vs. Level 3	Level 1 vs. Level 3	1	1.21	.283
		Level 2 vs. Level 3	1	.15	.698
Error(complinace* adhesion)	Level 1 vs. Level 3	Level 1 vs. Level 3	23		
		Level 2 vs. Level 3	23		
	Level 2 vs. Level 3	Level 1 vs. Level 3	23		
		Level 2 vs. Level 3	23		

a. Computed using alpha = .05

Table B.4 Tests of Within-Subjects Contrasts for perception of stickiness (Pressing condition)

Source		adhesion	df	F	Sig.	Partial Eta Squared
compliance	Level 1 vs. Level 3		1	.001	.978	.000
	Level 2 vs. Level 3		1	1.949	.176	.078
Error(compliance)	Level 1 vs. Level 3		23			
	Level 2 vs. Level 3		23			
adhesion		Level 1 vs. Level 3	1	1.640	.21	.067
		Level 2 vs. Level 3	1	1.291	.27	.05
Error(adhesion)		Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
compliance * adhesion	Level 1 vs. Level 3	Level 1 vs. Level 3	1	.895	.354	.037
		Level 2 vs. Level 3	1	1.024	.322	.043
	Level 2 vs. Level 3	Level 1 vs. Level 3	1	.847	.367	.036
		Level 2 vs. Level 3	1	.158	.695	.007
Error(compliance * adhesion)	Level 1 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
	Level 2 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			

Computed using alpha = .05

Table B.5 Tests of Within-Subjects Contrasts for perception of softness (Sliding condition)

Source			Df	F	Sig.	Partial Eta Squared
compliance	Level 1 vs. Level 3		1	31.347	.000	.577
	Level 2 vs. Level 3		1	16.199	.001	.413
Error(compliance)	Level 1 vs. Level 3		23			
	Level 2 vs. Level 3		23			
adhesion		Level 1 vs. Level 3	1	.181	.675	.008
		Level 2 vs. Level 3	1	1.185	.288	.049
Error(adhesion)		Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
compliance * adhesion	Level 1 vs. Level 3	Level 1 vs. Level 3	1	.166	.688	.007
		Level 2 vs. Level 3	1	.007	.933	.000
	Level 2 vs. Level 3	Level 1 vs. Level 3	1	.419	.524	.018
		Level 2 vs. Level 3	1	.341	.565	.015
Error(compliance* adhesion)	Level 1 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
	Level 2 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			

Table B.6 Tests of Within-Subjects Contrasts for perception of stickiness (Sliding condition)

Source			Df	F	Sig.	Partial Eta Squared
compliance	Level 1 vs. Level 3		1	19.65	.000	.461
	Level 2 vs. Level 3		1	10.38	.004	.311
Error(compliance)	Level 1 vs. Level 3		23			
	Level 2 vs. Level 3		23			
adhesion		Level 1 vs. Level 3	1	19.53	.000	.459
		Level 2 vs. Level 3	1	15.14	.001	.397
Error(adhesion)		Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
compliance * adhesion	Level 1 vs. Level 3	Level 1 vs. Level 3	1	2.63	.118	.103
		Level 2 vs. Level 3	1	.23	.633	.010
	Level 2 vs. Level 3	Level 1 vs. Level 3	1	.73	.400	.031
		Level 2 vs. Level 3	1	.01	.935	.000
Error(compliance* adhesion)	Level 1 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			
	Level 2 vs. Level 3	Level 1 vs. Level 3	23			
		Level 2 vs. Level 3	23			

Appendix C

Tactile Display

C.1 Psychometric function

There are two different procedures for measuring; the yes-no procedure and the 2-alternative forced choice procedure (2AFC). In the yes-no procedure, the correct response could range from 0% to 100% and the threshold could be 50%. This value is a value in which 50% of stimuli are detected (Figure C.1), while threshold and the range of correct responses depended on the alternative choices of the forced choice procedure. For the 2-forced choice procedure, the ogive starts from a chance level of 50% because there is a 50% chance of correct response with this procedure and the threshold is likely to be 75% because it is the middle point between the chance level of 50% for weak intensity to 100% for a very strong one as shown in Figure C.1. In the 4-forced choice procedure, the range of correct responses is considered to be 25% to 100% and the threshold in this case could be 62.5% as the mid-point of the range of correct response (Kalloniatis and Luu, 2011).

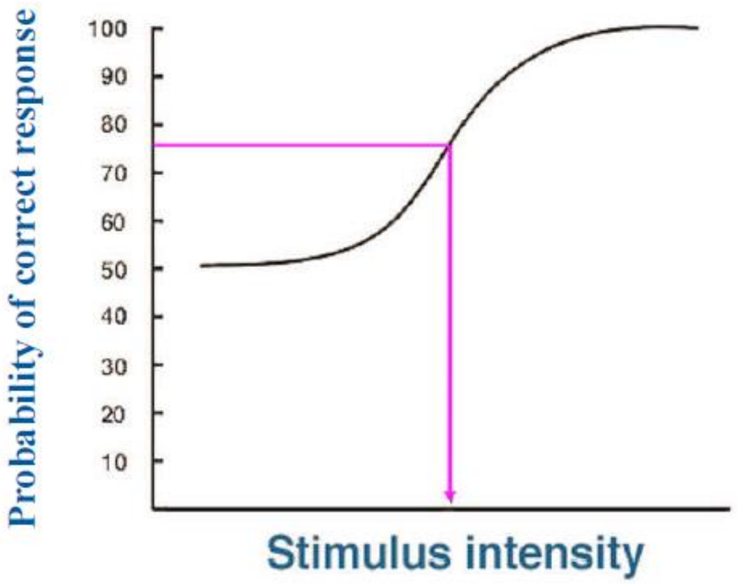


Figure C.1: Psychometric Functions for 2AFC. The threshold is taken at the 75% correct percentage.

C.1.1 Parametric Estimation

There are two methods for fitting psychometric functions and estimating parameters of functions; the methods are maximum-likelihood and Bayesian criterion. Also, there are four parameters to determine the shape of psychometric function. Two of parameters (guessing rate γ, lapsing rate λ) are fixed parameters and the others (α, β) are free parameters. The lower asymptotes (guessing rate) were dependent on the design of the experiment, in case of using mAFC, γ= 1/m while upper asymptotes (lapsing rate) λ = 0, other parameters can be estimated dependent on the function chosen. If λ is not equal to 0 then there is a significant bias on the threshold and slope parameters. To avoid large bias on the threshold and the slope, it might assume λ = fixed small value or it might estimate a value of λ from the data. It means λ is a free parameter (Wichmann and Hill, 2001a, Klein, 2001, Linschoten et al., 2001, Kingdom and Prins, 2010, Garcia-Perez and Alcala-Quintana, 2005, Strasburger, 2001b, Zchaluk and Foster, 2009).

The method was used to estimate parameters of psychometric function as maximum likelihood; Figure C.2 explains the parameter estimation and psychometric function fitting by the following equation:

$$\mathrm{PF}(\times;\alpha,\beta,\gamma)=\gamma+(1-\gamma)\mathrm{f}(\times;\alpha,\beta,\gamma)$$

Equation C-1

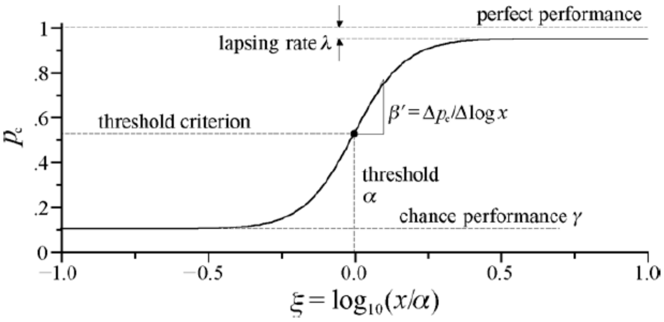


Figure C.2: Psychometric function with explanation of parameters (Strasburger, 2001a).

It is necessary to find the optimal (best estimation of) parameters combination α, β for each function that maximizes the log-likelihood of the data. The values of all parameters may be estimated by using the function PAL_PFML_Fit in the Palamedes toolbox associated with a PF. The Palamedes, which was downloaded, is MATLAB routines for analysing psychophysical data. The version used in our analysis is 1.5.0. This function applies in MATLAB, it is written as follows:

$$[\mathrm{paramsvalues},\mathrm{LL},\mathrm{exitflag},\mathrm{output}]\ =\mathrm{PAL}_{\mathrm{PFML}_{\mathrm{Fit}}}$$
$$(\mathrm{stimulevels},\mathrm{numpos},\mathrm{outofnum},\mathrm{paramsvalues},\mathrm{paramsfree},\mathrm{PF});$$

Equation C-2

Another function (PAL_PFML_BootstrapParametric) estimates the standard error of estimation. The standard error was estimated to discover how much our estimate for the parameters was in error. The function is shown below:

[SD paramsSim LLSim exitflag]
= PAL_PFML_BootstrapNonParametric
(stimulevels,numpos,outofnum,paramsvalues,paramsfree,B, PF

Equation C-3

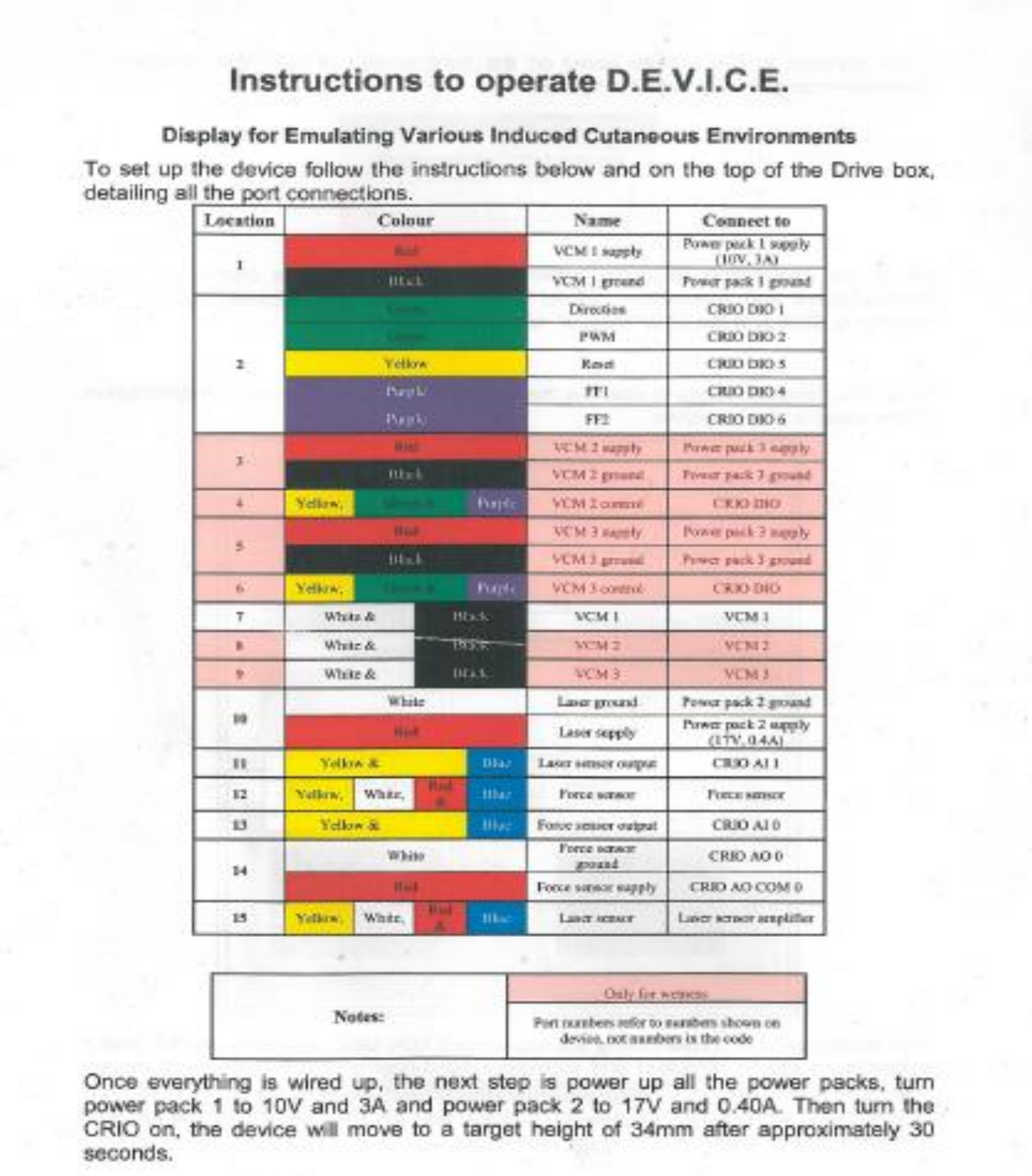
The other function is how to estimate deviance (Dev) and a p value of deviance (dev), this function is determined to compare between models; the best fit for the model has pDev as the largest value.

$$[\mathrm{Dev\ pDev\ DevSim\ converged}] = \mathrm{PAL}_{\mathrm{PFML}_{\mathrm{GoodnessOfFit}}} \left(\begin{matrix} \mathrm{stimulevels, numpos,} \\ \mathrm{outofnum, paramsvalues, paramsfree, B, PF} \end{matrix}\right);$$

Equation C-4

The distribution and parameters could be fitted and the estimate for the best one by the function explained above. After the parameters were estimated and the function was fitted, the thresholds were estimated from the chart to find the value of stimulus when the correct response is 75%. This value is the lowest value of Young’s modulus with which stimulus can be detected at 75% of correct responses. The results showed this value for all sessions.

C.2 Instruction sheet for using tactile display



Instructions to operate D.E.V.I.C.E.

Display for Emulating Various Induced Cutaneous Environments

To set up the device follow the instructions below and on the top of the Drive box, detailing all the port connections.

Location	Colour	Name	Connect to
1	Red	VCM 1 supply	Power pack 1 supply (10V, 3A)
	Black	VCM 1 ground	Power pack 1 ground
2	Green	Direction	CRIO DIO 1
	Green	PWM	CRIO DIO 2
	Yellow	Reset	CRIO DIO 5
	Purple	FF1	CRIO DIO 4
	Purple	FF2	CRIO DIO 6
3	Red	VCM 2 supply	Power pack 3 supply
	Black	VCM 2 ground	Power pack 3 ground
4	Yellow, Green & Purple	VCM 2 control	CRIO DIO
5	Red	VCM 3 supply	Power pack 3 supply
	Black	VCM 3 ground	Power pack 3 ground
6	Yellow, Green & Purple	VCM 3 control	CRIO DIO
7	White & Black	VCM 1	VCM 1
8	White & Black	VCM 2	VCM 2
9	White & Black	VCM 3	VCM 3
10	White	Laser ground	Power pack 2 ground
	Red	Laser supply	Power pack 2 supply (17V, 0.4A)
11	Yellow & Blue	Laser sensor output	CRIO AI 1
12	Yellow, White, Red & Blue	Force sensor	Force sensor
13	Yellow & Blue	Force sensor output	CRIO AI 0
14	White	Force sensor ground	CRIO AO 0
	Red	Force sensor supply	CRIO AO COM 0
15	Yellow, White, Red & Blue	Laser sensor	Laser sensor amplifier

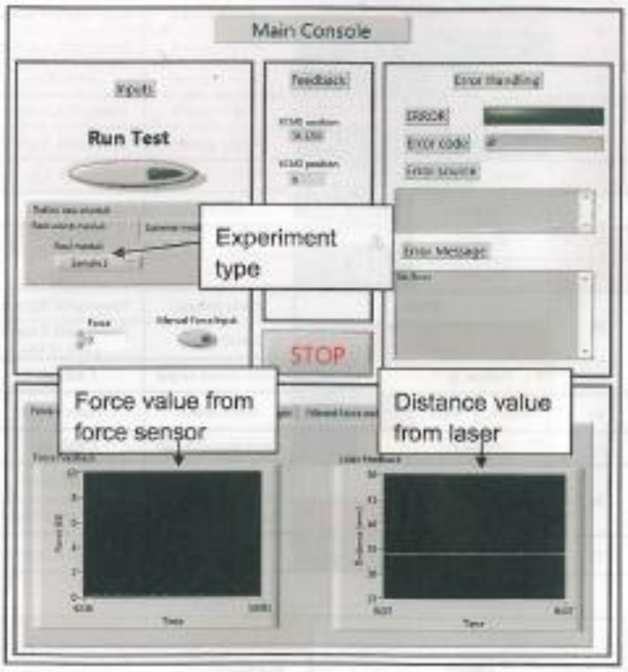
Notes:	Only for wetness
	Port numbers refer to numbers shown on device, not numbers in the code

Once everything is wired up, the next step is power up all the power packs, turn power pack 1 to 10V and 3A and power pack 2 to 17V and 0.40A. Then turn the CRIO on, the device will move to a target height of 34mm after approximately 30 seconds.

Then, connect to the remote panel on the front screen of LabVIEW navigate to *Operate>>connect to remote front panel.*

Fill in the information requested where the ip address is the one found using Measurement and Automation Studio (most likely will be 192.168.0.2), the port number is 8000 and the VI is "Main.vi" without the quotes.

When the device is ready to use, the main console window will appear. A description of the panel is shown below.



Two modes can be chosen using the experiment type tabs: real world moduli (using values from silicon samples) and extreme moduli (using extreme values of moduli from alternative materials), DO NOT USE "Define new moduli". If this happens, turn off the device and reset. Pressing run test will start the test and the device will now change in height depending on force applied.

Before repeating the experiment, the CRIO will require re-booting, switch it on and off again before reconnecting with the remote panel.

When stopping turn off Run test first!

C.3 Results of psychometric function for all sessions

C.3.1 Comparison of different real material stimuli with displayed softness as reference

Figures C.3, and C.4 show the psychometric function were fitting to different functions.

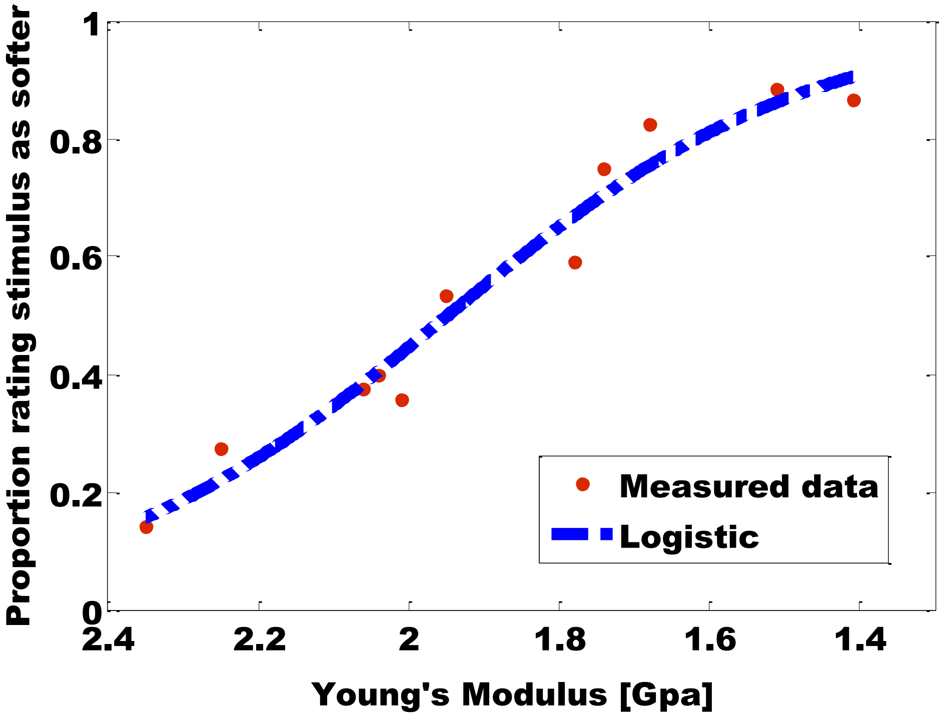


Figure C.3: Psychometric function representing logistic fits to the data for a range of real materials compared to a simulated, displayed reference.

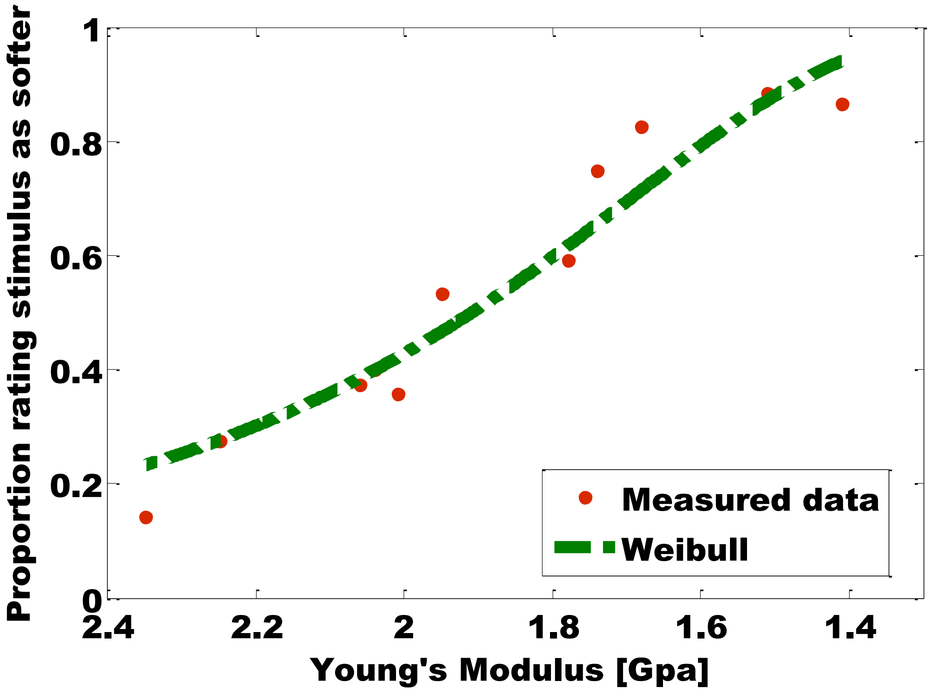


Figure C.4: Psychometric function representing Weibull fits to the data for a range of real materials compared to a simulated, displayed reference.

As explained in section C.1.1, the estimated parameters (α, β) depend on the function, the values of these parameters and for parameters (γ, λ) shows in Table C.1 for three functions (logistic and Weibull).

Table C.1 Parameters values for the psychometric function of people's discrimination between real, soft materials and a simulated, displayed reference.

		Logistic	**Weibull**
Free parameters	α	1.65	1.53
	β	-7.65	-8.58
Fixed parameters	γ	0.5	0.5
	λ	0	0
LL		-802.19	-809.95

To compare between the models which fit the data, three methods are used: the standard error; the likelihood and deviance (Dev) and pDev value. Firstly, the standard error is different between true parameter values and our estimates. The Palamedes function was used to estimate standard error, the function is PAL_PFML_BootstrapParametric. Table C.2 shows the standard error of our estimates of α, β, γ and λ.

Secondly, the model has Higher Likelihood, it is the better model when compare with other models. Table C.1 shows the likelihood values for each function.

A third method is calculated Dev and pDev values for each model by using the goodness-of-fit function in the Palamedes toolbox. pDev measures the actual goodness-of-fit, the better fit for the model when the pDev is the largest value compared with other models. Table C.2 presents the values of Dev and pDev for all functions.

Table C.2 Standard error in parameters and the values of Dev and pDev for all functions of people's discrimination between real, soft materials and a simulated, displayed reference.

		Logistic	**Cumulative normal**	**Weibull**
Standard error	α	0.016	0.015	0.016
	β	0.149	0.270	0.286
	γ	0	0	0
	λ	0	0	0
Dev		16.972	15.940	32.584
pDev		0.055	0.069	$-2.5*10^{-4}$

C.3.2 Comparing different simulated, displayed softnesses with a simulated, displayed softness reference

Three different functions fit for psychometric functions which are shown in Figures C.5 and C.6

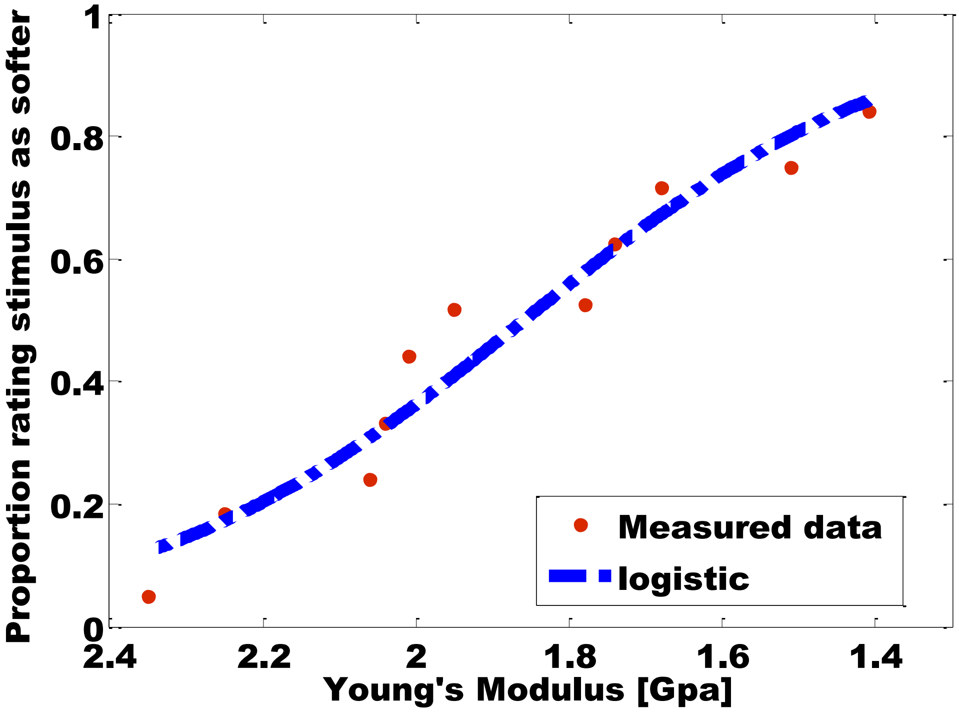


Figure C.5: Psychometric function represents logistic fits to the data for simulated softness compared with a simulated reference.

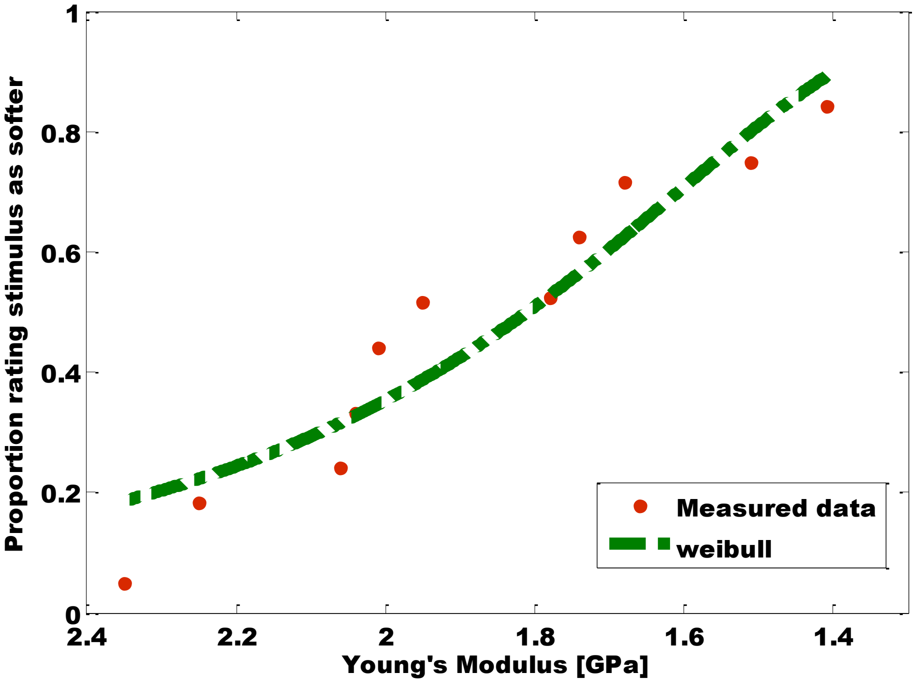


Figure C.6: Psychometric function represents Weibull fits to the data for simulated softness compared with a simulated reference.

As explained in section C.1.1, the estimated parameters (α, β) depend on the function, the values of these parameters and for parameters (γ, λ) shows in Table C.3 for three functions (logistic and Weibull).

Table C.3 Parameter values for the psychometric function of people's discrimination between simulated, displayed softness

		Logistic	**Weibull**
Free parameters	α	1.86	1.67
	β	-4.01	-4.66
Fixed parameters	γ	0	0
	λ	0	0
Likelihood		-755.26	-766.73

To compare between the models which fit the data, three methods are used: the standard error; the likelihood and deviance (Dev) and pDev value. Firstly, the standard error is different between true parameter values and our estimates. The Palamedes function was used to estimate standard error, the function is PAL_PFML_BootstrapParametric. The Table C.4 shows the standard error of our estimates of α, β, γ and λ.

Secondly, the model has Higher Likelihood, it is the better model when compare with other models. The Table C.3 shows the likelihood values for each function.

A third method is calculated Dev and pDev values for each model by using the goodness-of-fit function in the Palamedes toolbox. pDev measures the actual goodness-of-fit, the better fit for the model when the pDev is the largest value compared with other models. Table C.4 presents the values of Dev and pDev for all functions.

Table C.4 Standard error in parameters and the values of Dev and pDev for all functions of people's discrimination between simulated, displayed softness.

		Logistic	**Cumulative normal**	**Weibull**
Standard error	α	0.016	0.015	0.017
	β	0.249	0.142	0.269
	γ	0	0	0
	λ	0	0	0
Dev		24.413	23.354	47.347
pDev		0.005	0.005	0

C.3.3 Comparison of different displayed softnesses with real stimuli as reference

Figures C.7 and C.8 showed the data is fitting the different three functions.

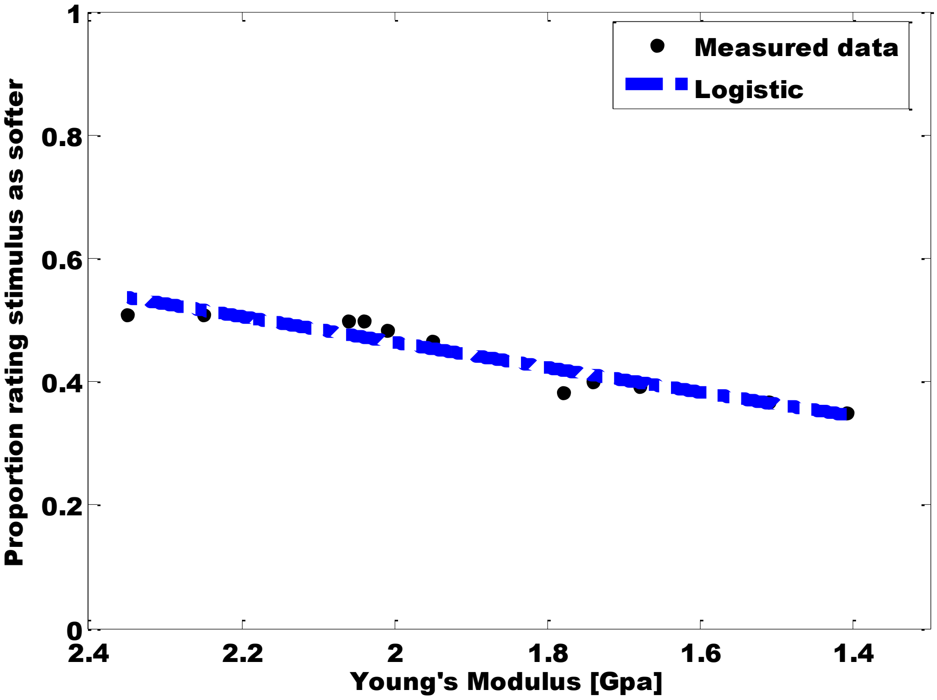


Figure C.7: Psychometric function representing logistic fits to the data for a range of simulated, displayed softness compared with a real reference.

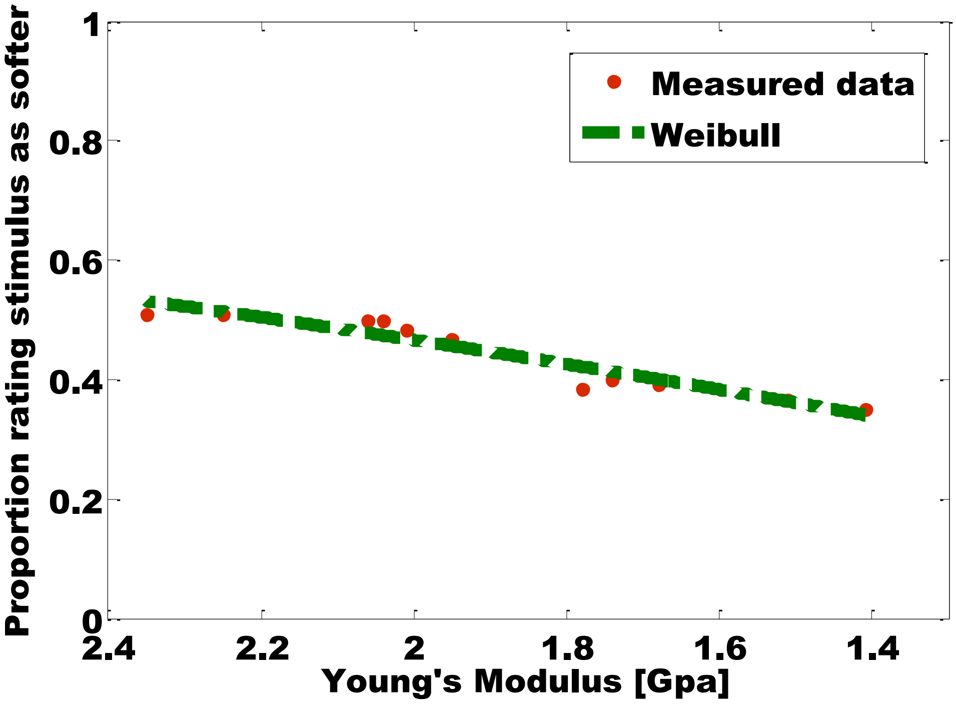


Figure C.8: Psychometric function representing Weibull fits to the data for a range of simulated, displayed softness compared with a real reference.

The estimated parameters (α, β) depend on the function, the values of these parameters and for parameters (γ, λ) shows in Table C.5 for three functions (logistic, Weibull and cumulative normal).

To compare between the models which fit the data, three methods are used: the standard error; the likelihood and deviance (Dev) and pDev value. Firstly, the standard error is different between true parameter values and our estimates. The Palamedes function was used to estimate standard error, the function is PAL_PFML_BootstrapParametric. Table C.6 shows the standard error of our estimates of α, β, γ and λ.

Table C.5 Parameter values for the psychometric function for a range of simulated, displayed softness compared with a real reference.

		Logistic	**Weibull**
Free parameters	α	2.18	2.98
	β	0.83	1.17
Fixed parameters	γ	0	0
	λ	0	0
LL		-897.23	-897.18

Secondly, the model has Higher Likelihood, it is the better model when compare with other models. The Table C.5 shows the likelihood values for each function.

A third method is calculated Dev and pDev values for each model by using the goodness-of-fit function in the Palamedes toolbox. pDev measures the actual goodness-of-fit, the better fit for the model when the pDev is the largest value compared with other models. Table C.6 presents the values of Dev and pDev for all functions.

Table C.6 Standard error in parameters and the values of Dev and pDev for all functions for a range of simulated, displayed softness compared with a real reference.

		Logistic	**Cumulative normal**	**Weibull**
Standard error	α	0.114	0.123	0.636
	β	0.200	0.126	0.285
	γ	0	0	0
	λ	0	0	0
Dev		1.996	1.993	1.902
pDev		0.992	0.994	0.993