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Psychophysics of touch and non-verbal characterisation of physical objects

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Abstract

Considerable information about texture can be perceived remotely through indirect touch with a probe. In this project, a series of studies were performed trying to understand how people perceive this information using both verbal and non-verbal explanations.

During the studies performed for this project, it was discovered that people tend to characterise unknown textures using similes of rubber objects rather than fruits as was stated by the initial test hypothesis, when feeling them through a probe and using verbal descriptions to characterise them.

Then they were asked to describe virtual representations of the same objects via non-verbal means, using a force feedback device. They did this by varying the quantities of stiffness, static and dynamic friction of a virtual object. These non-verbal descriptions caused some relationships between these three attributes to emerge. Even though there was no clear correlation between them, cluster analysis showed grouping of the data in clusters. This clustering in the data is an indication of the existence of a larger, more complex relationship between what we can feel through touch and how this information is processed by our sensory system. Further investigation will be necessary to ascertain whether this is caused by multimodal interference, cultural differences, and unique psychophysical factors of each individual, or even limitations of the force feedback device used.

Statement of Ethics

This experimental study, design and participant tasks have been all designed based on the ethical principles of “Do No Harm”, “Informed Consent” and “Data Confidentiality”.

DO NO HARM

The participants in the experiment were not put in any harmful situations or asked to take any risk different from those normally encountered in everyday life. All participants were informed they could withdraw from the experiments at any point with no consequences or questions asked.

INFORMED CONSENT

The participants recruited for the current research were all informed about the experiment design and tasks that they were going to undertake. All of the participants were over 18 years old and were well informed with the appropriate information before the experiment with a briefing session, and a debriefing session after the experiment. All participants were also asked to sign a consent statement form before the experiment (available in Appendix 1.).

DATA CONFIDENTIALITY

In order to process and analyze the experiment results, data were collected from the participants. All the information gathered was kept confidential and accessible only to the experiment and the supervisor of this research. In addition, any data recorded from the participants were stored and referred to anonymously, only by the participant number.

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Dad and Mom, ευχαριστώ για όλα.

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1. Introduction

When interacting with computers, a user can become overburdened by the ever-increasing amounts of visual information they have to take in and process [1]. This at first does not seem to impose a serious problem, since in our everyday life we can cope with huge amount of complex information of many different types, coming from our surrounding with virtually no difficulty. One reason for this problem is that computers communicate mostly through graphical output, which may strain our visual sense. On the other hand, in the real world, we have five traditionally recognized methods of perception, or sense (hearing, sight, touch, smell and taste), and by combining them we can prevent one from becoming overloaded [1,2].

To compensate for this in computer interaction, research has recently started looking at other modes of human computer interaction. This gave rise to what is called "multimodal" interaction. As the name suggests, multimodal interaction refers to the mode of communication with another system using more than one mode of interaction. This caused two major groups of multimodal interfaces to come together. The first group of interfaces is combining a number of user input modes beyond the traditional keyboard and mouse, such as speech, touch and manual gestures [3], gaze and motion control.

The other group of interfaces is combining input and output methods in order to make interfaces that merge a visual modality (e.g. a display, keyboard, and mouse), with a voice modality (speech recognition for input, speech synthesis and recorded audio for output). However other modalities, such as pen-based input or haptic input/output may be used.

Adapting technologies in our everyday computer use, to allow interaction and communication of information between the computer and its user via other senses along with vision is one possible solution. Extensive work has been done with auditory communication of information, e.g. [2], and the sense of touch as a mean to convey information in both safety critical systems and systems of casual use, such as mobile phones, and combinations of the two.

In order to design and create better interfaces that use haptics as a mean to express information, we first need to understand how the sense of touch works, in a similar way studies contacted for other senses helped us understand the sense of vision and hearing.

In addition, for creating and adapting haptic interactions with technologies in our everyday life, we also need haptic displays. One reason graphics are being used so much is because we have good visual displays, with the ability to produce high definition images and graphics. Haptic interfaces on the other hand lack in this area as they are, at the moment, confined in more specialised areas such as the area of medicine and the training of surgeons performing robot assisted surgeries [4].

Anderson and Sanderson [5] performed a number of studies, set to investigate the different dimensions of sound and their importance when trying to convey a message. In order to better understand the sense of touch, we need to first understand, not only how it works (physiology), but also how we perceive touch, a similar way Anderson et al. did for hearing and sounds. This way, we will be able to utilise touch more efficiently in system interfaces and for communicating messages and information in systems.

The aim of this project is to explore how people perceive touch and how they can describe what they feel through the sense of touch using non-verbal descriptions. In order to do this, a series of experiments were designed for evaluating the user haptic perception when touch occurs indirectly (via a probe or tool) and a method was designed and implemented where participants could replicate the haptic properties of objects in the virtual world. This way they could describe the objects they felt using their sense of touch instead of trying to verbalise a description. All experiments were designed based on pre existing literature and were set to investigate hypotheses arising from this said literature.

The next chapter contains a *literature review*, providing the reader with relevant background to this study. This is followed by chapter 3, explaining the *experimental procedure* used, and chapters 4 to 6, where all experiments performed are described and results obtained analysed and discussed. Finally, these chapters are followed by a "*Conclusions*" chapter talking about the findings of this study and how they can be tied together with the current, published literature.

2. Literature Review

2.1 What are haptics?

Haptics refers to the application of touch (tactile) sensation and kinaesthesia (knowing where your limbs are in relation to your body) as a mode of interaction with someone's immediate environment. In other words, touch and kinaesthesia are subgroups of the broader term referred as haptics (see Figure 1[1]).

Klatzky, Lederman and their colleagues have worked extensively on the area of adults' haptic perception. Through their work ([6], [7] and [8]), they argue convincingly that haptics is an "*impressive and distinctive perceptual system*", which is specifically oriented towards the encoding of the object's material (i.e. the material an object is made of) rather than its structure (i.e. how the object is positioned in space). Through studies, they have observed that people are good at recognising real, everyday objects solely by touch, but they were notably poor in recognising objects when they were just represented by raised contour "drawings" of objects, retaining spatial information but not temperature, texture, or hardness cues [7].

Along the same lines, Klatzky and Lederman investigated a particular hand movement; they called *exploratory procedure*, or EP [6]. An EP, according to them, is a stereotyped pattern of hand movement that when applied, it maximises the sensory input corresponding to a certain object property (e.g. the object's roughness). With this technique, the different dimensions of haptic perception could be isolated and a thorough investigation could be performed testing the relative efficiency (i.e. accuracy and speed) of different EPs for extracting information about various dimensions [8]. This bears a very close resemblance to what Sanderson and Anderson did in [5] with sonification and the understanding of the different dimensions of sound.

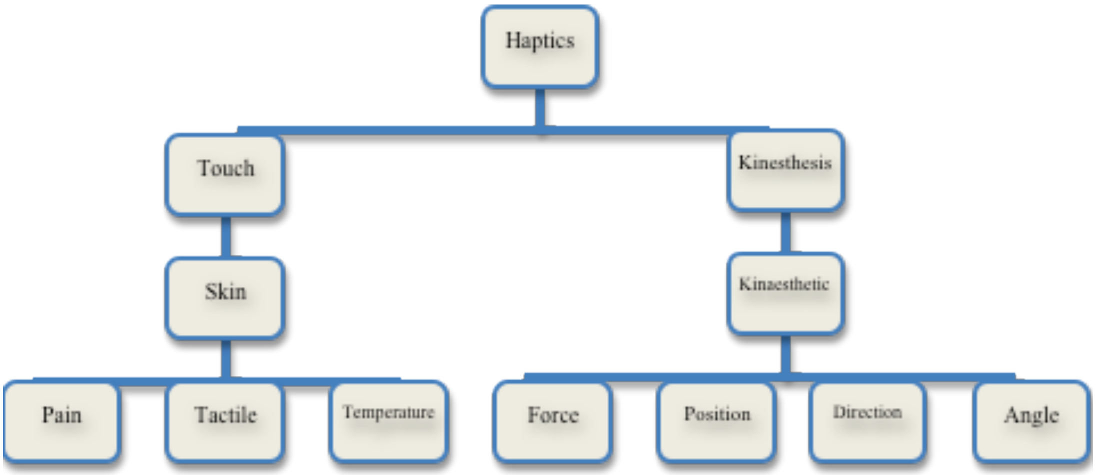

Figure 1 Diagram of Haptics and its subcategories

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[1] Adapted from professor's Steven Brewster presentation slides on Multimodality, 13 February 2012 at the University of York.

With their collective findings, Klatzky et al. found that the haptic perception of an object is closely linked to how easily it was to be encoded using an EP. The most noticeable object properties are those, which can be easily recognised using hand movements that are easy to execute. Properties such as the object's temperature, texture and hardness can easily be recognised by brief repetitive hand movements applied on just a portion of the object's surface [6]. The objects shape, on the other hand, is something that needs a more difficult to perform EP, requiring the full exploration of the object's contours and often involve the use of both hands [6].

Therefore, haptics is much more complex than we think it is. It is not just "touch"; it is something much deeper and more complex.

2.2 Development of haptic perception

Although people tend to think that vision and audition are the only senses that enable us to understand the world, the case of Helen Keller (American author, political activist, and lecturer) [9] who became deaf and blind in infancy and learnt to communicate solely on the basis of touch is just one example that shows this is not true.

The evolution of the human hand into a prehensile tool, highly adapted for exploration, manoeuvring and object exploitation, is recognised as one of the most critical factors in the phylogeny of humans [10]. In a very similar way, the development of the skilful use of the hands for these purposes played a very significant role to human's ontogeny and helped them climb to the top of the food chain, dominating the planet.

The sense of touch is the earliest sense to develop in an embryo [11]. Within eight weeks, an embryo shows reflexes based on touch. In the first years of life, humans can gain a considerable ability to use their hands for acquiring information about textures and surfaces in order to discriminate or identify them. Infants around 12-month of age, was found to be able to discriminate shapes and recognise familiar (to them) objects from novel ones [12]. Also, studies have shown that an EP exists for infants as well, but due to development issues (infants hands are not yet fully developed) it is significantly different and poses more limitations. Infants for example are able to sense and differentiate a soft from a hard object but because of smaller hands and not yet fully developed motor system they do this by gripping the objects in different ways and different frequencies [13].

Therefore, the sense of touch is constantly developing, starting at a very young age. During our first few years we are able to explore and understand our surrounding environment through the sense of touch, exploiting enough information to build a mental picture of the surface or the objects we are in contact with.

2.3 Physiology of Touch - Tactile and Haptic Sensing

The sense of touch is often defined as the sensation obtained by non-painful stimuli placed against our body's surface. The sense of touch, generally, is a very complex system with many different receptors in joints, muscles and the skin, with each one having its own characteristics and responding to different stimuli [14].

Tactile sensing is the result of a chain of events that starts when a stimulus such as heat, pressure or vibration, is applied on the body [15]. This stimulus triggers a response from specialized receptors, depending on the type, magnitude and location on the skin it is applied to [15].

Hairless (glabrous) parts of the skin, covering the palm and fingertip regions of the body, play the most active role in tactile exploration and tactile sensing. These areas have high density of specialized receptors for sensing the constituent components of what we call "touch" and are able to accurately detect any mechanical input due to skin deformation and vibrations caused by a tangential movement [16].

Haptic sensing, on the other hand, is the proper terminology of the perception used for describing the more general sense of touch. Tactile sensing or perception only accounts for small-scale forces coming from slight touch and surface movement, which allows us to feel the smoothness or bumpiness of textures [16]. Haptics also include proprioception or kinaesthetic perception, which is responsible for perceiving the gross mechanical forces, like the weight and resistance of objects and the position of our extremities in relation to our body and other extremities [16].

Therefore, the ability of kinaesthesia and the high density of "touch" receptors in the skin of our hands, makes us humans very good in haptic perception and extremely efficient in the process of recognizing objects through touch [7].

2.4 Intermodal sense of touch

Alternatively, touch and tactual perception is not completely independent of vision. Even though vision and touch are capable of processing the same or similar events, they may do it in a largely autonomous way, with little or no interaction. In some cases, vision may be better in negotiating perception than touch when both modalities are available, and one sense completely override the other for processing information about the same event. In general, both senses are differentially suited for different events and situations, and may interact differently depending on the nature of the perceptual performance involved [17]. This last statement underlines the complexity of intermodal interactions and how two different senses can overlap and override each other, work together or work independent of each other depending on the particular event they are trying to process.

Studies ([18], [19]) suggest that information coming from two modalities (bimodal) describing the same event or surface, is better than information from a single modality for sensing surface properties. More specifically Manyam [19] found that people could judge shapes easier and more accurately when both vision and touch were used than when only touch was available. In addition, Heller [20], found that people could judge more accurately the surface's texture when both senses (vision and touch) were available rather than one alone.

Summing multimodal perception up, we can conclude that, even though any changes in tactual performance when vision is added to touch can be accounted for, there is not a simple global relationship that can help to define the interaction and association between the two modalities. The only way of possibly coming closer to the formulation of a relationship is by directly analysing and evaluating the kinds of information that are available as stimuli for a situation and evaluating the properties of the tactual and visual systems involved when engaging to the available stimulus information. This more practical approach is the only way for coming closer in analysing and understanding situations of intermodality relations.

2.5 Indirect Touch

Indirect touch refers to the situation where a surface is felt through the tip of a tool. Similar to kinaesthesia or proprioception, the information someone can gather with the tip of a rigid tool can be perceived as if it was part of the body. It is believed this “ability” comes from post tool-using evolution [21].

Despite the indirect touch, exploring a texture with a probe or a tool, a rigid link between the skin and the surface is shaped [22]. A rich impression of the object, and not the tool can be constructed by only feeling the vibrations created by the object’s texture surface [23]. As David Katz [24], observed, when you explore a surface with a tool, you feel the surface and not the tool; getting a rich impression of the surface you are in contact with, and not the tool or the vibrations themselves.

People physically contact objects in their surrounding environment by touching them, not only with their hands but also through tools. The use of tools to touch on objects may seem unusual, but in fact, it is much more common than one thinks. For example, when people use a pencil to draw on a rough paper, use cooking utensils or in much more specialised cases, performing minimal invasion surgery, are all examples where physical objects are felt through a tool object [22]. When drawing using a pencil on a piece of rough paper, the surface texture of the paper (roughness) and the interaction components between the pencil tip of the pencil and the paper surface are felt and not the vibrations that travel through the tool (pencil). The vibrations are just the medium that conveys this information to the touch sensing receptors on our skin.

The sense of touch when coming through a tool can be characterised as a perceptual process. Having said that, three general components need to be taken into consideration [25]. The first one is the physics involved at the point of interaction between the tool’s tip and the surface it is in contact with and the transmission of vibrations through the tool’s shaft. The second component involves the filtering the skin and the responses of the mechanoreceptors impose on the information received. The third, and final, component involves higher order factors that are possible to alter the perception of surface roughness. These factors include the mode of exploration (i.e. how fast the tool moves across a surface) or knowledge carried forward from previous experience with the same, or similar texture [25].

Moreover, touch can be characterised as being a temporally dissipative sense [26]. When a stimulus is received, the touch (or haptic) receptors involved begin to adapt to it, tuning the sensation caused by the stimuli out. This makes touch particularly sensitive to changes in haptic stimuli. No centralised organ to perceive the sense of touch [16], like the other senses do (e.g. eyes for vision), exists. Instead touch relies on sensors, called receptors, distributed through our entire body, encoding perceptual information upon receiving a stimulus. Our whole haptic sense then depends on our ability to piece together information coming from different spatial locations on our body [26,27]. Given that, and the fact that they are most sensitive in changes, haptics is an ideal medium for receiving a constant stream of useful information about our surrounding cancelling out anything that could be regarded as noise and reporting only the changes that occur.

2.6 Direct versus Indirect Touch

For the purpose of this comparison, the specific characteristics of texture I will be concentrating on will be roughness. Roughness is considered to be one of the most important attributes of objects when they are being felt [28], and can be a persuasive cue for an object's identity [29]. When the texture of a surface comes in contact with the bare skin, the sensory system responsible for encoding and conveying information about touch related stimuli makes use of a spatial code to construct a spatial pressure map [28].

This spatial map produced consists of slowly adapting mechanoreceptors. The position of each activated mechanoreceptor directly maps features of the surface in contact, creating a direct correlation of features and stimuli [7] [23].

Alternatively, when the finger holds a probe, contacting the surface, the spatial map reflects the contours of the probe, and not those of the surface. Nevertheless, when the surface is explored with a probe, the surface properties that make up textures, give rise to vibrations, which are transmitted to the skin via the rigid link (tool or probe) [7], [23], and the spatial map constructed to replicate the tool's or probe's surface is tuned out.

Consequently, this vibratory input resulting from a probe passing across a surface is more than enough to provide a perceptual impression regarding the surface's roughness. The amplitude and frequency of these vibrations excites four mechanoreceptor sensor population groups in the skin. These mechanoreceptors are frequency-tuned, which means that their lever of excitation depends on the frequency parameter of the vibration received [28]. When the same surface is felt with a bare finger, the total area of skin that the surface has instantaneously indented from a resting position defines the object's roughness; causing the speed the finger passes over the surface to play very little effect on the information perceived [28]. Alternatively, when exploring a texture with a probe, the speed the probe passes through the texture affects the frequency of the vibrations, and consequently the perception of the texture.

Therefore, the perception of textures, even though it appears intact when felt through a tool, the information received about the surface is different through a tool than that through bare skin. When exploring a surface using a finger (i.e. direct touch), a clearly defined two-dimensional spatial image of the texture and vibratory information are available to the receptors on the finger. Instead, when using a tool, the information received relies only on the vibrations transmitted through the tool's shaft. No special cues are available for texture perception since the pattern of deformation of the skin reflects the contours of the tool and not the surface [25]. In other words, there is a big and important difference in the information sent to the central nervous system forming the spatial map of a surface texture when comparing the sensation information obtained by the two exploratory techniques.

This can be reflected on the results from experiments performed by Susan Lederman and Roberta Klatzky [30], where they found that both, the accuracy and time taken for recognizing an object, were significantly different between direct and indirect touch conditions. More specifically, it took longer for participants to give less accurate descriptions of objects when exploring an object with a probe (indirect touch) than with bare skin (direct touch). Klatzky and Lederman note that this is mainly due to the elimination of thermal and spatially distributed force patterns and spatial and temporal kinaesthetic cues. The results from these experiments also show that, in order to achieve accuracy levels with a probe for the shape and size of an object, similar to those of bare finger exploration, people had to explore the object for more time [30].

For that reason, and based on the work of Klatzky et al., we can safely conclude that surface exploration with a probe or tool can provide people with sufficiently informative perception of a range of roughness values, but the level of roughness they perceive is not directed by variations in the stimulus in the same way as when a surface is felt through bare skin. In particular, with a probe or tool, exploratory parameters such as the force applied during exploration and the speed with which the tool passes over the surface play an important role in the perception of texture roughness, making recognition slower and less accurate.

2.7 Experience of haptic interactions

Haptic feedback can be an aspect of the design of human computer interactions, which has the potential of achieving a number of user experience goals. In order to do this, we first need to understand the physical interaction not only in the physiological sense but also the psychological and the cognitive aspects of such interactions.

First we need to consider that "touch" is intentional, socially invasive and committing [31]. With the simple gesture of reaching out to touch, intentions are shown, other's personal space may be invaded or taboos violated. One may also expose oneself to physical danger, pleasure or obtain information for the environment around him. Since touch is such intimate, social touch is considered salient and immediate [27] (e.g. a business handshake).

The intentions that may initiate or prolong a touch gesture vary. More caution is taken on what we touch than what we look at. This is something a designer must keep in mind when designing a haptic interface. The focus for the designer therefore, must shift from drawing the user's attention or designing visually ergonomic interfaces, to anticipating, directing and accommodating a potential user's preconception of what the interaction will do, and what the experience will be like [31].

There is always some kind of intention when touching something. This intention may be just to probe an object, communicate a message or just poke something to elicit a reaction or verify that an action is completed [31]. In some other, more recreational situations, we may use our sense of touch simply for the enjoyment of aesthetic pleasure or comfort, fidget to relieve tension, or connect physically or emotionally with another person or other living thing [27] [31]. In the same way, we avoid certain interactions through the perception that something can be potentially dirty, painful, forbidden or too intimate. Beyond this, many people (often culturally associated) are "haptically challenged", and do not generally find touching natural, informative or pleasant [31,19].

In addition, individuals may sense the world around them in a slightly different way from each other but being such a personal feeling, they may not be aware of this difference. Tests exist to check for perception differences in other senses. An example of such a test is the Ishihara test, designed for testing colour perception for red-green colour deficiencies [32].

The Ishihara test consists of a number of coloured plates, called Ishihara plates. Each plate contains a circle of dots appearing randomized in colour and size, and within the pattern are dots, which form a number or shape clearly visible to those with normal colour vision. These numbers or shapes, on the other hand, appear invisible, or difficult to see, to those with a red-green colour vision defect [32].

The existence of perceptual differences in touch in a similar way they exist in other senses, such as vision, is very philosophical and at the moment there is not a straightforward way of measuring it.

These are some of the parameters one must consider when designing a haptic interface in order to meet and satisfy some of the user experience requirements [33]. However, even though haptic interfaces, such as in art-related applications, are proven to improve users' performance and expand their creative process, users may reject a haptic drawing application, for example, if the features it provides does not meet or support their requirements and do not offer significant advantages over drawing in the real world [34].

Overall, there is relatively little research on users' experience of haptic interactions, giving designers little information on users' perception of haptic feedback in design. Most existing systems use abstract representations of real world objects and any haptic representation tries to mimic real world sensation in approximation and not via solid psychophysical and psychological methods [33].

3. Experimental Procedure

3.1 Introduction

In this section I will be describing the experiments I designed to elicit information regarding how touch is perceived and what parameters and attributes affect this sense during object exploration and recognition. Information obtained from these experiments is then considered and any relationships between them analysed and discussed.

Three experiments were designed to test primarily two hypotheses and investigate people haptic perception when exploring an object through a probe. These experiments are referred to as being parts of one experiment since they were all done using the same group of participants in one session. The first experiment (or Part 1) was designed as a training session for the force feedback device used in a later part of the experiment. During this training session the hypothesis stating that participants would describe an unknown texture using fruit similes was tested. While investigating this hypothesis, a link between vision and touch was thought to exist leading me to believe that an intermodal relation existed as Warren and Rossano proposed [17].

The second part was designed to test the recognisability of five objects when relying solely on the sense of indirect touch (through a probe-like tool). People manually perceive and manipulate the world around them both directly (with their bare hands) and indirectly (with a probe or a tool object). When the haptic exploration has no constrains, a vast number of different information inputs is available, describing the surface and textures the skin is in contact with. In this part of the experiment, I was testing the perceptual recognisability of object when haptic exploration is limited to being only through a probe (indirect), while all other senses were masked. The results from this part helped me to identify which of the objects considered were the most recognizable by the set of people participating in the experiment and which are not so recognizable and could be regarded as abstract to them. These results also helped in my conclusions for the third part of the experiment and the overall conclusions giving the bigger picture when all three parts of the experiment are considered together.

The third, and final part was designed to collect quantitative data used for describing each of the five objects by haptically replicating them using a force feedback device. With these descriptions, the values for each of three of the main haptic attributes (stiffness, static and dynamic friction), used for describing physical objects were obtained. Considering these results, a better picture can be drawn as to what people consider haptically important on an object, and secondly how they perceive an object when they have to describe it using their sense of touch instead of describing it verbally. This kind of research can, in a longer term, lead us to be able to break away from what Sulaiman et al. [33] describe as being the current practice of most existing system that use abstract representations for replicating real world objects in the virtual haptic world, and start building haptic objects that closely resemble the way we perceive them.

All steps and the experimental design and procedures are described in the sections below.

3.2 Equipment Used

3.2.1 Force Feedback device

For the purpose of this experiment a force feedback device was used. When operating this device, the sense of kinaesthesia is crucial since the user has to have a clear perception on where exactly their hand is in relation to their body, and how their movement relate to the output they see on a computer screen.

A force feedback device (or Haptic device) is in its design very similar to a robot arm. They are both typically made up of motors actuating the robotic arm's joints to either control its position, or the force at the end of a kinematic chain. A kinematic chain is defined as being a chain of interconnected rigid bodies, or links, controlled by motors at their joints. The main difference between a force feedback device and a robot arm lies solely on their use; where a robot arm is designed to manage manipulative tasks that have a specific end effect, and a force feedback device is designed for transferring forces to the user at its end effectors (last part of the kinematic chain). This gives its user the ability to perceive forces coming from the interaction with a remote location or with the virtual world [16].

With the increased commercial availability of such devices, the relative price drop of hardware and the increasing interest of research in more sophisticated virtual reality environments, such devices gained attraction to the computer graphics community and haptics researchers.

The force feedback device chosen for the purpose of this study was a PHANToM OMNI by SensAble™[2]. This is a haptic device, which makes it possible for users to touch and manipulate virtual objects. It has six degrees of freedom with positional sensing and uses an array of piezoelectric motor sensors attached on a mechanical, robotic arm to replicate haptic properties of virtual objects in the real world.

Figure 2 PHANToM OMNI Force feedback device by SensAble™

The OMNI works in a virtual environment which when translated in "real world values" measures in approximately 160 W x 120 H x 70 D mm [35]. This makes it very compact and capable in working in space-limited environments such as a lab workbench.

The device can also replicate a pulling force[3] of approximately 3.3N and pushing force of 1.26 N/mm in the X-axis, 2.31N/mm in the Y-axis and 1.02N/mm in the Z-axis. These forces are more than enough for the purpose of my experiments.

In the code and throughout this thesis, these forces as treated as percentage of the efficiency output of the OMNI device, with values ranging between 0.0 and 1.0 (0% and 100%). The reason for this is the way the PHANToM OMNI works. Piezoelectric motor sensors are affected by the room temperature and also by their internal temperature changes during use. Temperature changes can affect the way a motor works in the sense that when the temperature is high, more energy is needed to

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[2] http://www.sensable.com/haptic-phantom-omni.htm

[3] Forces measured in Newtons (N)

produce the same end effect as with a cooler motor. Therefore, instructing the force feedback device to apply a force in Newton's (N) may not be always accurate as some energy is lost through heat. In order to compensate for this potential differences, since I was investigating how users interpret feel using values obtained from this device, and to keep readings constant, I used the efficiency output values at the time the readings were taken. The OMNI is capable of monitoring these changes, therefore using a formula which takes into consideration the temperature difference (room temperature and motor temperature) and the force I was instructing the device to apply, I could ask the device to change the efficiency output and apply a constant force regardless of temperature changes.

The device is connected to a computer via an IEEE-1394 FireWire® port: 6-pin to 6-pin and the interface used was written in C++ using SensAble's own API.

The graphics used for building the virtual environment were made using standard OpenGL.

3.2.2 Computer setup

The machine used was a computer system with an Intel® Pentium® 4 Core 2 Duo processor at 3.00 GHz and 4GB of RAM. It also had a Radeon™ graphics card, capable for supporting two screens. The use of two screens was essential to parts of the experiment where the facilitator had to monitor values, which the participants should not see.

3.2.3 Software used

The lab machine used was running a 64bit version of Microsoft Windows 7 operating system and the code used for controlling the PHANToM OMNI was written and compiled in Microsoft's Visual Studio 2010 with the OpenHaptics (Academic Edition) software development toolkit integrated into it. This code can be found in Appendix 3.

3.3 Materials Used

3.3.1 Objects

The objects used were: (i) a Navel orange, (ii) a Braeburn apple, (iii) a Clementine mandarin, (iv) a Hass avocado and (v) a billiards cue ball (see Figure 3). These objects were used for their uniform and individually unique surface texture and stiffness. Also, all objects chosen have a round shape, keeping this variable constant (or as constant as possible) making it easier to pinpoint the cause of any interesting finds in the result analysis stage. An orange, for example, has a rougher surface than an apple but it is smoother than an avocado. On the other hand, a cue ball has the smoothest surface of all but it is very stiff. The mandarin was chosen because of the similar texture and stiffness of that of an orange. Aim of choosing the mandarin is to see if the size of the object also helps in its recognisability.

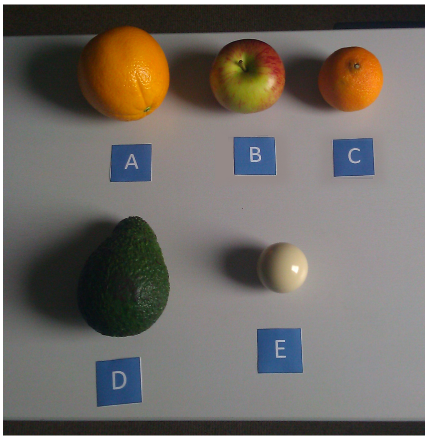


Figure 3 Objects Used

The billiards cue ball is of standard 1 and 7/8 inches of diameter (English Pool) and it is made out of hard plastic.

The rest of the objects, which are all fruits, where bought fresh every three days from Marks & Spencer Food. Fresh fruit was obtained in regular intervals in order to keep the texture across all object sets relatively constant since texture and stiffness tent to change in fruits as they mature. A spare set of fruits was bough for replacing fruits damaged during the experiments (e.g. participants poking through a fruit skin).

The room and all fruits were also directly sprayed with the same air freshener in regular intervals to eliminate any odours that may give clues to the participants as to what the object is. "Dettol's neutral air" air freshener was used with "fresh morning dew" scent.

In addition, a base made out blue tack was made to hold the object on the table.

3.3.2 List of apparatus

The probe used is an ergonomic STABILO pen (see Figure 4.a).

The blindfold used for covering the participants' eyes during the second part of the experiment where they were asked to recognise the objects through indirect touch was a simple sleep mask with adjustable strap on the back (see Figure 4.b).

The camera used for recording the second part of the experiment was a Logitech HD Pro Webcam C920 (see Figure 4.c). Logitec's own recording software was used for all recordings at a 720p HD resolution.

3.4 Implementing the haptic Interface

3.4.1 Graphical Interface

There are two main components of the graphical interface in the system, namely: the sphere and the PHANToM cursor (see Figure 5).

3.4.2 The Sphere

The implementation of the sphere involved creating a visual and a haptic sphere. Both spheres had the same radius size and surface contour density and were both drawn exactly on top of each other.

The rendered sphere was a perfect sphere (completely symmetrical around its centre) and was created with abstract haptic properties. To define these properties,

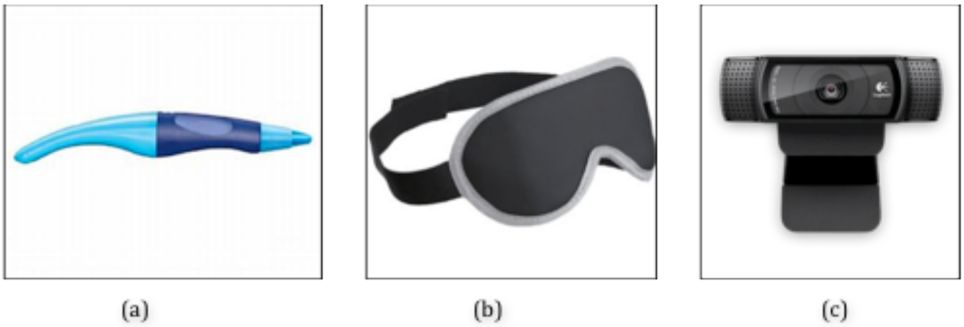

(a) (b) (c)

Figure 4 (a) Probe used (b) Blindfold (c) Logitech HD Pro webcam

a Java program was written that produced three random numbers ranging from 0.1 to 0.9 (10% to 90% efficiency). This program was run once and the values produced were used throughout the experiment. These values were 0.8 for its stiffness, 0.1 for its static friction and 0.4 for its dynamic friction. The absolute minimum and maximum values (0.0 and 1.0) were not included because after a few minutes of use they would sometimes cause the OMNI to misbehave, giving unreliable data.

The “dumping” value remained constant throughout the experiment to a small value (0.1) because I wanted to concentrate more on the effects and correlations stiffness, static and dynamic friction have on the way humans understand the feeling of touch.

3.4.3 PHANToM Cursor

Another sphere was created to function as the cursor. The x, y and z coordinates of the PHANToM were attached to this sphere and moved accordingly to the PHANToM’s movements.

A spherical shape was chosen for the cursor to (a) simulate the round shape of the physical probe that was used and (b) to stress the fact that exploration can occur in all degrees of freedom on the object, meaning that unlike the real world, in the virtual environment, only the tip of the exploring probe is of importance while the rest can go through the object without affecting the interaction.

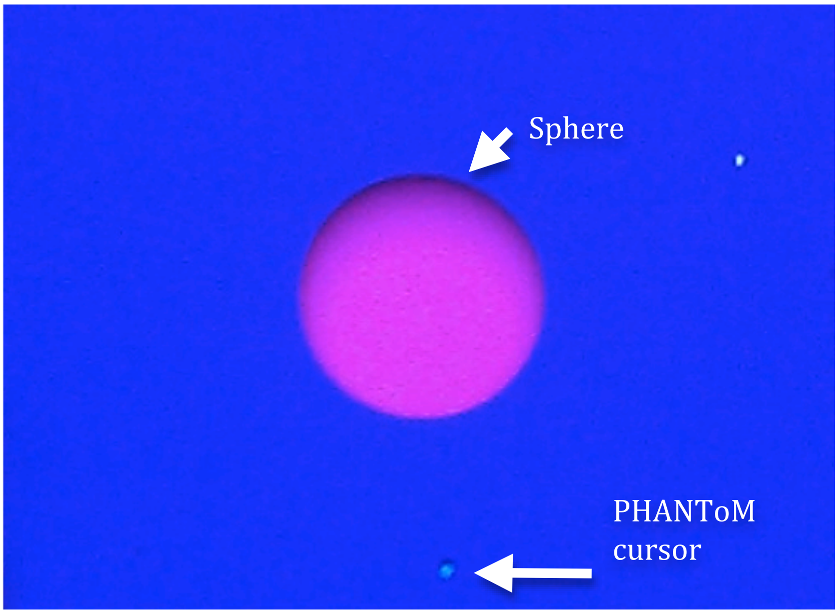
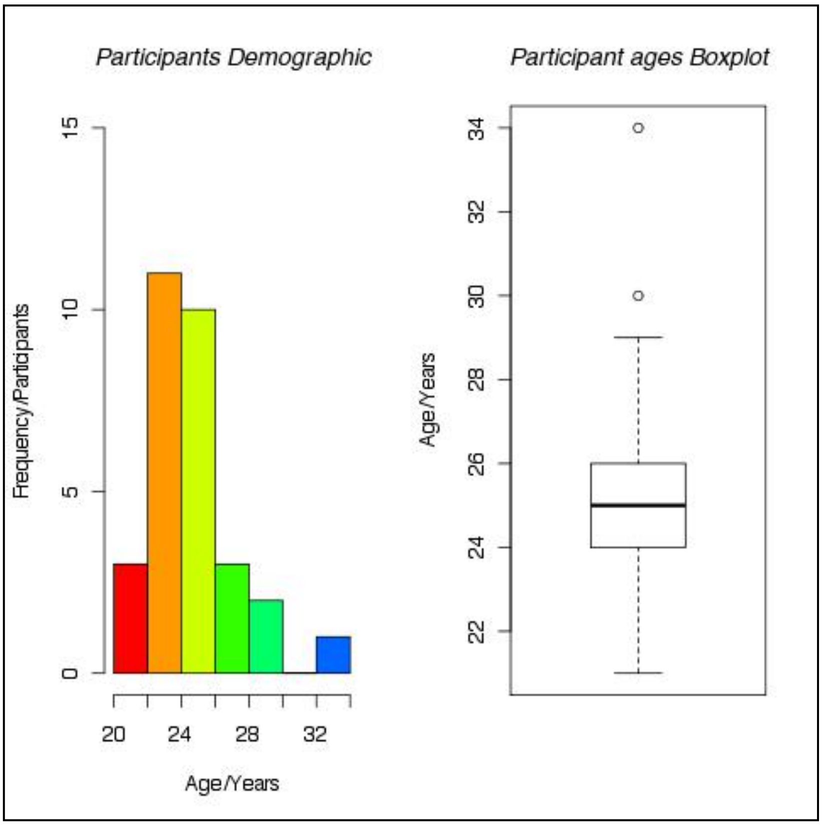


Figure 5 PHANToM visual environment

3.5 Demographics

The same group of participants was asked to complete all three experiments as described in the sections below. In total, thirty participants took part in these experiments; fifteen of which were males and fifteen females. Their age ranged from 21 to 34 and they all were postgraduate students in the University of York.



Min.: 21.00
1st Qu.: 24.00
Median: 25.00
Mean: 25.23
3rd Qu.: 26.00
Max. : 34.00

Figure 6 Participant Demographics

The majority of the participants were within the 24 to 26-age range. 17 out of 30 were Computer Science students, 4 Psychology students and 2 students in the Electronics department. The other 7 were students in art faculties, such as Politics and Education. Their results did not vary therefore they were all treated as one group.

Twenty-eight participants were right handed and only two left-handed. Changes were made in the experiment setup to accommodate left-handed participants since the experiment was primarily designed with right-handed people in mind.

In addition, 8 participants were given a small demo a few weeks before the experiments began with the OMNI. These were all students working with me in the lab and were curious on what the OMNI was. The demo had nothing to do with the later experiments contacted so having a first encounter with the device did not affect the results in any way.

4. Experiment Part 1 – Training

4.1 Aim

Aim of this experiment was primarily to train the participants on the use of the force feedback device and help them familiarise themselves on navigating a cursor in a three dimensional environment. As a training exercise I gave the participants a task to feel and try and recognise, using solely their sense of touch, a virtual object rendered using computer graphics. This gave me another aim, which was to test an anecdotal piece of information that states that people tend to describe unknown textures using fruit similes. This anecdotal information comes from linguistics where metaphors with fruit similes are used to describe feelings, life situations or describe real life objects (e.g. "*She has skin like a peach*").

4.2 Methodology

During this training session the participants were asked to use the OMNI to feel a spherical virtual object. The user was able to see the object rendered on a screen in front of them. This made it easier for users to find their way around the virtual space the OMNI operates. Also, shape plays no role in this experiment, therefore being able to see an object visually did not affect the output of this experiment. The object was rendered as a pink sphere floating in front of a blue background (see Figure 7). As mentioned in the section 3.4, the haptic properties used for this sphere were completely random, generated using numbers given by Java's random() function (see Appendix 3).

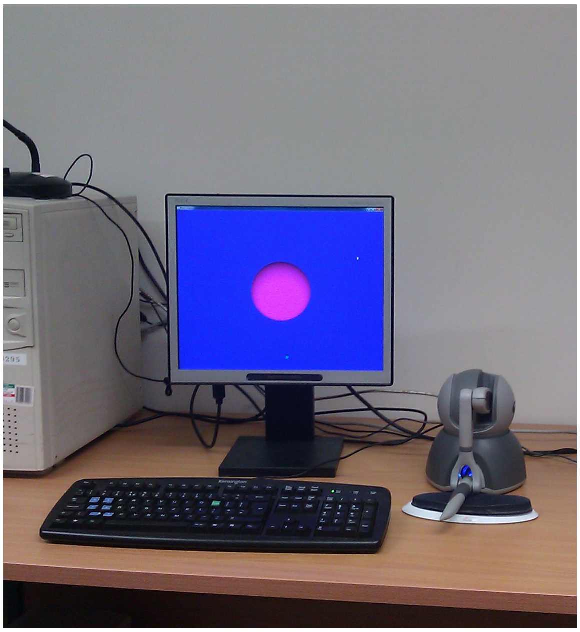


Figure 7 OpenGL rendered sphere

During this training session the participants were asked to try and describe what the sphere felt like. By asking them to perform a task gave a meaning to the training and helped them familiarise themselves better with the device as a mean of interaction with the virtual world.

Participants were also informed that they had no time restrictions and could take as much time as they needed to explore and try to recognise the object.

The qualitative data collected (object descriptions) helped in investigating the stated hypothesis that abstract and unknown textures are described using fruit or vegetable similes.

Participants were asked to keep their description short and if possible make a simile with a known object.

All environmental conditions in the experiment area were maintained at a constant status. The window blinds were always drawn down and air freshener was sprayed before the start of every experimental session.

4.2 Results

Answers given by the participants while feeling the virtual sphere where noted down on the experiment data sheet (see Appendix 1.). The table of the participant's descriptions on as to what they thought the virtual sphere was can be seen below (Figure 8 and Table 1).

All data in their raw format can be found in Appendix 2.

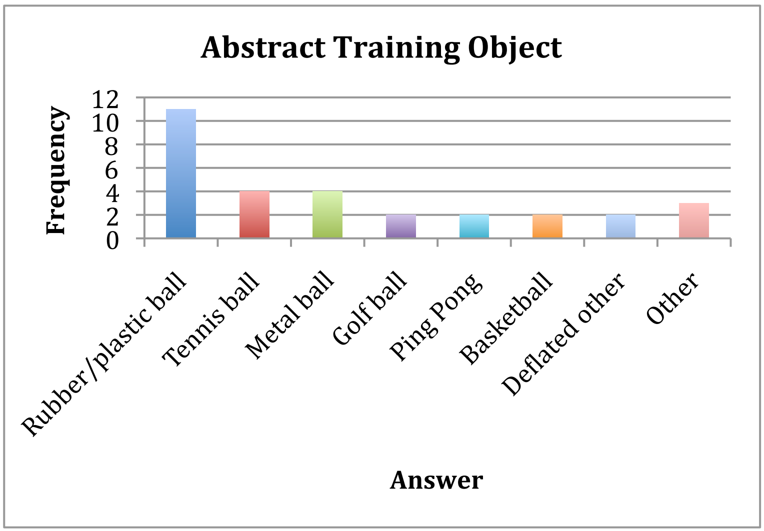


Figure 8 Bar Chart of participants responses textural feel of an abstract object

Abstract/Training

Answer	**Freq.**
Rubber/plastic ball	11
Tennis ball	4
Metal ball	4
Golf ball	2
Ping pong	2
Basketball	2
Deflated other	2
Other	3

Table 1 Table of responses (abstract virtual object)

By plotting these data on a table, it is immediately obvious that the most "popular" description of the virtual object was a rubber or plastic ball (11/30 or 36.67%). All other descriptions were of round or spherical objects.

An interesting phenomenon I observed was that 12 participants chose to close their eyes or look away from the screen while exploring this virtual object. When I asked them why they did that all of them said because it helped them concentrate on the feeling of touch (by blocking out their sense of vision). This goes against what Heller [20] mentioned, that people could judge more accurately the surface's texture when both senses (vision and touch) are available rather than one alone. These participants, by closing their eyes or looking away, they were masking their sense of vision and concentrating on their sense of touch. Out of these participants, only two though the virtual sphere resembled a rubber sphere, while the most popular answer when they masked their sense of vision was that of a tennis ball.

4.3 Discussion

The results showed that most of this experiment's participants thought the virtual sphere haptically represented a "Rubber or Plastic ball" (11/30 or 36.67%). As mentioned in the methodology, the virtual object haptic properties where decided via a random number generator, therefore there is no way of knowing at this point if the sphere actually represented haptically a rubber or plastic ball.

It is also interesting to note that almost all of the participants described what they were feeling as a round or spherical object. Almost all answers were describing a ball or another spherical object. More specifically, only one participant out of thirty, described the object as a non-round object (wooden table).

This shows that, even though I stressed in the beginning of the experiment that they should not try to associate the shape or colour with the description of the object, almost everyone did. This can also be observed if we consider the range of different kinds of balls the participants described the virtual sphere to haptically represent. Some of them have a completely different feel both when considering their surface friction (e.g. tennis ball versus a Ping Pong ball) or their stiffness (e.g. metal ball versus a deflated ball).

Another interesting finding I can take out of this data is the possibility that the colour of the virtual sphere misguided the participants into thinking the ball was a rubber or plastic ball, even though they were instructed not to consider the colour they were seeing. Vision is a dominant sense [17] so, even though they did not think about it, maybe subconsciously the colour of the sphere (being pink) had played an important role in their description. This hypothesis is further strengthened by the fact that only 2 out of the 12 participants that chose to close their eyes or look away while exploring this sphere described it as being made out of rubber.


Figure 9 Experiment carried out in the festival

To investigate further this new hypothesis, I took the opportunity and set a casual experiment in a festival organised by the University of York (Figure 9). This festival was organised for the community of York at The Ron Cooke Hub, on the Heslington East campus, and was open for everyone. My experiment was mostly based on the idea of having a big number of people coming and using the OMNI device and trying to guess what the object they were feeling was or what material they thought it was made of/felt like.

The virtual object's attributes for stiffness, static and dynamic frictions were kept the same as with the experiment explained above. The only difference was that at regular intervals I would change the sphere's colour. This helped me to investigate if the colour played any important role in people's answers and if there was multimodality involved in their answers.

After getting answers from 72 people, the results were extremely similar as the initial results from my first set of participants. Regardless of the sphere's colour, the most popular description was again rubber. More specifically, 10 out of 23 presented with a pink sphere, 10 out of 26 presented with a green sphere and 6 out of 23 presented with an orange sphere described it as being something made out of rubber. This gives a total number of 36 out of 72 (or 50%) describing what they felt the sphere was as “something made out of rubber”, across all colours. The rest of the answer’s frequency given for each colour had a very big difference from rubber, which as I said was the most popular one. Only one out of 72 thought the sphere felt like an orange, so again, the initial hypothesis stating that unknown textures are characterised with fruit similes can be rejected.

From these results we can clearly see that the results for the pink sphere are very similar as the results obtained from the other experiment (see Table 1). The same can be said for the results given when a green sphere was displayed. An interesting remark one of the participants made after exploring the green sphere was that she thought it was a “tennis ball because it is [was] green”.

The orange sphere, on the other hand, even though, it had identical haptic properties as the other two spheres, it produced answers describing much smoother objects. The second and third most popular answers when an orange sphere was displayed, were steel and glass spheres. Unfortunately, the participants could not tell why these answers came to their mind and the experiment being in a more casual, festival setting, discussion was not always possible. It would be interesting though to repeat this experiment within proper experimental conditions and see what results it produces. Table 2 contains all the data gathered from this experiment for all three colour conditions.

Answers	Pink Sphere	Green Sphere	Orange Sphere
Rubber	10	10	6
Plastic	2	2	2
Tennis ball	2	4	2
Sponge	1	2	0
Steel	0	1	5
Glass ball	0	0	2
Beach ball	1	0	0
Clay	1	0	0
Orange	1	0	0
Polystyrene ball	1	0	0
Air bubble	1	0	0
Stress ball	1	1	1
Wood	1	0	0
Balloon	0	1	0
Basketball	0	1	0
Golf ball	0	1	1
Oasis	0	1	0
Ping pong ball	0	1	0
Stone ball	1	1	0
Brick	0	0	1
Cobblestone	0	0	1
Foam	0	0	1
Lollipop top	0	0	1

Table 2 Varying colour of the sphere experiment results

In conclusion, with the data gathered, even though I can now safely reject the initial hypothesis that people tend to characterise unknown textures and surfaces using fruit similes, a new hypothesis arises; do people tend to characterise unknown textures and surfaces as being made out of plastic or rubber? This is an interesting question since objects made out of plastic and rubber can have any shape or form and can describe haptically almost every man-made texture, so there could be a new haptic adaptation evolving in human perception. A new experiment needs to be designed in the future to investigate this new hypothesis.

5. Experiment Part 2 – Real object recognition

5.1 Aim

Aim of this experiment was to test the recognisability of the five chosen objects (see "3.3.1 Objects" section) through indirect touch. Recognisability is measured by taking the percentage of participants that can successfully recognise an object when feeling an object solely through their sense of touch when exploring it via a probe. Statistics are also taken for other possible answers the participants give as to what they thought the objects feel like. This will help to gain a better understanding on how the feeling of touch helps in recognising objects in the absence of other sensuous cues.

5.2 Methodology

The next part of this experiment asked the users to feel five objects, one at the time, through a probe while blindfolded and try to guess what the objects are. The objects used were: (i) a Navel orange, (ii) a Braeburn apple, (iii) a Clementine mandarin, (iv) a Hass avocado and (v) a billiards cue ball (see Figure 3). All objects remained out of the participants' sight and participants were asked to put their blindfold on before this part of the experiment could start. The blindfold used was an ordinary sleep mask (see Figure 4.b), which is designed to block any light from the surrounding environment, ensuring the participants were not be able to see the object they were asked to recognise. Air freshener with a natural scent was used in the experiment room and on the objects to ensure the absence of any smells that may help the participant recognising an object and keep the room's ambient smell constant.

Figure 10 Camera Position

The objects were then placed on a mould made out of blue tack to ensure it would not roll around while being felt with a probe. All objects were placed on the mould facing to the same direction for all participants. The participant was then given the probe and asked to hold it like a pen and feel the object. The participant's hand was guided by the facilitator (me), to the object and left them explore the object. The exploration process was recorded using a digital web camera mounted directly above the object (Figure 10). The video recorded can help later on in analysing if there was a pattern on how participants choose to explore an object (EP) and, if there is one, compare it with any patterns during exploration of virtual objects in later experiments. Sound was also recorded for helping me understand the thought process of the participants and also how they derived to their answer. The camera angle used was shown to the participant before the blindfold was on to prove the anonymity of the recording.

The order the objects were presented to the participants was the same throughout the experiment. By keeping the order the same, even though some bias may be introduced, any interesting findings will be easier to see where they are coming from. A Java program I made was used to obtain the order used out of the 120 possible combinations (5!). As mentioned before this order remained the same throughout the experiment. After running this program the order obtained was: (i) Clementine mandarin, (ii) Hass avocado, (iii) Billiards cue ball, (iv) navel orange and (v) apple. A screenshot of the program's output can be found in Appendix 2.

Participants were then asked to name what they thought the object was. Each response was then recorded by the facilitator (me), before proceeding to the next object. In case the participant felt like they could not recognise an object, the response was recorded as NR (No Recognition) and the participant was asked to try and describe what they thought the material the object is made of. The participants were also instructed to take as much time as they needed to explore and recognise the object.

When participants felt all objects and an attempt was made to recognise each one of them, they could remove the blindfold and we could proceed to the next part of this experiment.

A short break was offered at this time for the participants to rest their eyes.

5.3 Results

All results were recorded on the experiment results form (see Appendix 1.) and later transferred in a Microsoft Excel worksheet.

In order to construct a more concise summary of these results, some answers had to be categorised. For example, answers such as "grass hockey ball" and "squash ball" were categorised as a "rubber ball". This meant that I ended up with a smaller number of categories, which I could analyse easier. These tables and bar charts of the summarised data are presented below. The full set of raw data can be found in Appendix 2.

5.3.1 Clementine Mandarin

The Clementine Mandarin was chosen to be the first object of the experiment. Even though no time was recorded, I noticed that it took the participants appreciably more time exploring the mandarin than with any of the other objects. This may be due to the fact that it was the first object and they needed some time to familiarise themselves with the procedure and with the new environment and conditions (being blindfolded and exploring an object with a probe).

Interestingly, most participants (11/30 or 36.67%) thought the mandarin was an orange. This may had been because of mandarin's relatively similar texture and shape to that of an orange. Another factor that may have influenced the results for this experiment may be that all of the participants were international students whose first spoken language was not English, therefore they may had been struggling to find the word "mandarin" whereas "orange" was much easier to come up with. Only three participants (10%) managed to describe it as a "mandarin".

Assuming the cultural and language barrier was a factor that affected the verbalisation of some of the participants' answer, we can group the categories of "orange" and "mandarin" together. This gives a high percentage of participants actually recognising the texture they had in front of them and comes close to the recognition percentage of an "Orange" (see below).

The second most popular answer was that of a rubber ball with 6/30 (or 20%) giving me that answer. All other answers ranged in the "soft ball" ranges while no other fruit similes were given.

Three participants (10%) could not recognise the object. These were marked with an NR (*No Recognition*) on the results form. Out of these three NR cases, one thought it was a fruit but could not recognise exactly what fruit it was while the other two thought it was a plastic and rubber ball respectively.

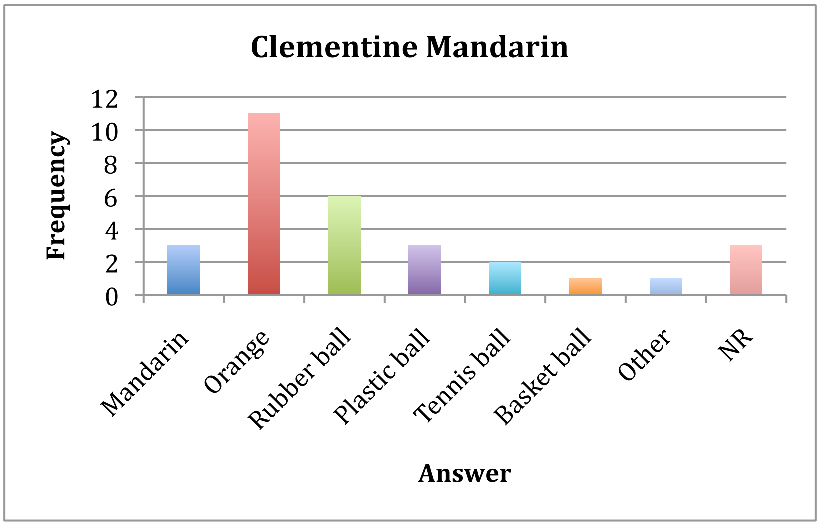


Figure 11 Responses to Clementine Mandarin

Clementine Mandarin

Answer	**Freq.**
Mandarin	3
Orange	11
Rubber ball	6
Plastic ball	3
Tennis ball	2
Basket ball	1
Other	1
NR	3

Table 3 Table of responses to Clementine Mandarin

5.3.2 Avocado

The recognition frequency of the avocado was the lowest of all the objects tested. Only 3/30 (or 10%) managed to recognise the avocado. Most of the participants that managed to make a guess as to what the object they were feeling was, described it as a basketball. We may attribute this description to avocados round surface and rough texture, which may resembles that of a basketball.

It is important to note that the biggest portion of the participants failed to recognise the avocado and to give a description as to what the object they were feeling might had been, marking it with an NR on the results form was 7/30 (or 23.33%). This is mostly due to the fact that after the experiment, when I showed the participant the avocado, 21 out of 30 said they had never seen an avocado before. Their only experience with the fruit was chopped up in salads or as a paste in guacamole. Considering this new information allowed me to treat the avocado as an abstract, for the participants, object and texture. With this in mind, and comparing the avocado to the virtual sphere of the first experiment, I was able to see a clear trend emerging where all descriptions are similar to each other in their frequency they appear and only one has a clear difference over the others (basketball for avocado). This may be linked to what mentioned earlier in the first part of the experiment, where abstract objects may be characterised as being made out of rubber when no other sensuous cues exist. A basketball is made out of rubber, has a rough surface and is relatively common in most cultures and both as an object and as a name.

The high NR frequency, when compared to the NR answer frequency of the abstract virtual object in the first part is more than double. The reason may be because in the virtual object, the participants were able to see something, even if it was on a screen (they had a virtual cue) whereas with the avocado, they could not.

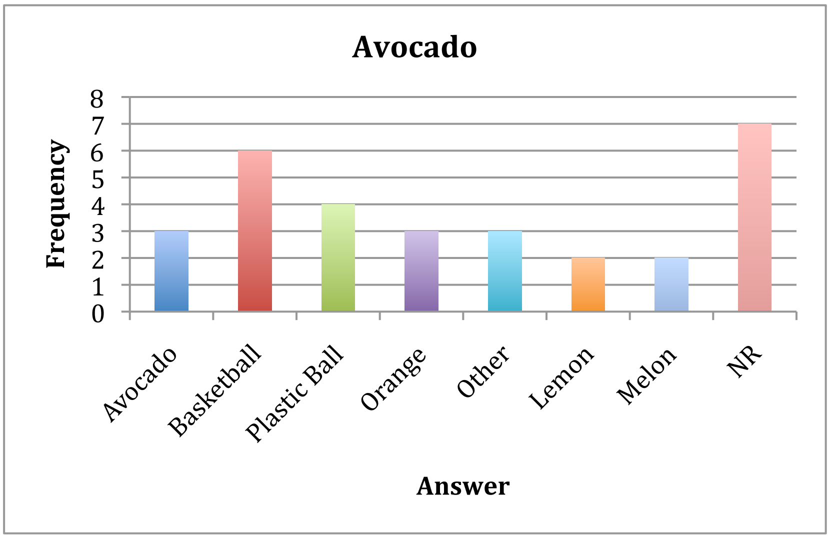


Figure 12 Responses to avocado

Avocado

Answer	Freq.
Avocado	3
Basketball	6
Plastic Ball	4
Orange	3
Melon	3
Lemon	2
Other	2
NR	7

Table 4 Table of responses to avocado

When an "NR" answer was given, I would ask what they thought the object is made out of, i.e. what material. Most of the answers I got from that question lead to a plastic or rubber texture (5/7). Only one thought it was leather and one could not answer.

5.3.3 Billiards Ball

Most of the participants recognised that what they where feeling was a solid smooth sphere. 8/30 recognised it was a billiard ball but another 13/30 described it to be a glass ball or a large marble (classified as a glass ball). For the purpose of this study, I can assume that a billiard ball, a glass sphere and a track ball are the same since they all exhibit similar or the same haptic properties. All three are perfect spheres with little surface friction and approximately of the same stiffness and weight. If we hold this assumption, these results show that 23/30 recognised or came extremely close in recognising this object bringing its recognition percentage to 76.67%; the highest of all the objects I was testing for.

Some participants said they had never seen a billiards ball or they have never touched one before or simply they did not know how to verbaly describe it in English. One of the participants commented that "he is more familiar to the american style pool (where balls are much larger is size) and did not know that british billiards is played with smaller balls", therefore, he thought it was a glass ball.

Another interesting finding is that all participants made an attempt to recognise the object and nobody gave NR as an answer.

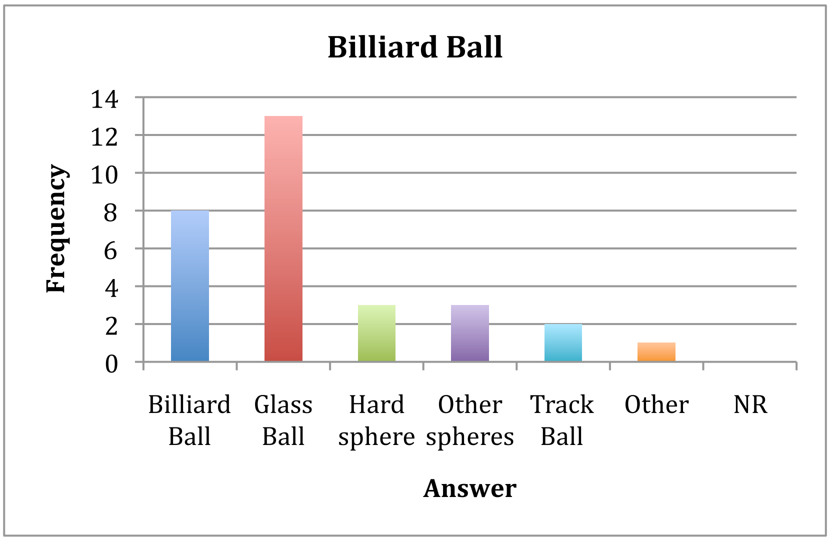


Figure 13 Responses to billiard ball

Billiard Ball

Answer	**Freq.**
Billiard Ball	8
Glass Ball	13
Hard sphere	3
Other spheres	3
Track Ball	2
Other	1
NR	0

Table 5 Table of responses to billiard ball

5.3.4 Orange

Orange was one of the most recognisable objects. 18/30 (or 60%) of the participants made managed to accurately recognise the orange when feeling it through a probe.

There is also a significant difference between the number of participants giving the answer of “orange” and all other categories. This shows that orange could be easily recognised, even though, according to some participants the object felt like a basketball or a lemon.

Three participants failed to recognise the object and gave an NR as their answer. These participants described what they were feeling as being something plastic or made out of rubber.

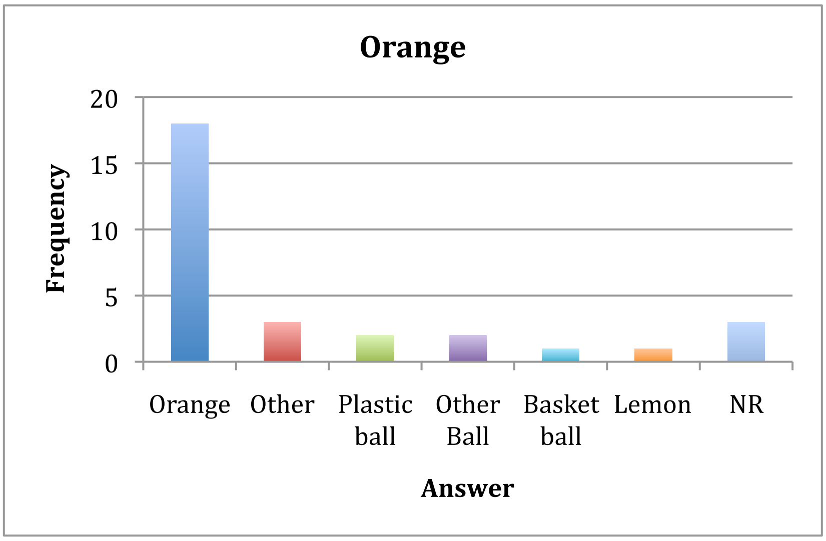


Figure 14 Responses to orange

Orange

Answer	Freq.
Orange	18
Other	3
Plastic ball	2
Other Ball	2
Basket ball	1
Lemon	1
NR	3

Table 6 Table of responses to orange

5.3.5 Apple

Apple had the biggest percentage of successful recognitions of all the objects used. More specifically 19 out of 30 (or 63.33%) of the participants, succeeded in recognising the apple. This high successful recognition percentage may be attributed in two factors. One is apple's unique shape and the other was the stalk, intentionally left on the apple (in all batches of apples used). Interestingly, participants who failed to identify the apple gave descriptions that matched in both soft and hard balls or spheres. This may indicate either that some participants failed to identify what they were feeling through a probe or shape was more important to them than the object's softness.

On the other hand, apple had a very high percentage of NR's. 6 out of 30 or 20% of the participants could not recognise the apple. Participants that failed to recognise the apple described it as a rubber or plastic object; but also as having a leather or even paper/cloth texture.

In general, apple had the highest percentage of successful recognitions but it also had the second highest percentage of NR's (after the avocado). This makes it hard to interpret since the object with the highest successful recognition percentage (apple) had almost identical percentage of failed recognitions as the least recognisable object (avocado) of this experiment.

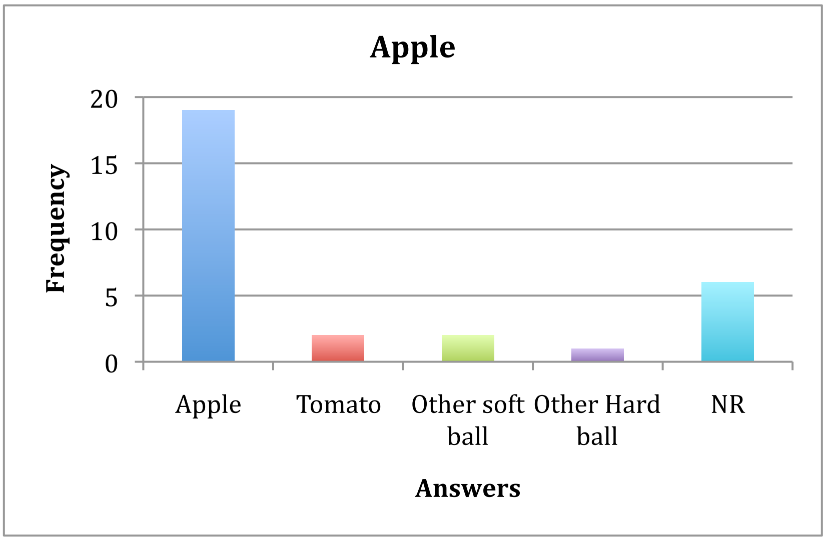


Figure 15 Responses to apple

Apple

Answer	**Freq.**
Apple	19
Tomato	2
Other soft ball	2
Other Hard ball	1
NR	6

Table 7 Table of responses to apple

5.4 Discussion

Data collected from this experiment were mostly qualitative. Descriptions given by the participants while they were blindfolded for each object when feeling it with a probe were analysed and compared among each other.

The frequency of successful recognitions for all objects was expected to be low. Lederman and Klatzky found that the accuracy is reduced by more than half when a probe is used to recognise an object versus bare fingers [30,28]. Even so, the orange and the apple showed a successful recognition percentage of 60% and 63.33% respectively. A factor that may have played an important role on apple's high successful recognisability rate may have been its stalk. I did not think of it when designing the experiment but after seeing the first participants noticing the stalk, I decided to keep the stalk on the apple for every fresh batch of apples. So all participants had the chance to find and feel the stalk. This helped a number of participants to identify the apple, and some even commented on it saying that they "knew it was an apple as soon as they felt it (the stalk)".

Despite these clues, the apple also had a very high percentage of NR (No Recognition) answers. More specifically, the apple had a very similar percentage of NR answers to that of the avocado, the least recognizable object. This may strengthen the theory that the stalk played an important role in the recognition of the apple. Participants that "found" the stalk and explored it, managed to find a connection to a fruit and an apple more easily than those that did not find the stalk while exploring the object with the probe.

An orange has a very distinct shape and texture therefore, there are no other external factors we can attribute this high recognisability rate. Also, the orange in the experiment came after the billiard ball so we can also safely assume there is no bias introduced from the object before (i.e. "the last was a fruit so this must be a fruit as well").

The orange can be compared visually with a Clementine mandarin. This seems to be the case haptically as well since the most frequent answer I got from the participants about the mandarin was that it was an orange. They both share similar shape and texture but are very different in size and how "squishy" they are. This softness or "squishiness" factor may attribute to the high percentage of the participants saying they thought the mandarin of being a rubber ball.

Another factor for mandarin being described as an orange may had existed due to the cultural and language differences of the participants. The word "orange" is more common in every day English and it is easier to remember for non-native English speakers. Also, one participant noted, after she saw the mandarin, that it was much bigger than the ones she was used to in seeing, in her country and that it looked "like a small orange".

The least recognizable object (lowest successful recognition percentage) was the avocado. As mentioned in the results section, 21 out of 30 participants had never seen or touched an avocado fruit before. This made the avocado an "unknown" or "abstract" texture for them in a similar way as what was happening in the first experiment with the abstract virtual sphere.

All answers given for the avocado had low frequency of occurrence, except those of a "basketball" and NR. This shows that, even though avocado was an unknown object for most of the participants, its rough surface made them think of objects that also had similar textures. It is interesting to also consider the material participants gave an NR answer thought the object they were feeling was made of; plastic or rubber, with the exception of one who thought it was leather. This also coincides with the answers given for the abstract object in experiment one. Therefore, a plastic or rubbery texture may be a general term people may use for describing unknown textures where there is no other cues from the rest of their senses; similar to the initial hypothesis in section 4, with the fruit similes. Also, rubber and plastic point to artificial or man-made objects, so it may be a general term used for describing anything that does not occur in nature.

The object that was the easiest to recognise was the billiard ball. A billiard ball is generally a very hard ball with a smooth surface. Even though all participants managed to recognise the shape and how smooth the ball was, not many managed to relate it to a billiards ball. One reason was, as one of the participants mentioned the size. Billiards ball is significantly smaller in size than the balls used in American style pool; therefore it was hard for him to make the association.

A very common answer on the other hand was that of a glass sphere or a large marble. This is essentially what a billiards ball is; therefore, after gathering all the data, I decided to classify the answers that described the billiard ball as a glass sphere, a large marble and a track ball (ball used in a pointing device) in the same category as that of a billiard ball. This gave the billiard ball a successful recognition rate of 76.67%; the highest of all the objects I was testing for.

Data collected from this experiment helped me in the analysis of data obtained in the third part of my experiment (see next section). Knowing which objects are the most recognizable and also seeing what the participants compared the objects with when they used only their sense of touch to explore gave me a better insigth on how objects are perceived and interpreted.

6. Experiment part 3 – Replicate Objects in the Virtual World

6.1 Aim

The aim of this experiment was to see how people use their sense of touch to feel an object with a probe and how they understand what they are feeling when they have to describe it. To do this a simple experiment was designed which asked thirty participants to feel a real object with a probe and then try and replicate its haptic properties (the way it felt) on a virtual object using the PHAToM OMNI device. This allowed for non-verbal descriptions to be obtained for the objects tested.

Analysing the data gathered from every participant for every object I was testing for helped me understand how objects were defined according to the participants' understanding.

6.2 Methodology

For this part, the PHANToM OMNI device was used. The reason for having the training session at the beginning (see section 4.) and not now was so that no bias would be introduced when asked to try and recognise the abstract virtual object. Bias could be introduced towards fruits (since most objects were fruits in part 2) and this is what we are investigating by collecting qualitative data from this training session. Therefore, the training was done at the very beginning to ensure better accuracy of our results.

The physical objects were given to the participants in the same order as during the previous part of this experiment. Order now had no significance since the participants were not blindfolded. They were presented with the OMNI device again and the same virtual sphere as in Part 1, on the monitor in front of them. The only difference was that all the haptic properties of the sphere were reset to 0.05.

Each of the five objects were then given to the participants by placing it on the blue tack mould (as in the step before) and asked to feel it again with the probe, this time with no blindfold. Then they were asked to feel the sphere with the OMNI and try to replicate the feeling of the real object to the virtual object. Participants were asked to perform all interactions with the physical (real) and the virtual object using their dominant hand (right if right-handed or left if left-handed).

The participants knew they could change three haptic attributes of the sphere but they did not know the labels of each attribute. They only knew they could change attribute "A", "B" and "C". I chose not to tell the participants what each attribute is in order to let the participants try and make the virtual object feel as close to the real object without thinking how they could replicate each one individually (e.g. avoid them trying to exactly replicate stiffness, for example, before going to the next one). These attributes were the objects Stiffness, Static and Dynamic friction. Dumping was kept constant at 0.1.

Figure 16 Keys used to change variables "A", "B" and "C"

Attributes could be changed using six marked keys (one to increase one to decrease each of the three attributes) on a keyboard in front of them (see Figure 16). The initial virtual object had a value of 0.05 (minimum) for all attributes. Participants could not see any change on their monitor while changing an attribute. The facilitator on the other hand could see all the numerical values of all attributes as they were changing on a second monitor, which was turned at an angle so that the participant could not see these readings (see Figure 17, Control screen). Attributes could be changed in 0.05 intervals, with 0.0 being the minimum value and 0.95 the maximum. The reason why 1.0 was not made the maximum was because 1.0 caused the motors inside the OMNI overheat faster and the device was starting to misbehave or causing the program to crash.

Once the participant felt confident that they replicated the object they were asked to press a seventh key on the keyboard marked as “finish”. This reset the object attributes back to 0.05 and displayed to the facilitator the values for each attribute the participant chose. These values were marked on a form (see Appendix 1.) by the facilitator.

After this step, the participants were asked what they thought “A”, “B” and “C” was, before being debriefed. Their answers were also noted down on their results form. During the debriefing session, everything that went on during the experiment was explained to them and any questions they had were answered.

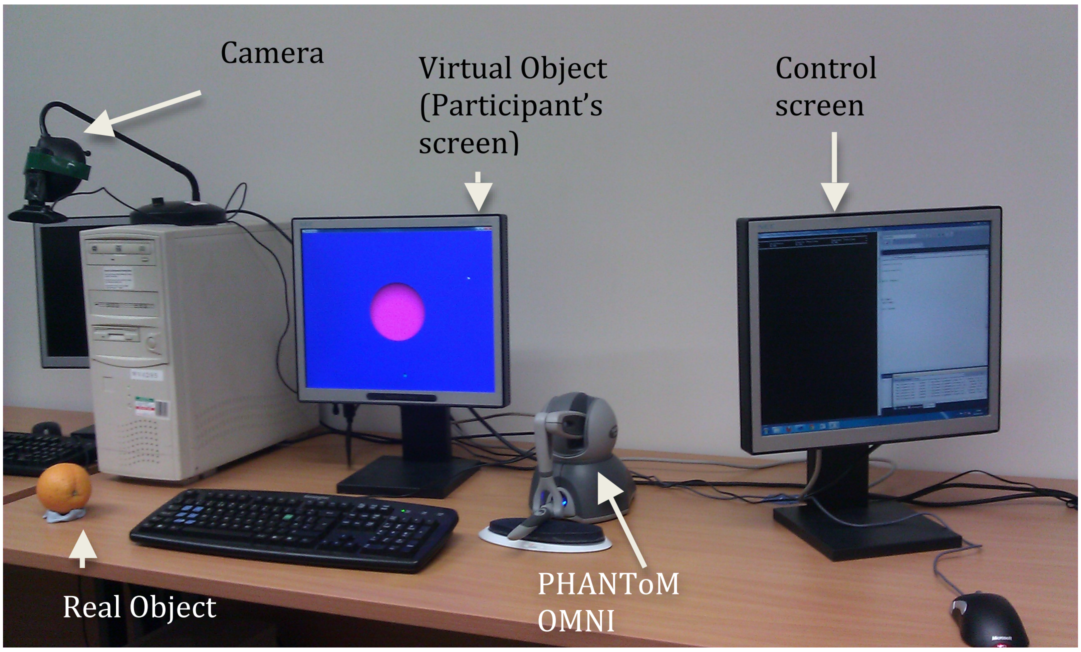


Figure 17 Experiment equipment setup

6.3 Results

The feeling of touch was explored in three possible ways. The feeling of abstract objects with a combination of characteristics that have no immediate connection to a real world object, the recognition of common physical objects via a probe when there was no other sensuous cue except from touch, and the replication of physical objects in the virtual world.

Replicating physical objects in the virtual world helped me investigate how people understand what they are feeling and describe it using their sense of touch by manipulating the objects stiffness, static and dynamic friction, instead of using a verbal description.

The results obtained from this experiment were analysed in four different ways. At first, they were analysed individually. Each attribute of every object was considered on its own. Then, a comparison was made between all possible combinations of the three attributes using ratio and correlation analyses. Finally, all three attributes were considered together and the relationships arising on how they interact and influence each other analysed was analysed.

6.3.1 Means

Prior to this experiment, I was expecting to get a set of values for every object. This would allow me to get mean averages from every attribute of each object (Stiffness, Static friction and Dynamic friction) and say that these are the values that characterise each object. If this was the case I then would be able to say, for example "mandarin is characterised by the values x, y and z" and these are the values we need to use to replicate a haptic orange in the virtual world.

The expectation was by the end of this experiment to be able to construct a table similar to Table 8.

Object	**Attribute**		
	Stiffness	**Static Friction**	**Dynamic Friction**
Orange	X_1	Y_1	Z_1
Apple	X_2	Y_2	Z_2
Billiard Ball	X_3	Y_3	Z_3
Avocado	X_4	Y_4	Z_4
Mandarin	X_5	Y_5	Z_5

Table 8 Expected results format

Instead, the results did not cluster in the way I expected. On the contrary, the data for every attribute of every object varied in a range so wide, no average value could be trusted to be representative. In Figure 18, we can see the mean values of all the attributes I was testing for, for every object, as obtained from the participants. The standard deviation is too large (shown as error bars on plot) to allow any useful statistical outcome. High standard deviation indicates that the data points are spread out over a large range of values making the mean values not being representative of the whole data sample.

In Figure 19 and Figure 20, a series of box plots were made showing the median values and the dispersion of values around it. These plots only come to confirm the initial conclusion that the values are spread into an extremely wide range, therefore, any average would be meaningless, and would not describe accurately the object.

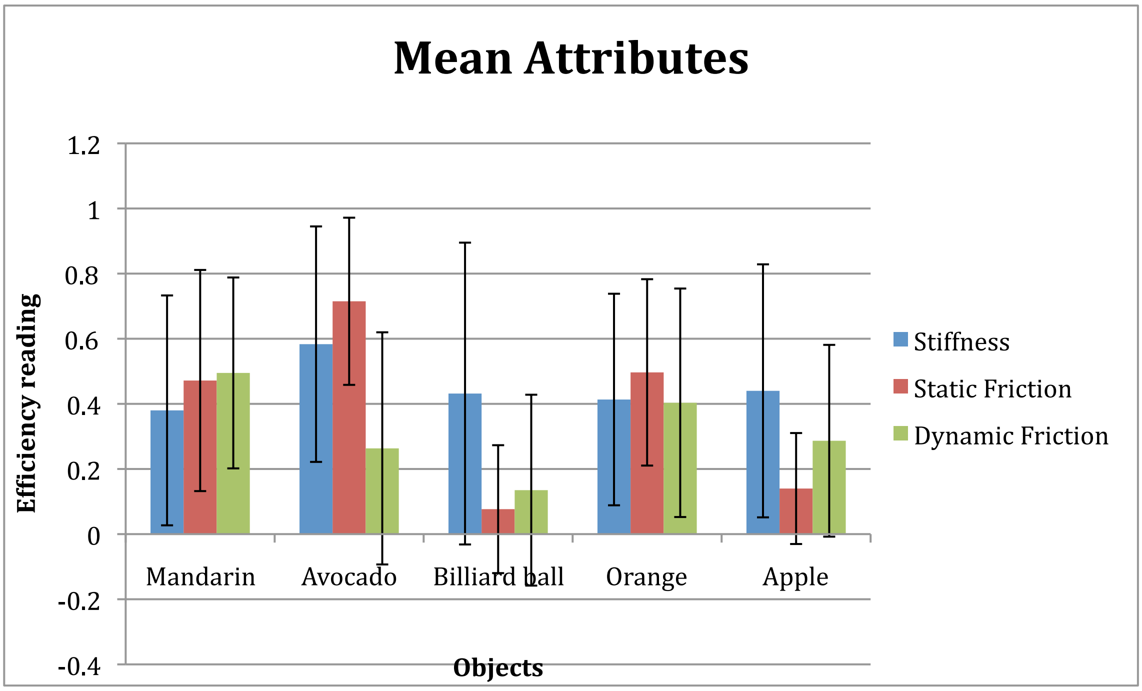


Figure 18 Mean average values of every object tested with standard error bars

Object	Stiffness mean (standard deviation)	Static Friction mean (standard deviation)	Dynamic Friction mean (standard deviation)
Mandarin	0.38 (±0.35)	0.47 (±0.34)	0.50 (±0.29)
Avocado	0.58 (±0.36)	0.72 (±0.26)	0.26 (±0.36)
Billiard Ball	0.43 (±0.46)	0.08 (±0.20)	0.14 (±0.29)
Orange	0.41 (±0.32)	0.50 (±0.29)	0.40 (±0.35)
Apple	0.44 (±0.39)	0.14 (±0.17)	0.29 (±0.29)

Table 9 Mean average values of every object with their standard deviation values

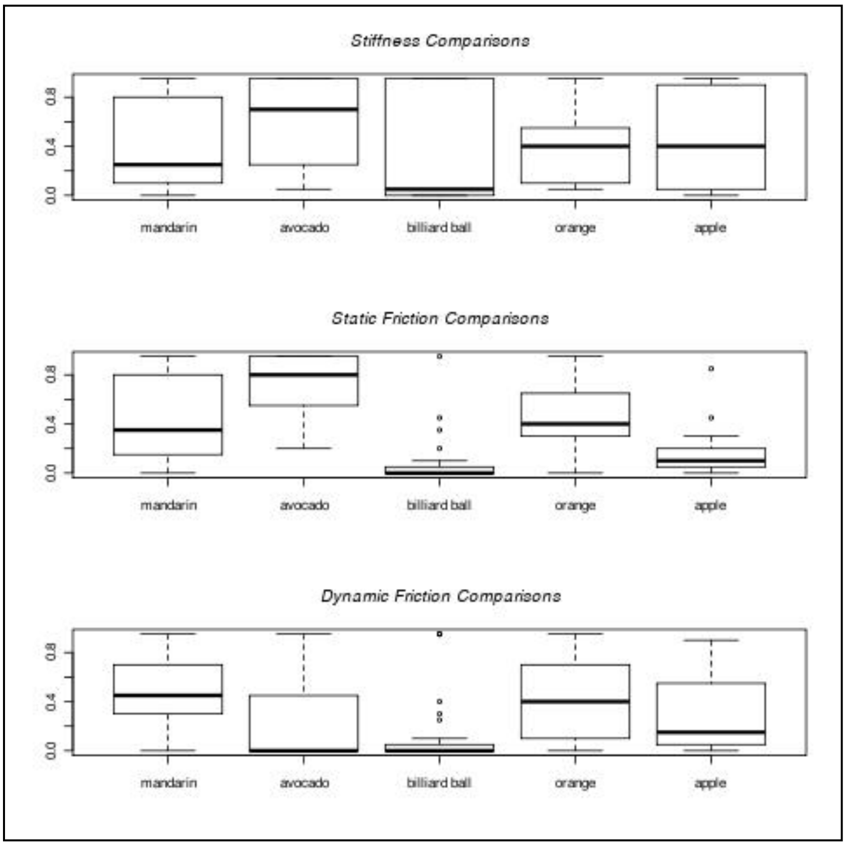


Figure 20 Box plot comparing the three attributes

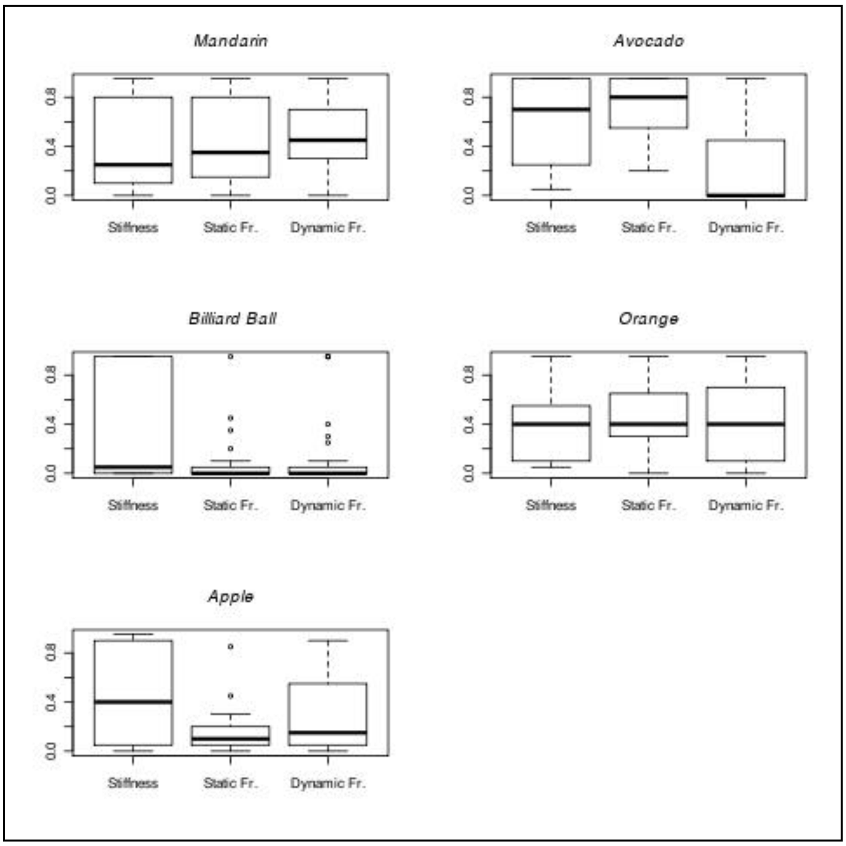


Figure 19 Box plot comparing the five objects

After seeing there was no definite set of values that could characterise the objects I was testing for, I tried to test for relationships between the values. During the experiment, I observed a pattern when the participants increased and decreased every haptic variable they could change. For some objects the higher they defined the stiffness, for example, to be the lower they would set the static or dynamic friction and vice versa. The same occurred between static and dynamic friction. This gave me an idea that I should test for relationships between the variables. Therefore, I chose the approach of taking ratios between my variables.

6.3.2 Ratios

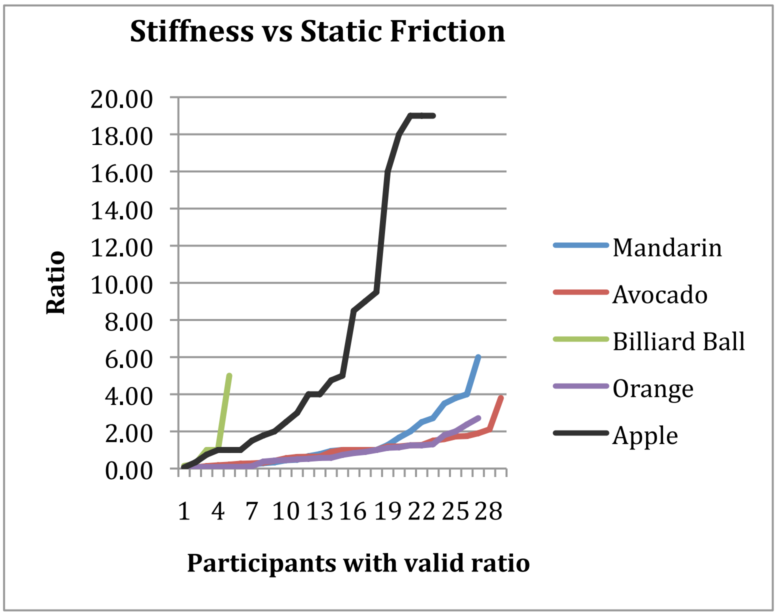


Figure 21 Stiffness vs Static friction ratio graph

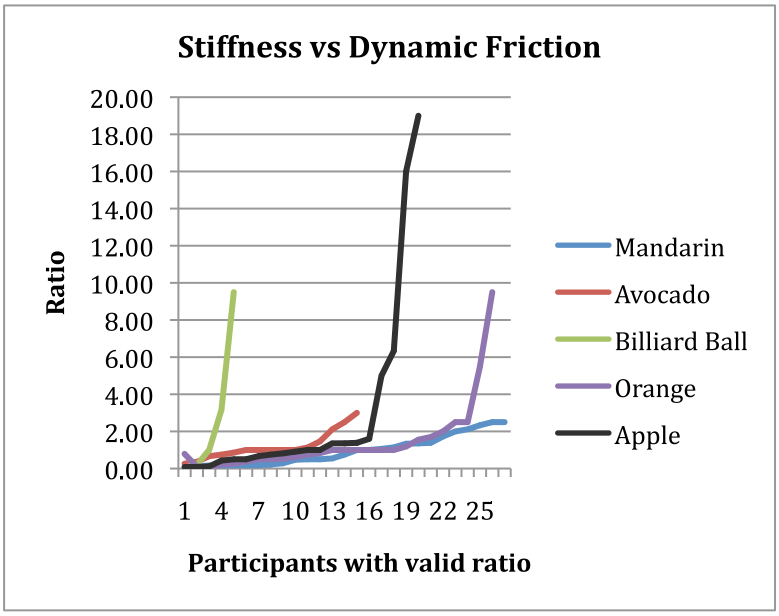


Figure 22 Stiffness vs Dynamic friction ratio graph

A ratio shows the relative sizes of two or more values. Ratios were taken for every object comparing Stiffness to Static Friction, Stiffness to Dynamic friction and Static to Dynamic friction. These results were then plotted in a series of line graphs for better visualisation.

Any participants whose ratio came to infinity (i.e. 0/X or X/0), was excluded from the analysis.

Ratios are calculated by dividing the first value I am testing for (e.g. Stiffness obtained from participant X of object Y, by the Static friction obtained from participant X for object Y).

After all ratios were calculated, and values approaching infinity removed, the ratios were sorted in ascending order (smallest first) for every object and a series of line graphs was produced (see Figure 21, Figure 22 and Figure

23).

In these graphs we can see that there is a pattern when considering the ratios between the variables. In all cases the mandarin seems to closely follow the orange pattern while the avocado follows these two very closely. The billiard ball and the apple on the other hand are grouped together. The apple and the billiard ball were expected to share some similar characteristics during the analyses since they both have similar surface friction attributes and stiffness.

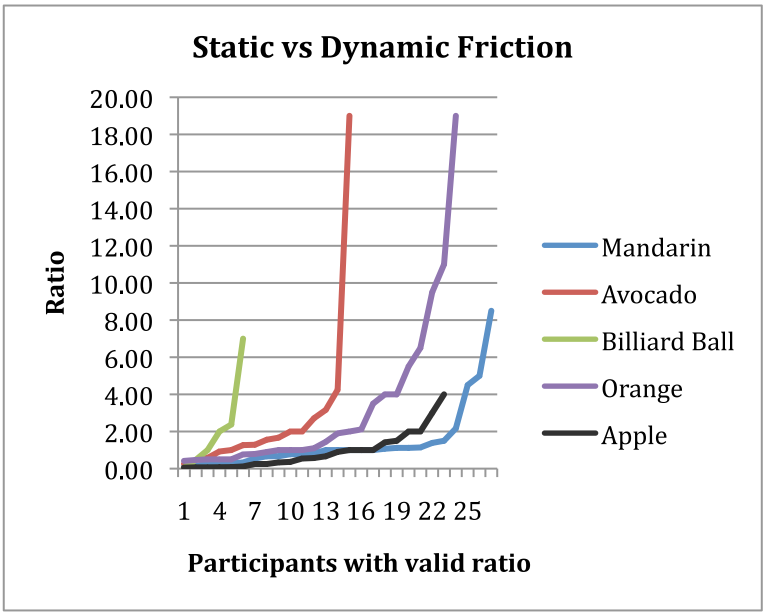


Figure 23 Static vs Dynamic friction ratio graph

In the Static vs. Dynamic friction ratio graph (Figure 23), all ratios show an exponential growth. This may indicate there is a close relationship between static and dynamic friction.

On the other hand, this being a study with live participants and personal feeling and interpretation of a sense, resolving where the noise lies on these data sets is impossible. The large number of ratio values that had to be removed because they were leading to infinity introduces this noise. In addition, the fact that only one ratio value was given by each participant for every pair of attributes, which was then sorted in ascending order, introduced even more statistical noise to the results. This on its own makes it impossible to predict if and were noise exist in the data during analysis. Also due to the small sample size no valid conclusions can be drawn from these graphs.

Therefore another solution had to be figured out to investigate if there were indeed some relationships between these data.

This solution would be a purely statistical analysis solution. What I did was to perform a statistical test on all variable combinations for each object and test for relationships between them using statistics. Relationships would be found by measuring the correlation between each variable combination.

6.3.3 Correlation study

There are a number of different statistical tests that can be performed to test for correlations between data sets. Since my data are not expected to follow any particular probability distribution and are therefore non-parametric, Spearman's rank correlation coefficient or Spearman's rho (ρ) was chosen as my statistical analysis test.

Spearman’s correlation coefficient, as mentioned previously, is a non- parametric statistic, and therefore, can be used on data that do not follow parametric assumptions such as normally distributed data. It works by ranking the data according to their value and then applying Pearson's equation to these ranks [36]. The numerical value of this correlation coefficient obtained from this test (ρ), can range between the values of -1 and +1. The number obtained, indicates how the values I was testing relate. If ρ was more than 0 it implied positive agreement. The closer this value was to 1, the stronger the correlation. The same was true for the opposite side; the closer it was to -1. On the other hand, the closer the number was to 0, the weaker the correlation was. A table of critical values exist that indicate what the critical values for every dataset size (degrees of freedom) are.

For this test a statistical package, SPSS[4], was used and the following values were obtained.

Object	**Stiffness vs. Static Friction**		**Stiffness vs. Dynamic Friction**		**Static vs. Dynamic Friction**	
	Correlation Coefficient	Significance	Correlation Coefficient	Significance	Correlation Coefficient	Significance
Orange	0.022	0.909	0.510	*<u>0.004</u>*	0.207	0.272
Apple	-0.167	0.378	0.031	0.869	0.315	0.090
Mandarin	0.063	0.743	0.314	0.092	0.433	*<u>0.017</u>*
Avocado	-0.012	0.949	-0.03	0.989	-0.115	0.546
Billiard Ball	-0.423	*<u>0.020</u>*	-0.357	0.053	0.455	*<u>0.012</u>*

Table 10 Spearman Rho values and their significant level

Correlation coefficients in the table above refer to the Spearman's rho value. The columns labelled as "Significance" indicate the significant interval this value falls into. Values with significance of less than 0.05 (or 5%) are regarded as being significant and indicate the existence of a relationship between the attributes that produce it.

From the values obtained, we can clearly see that there are significant correlations (marked by italics and underlining in the table) between just four of the pairs of variables of the five objects I was testing for. In order for these variables to be correlated to each other, their rho values should had been close or equal to +1 or -1. This would make a line or curve graph, showing that as one variable increases the

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[4] http://www-01.ibm.com/software/analytics/spss/products/statistics/

other one decreases (or vice versa) and the points would be laying either on or very close to it depending on how close they were in +1 or -1.

As this is not the case we can reject the hypothesis that these variables are correlated to each other for an acceptable number of objects.

These new piece of information, with the advice of Dr. Paul Cairns, senior lecturer at the University of York, lead me to a new analysis method, using three-dimensional scatter plots.

6.3.4 Three-dimensional Scatter Plots and Cluster Analysis

A scatter plot is a type of mathematical diagram that uses Cartesian coordinates to display the values of two variables for a set of data as points on a plot. With the use of a third dimension, a third variable can be added. A three-dimensional scatter plot is one possible way of analysing three variables and how they affect each other.

R, a script based programming language for statistical computing and graphics was used for producing a three-dimensional scatter plot for every object (scripts used can be found at see Appendix 3).

Mandarin

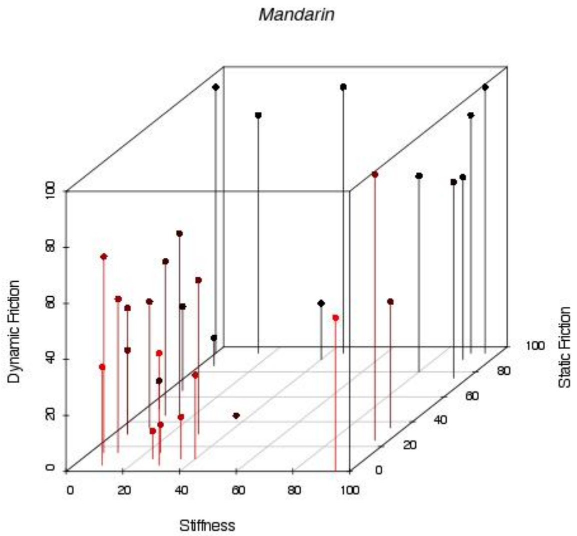

Figure 24 Three-dimensional scatter plot for the mandarin

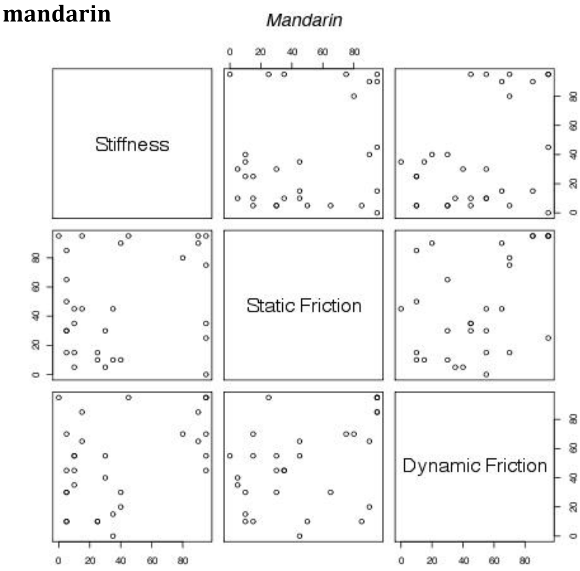

Figure 25 Matrix plot for the mandarin

The first three-dimensional scatter plot drawn was that containing the attributes of a mandarin. This plot (Figure 24) shows this scatter plot while the next figure (Figure 25) is the same three-dimensional cube opened up for better interpretation. Values ranging from 0 to 100 were used for these plots and are defining the same readings as with the analyses done before (efficiency output for every variable tested). The reason decimal values are not used is because of the way three-dimensional scatter plots are drawn in R.

From these plots we can more easily interpret the data when considering all three values at the same time. Areas where the points cluster (group) together can indicate areas of interest and show relationships that no other statistical analysis applied on the whole dataset can show.

In the plots for the mandarin (Figure 24 and Figure 25), we can observe a large cluster forming in the area between the low values of Stiffness and Static friction. This cluster forms in the middle values of dynamic friction. This may give an indication that for a mandarin, the most popular combination is somewhere between the lower values (<50) of Stiffness and static friction, when the dynamic friction is around its middle values.

Another interesting finding that comes out from this plot is the fact that there are no middle values for stiffness. All values for stiffness concentrate on the low to middle range and to the extreme high area. This gap in the values is not affected by either static or dynamic friction.

Overall, from this dataset, we can conclude that a mandarin can be defined by two different sets of values. One is the low to medium stiffness with low to medium static friction and medium dynamic friction, and the other one by high values in all three attributes.

Avocado

Avocado is an object of high static friction. There is a relatively large amount of participant values clustering in the corners defined by high static friction and low stiffness and dynamic friction. The rest of the participant data are scattered all over the three dimensional space. One reason for this inconsistency in participant responses may have been the fact that most of the participants had never seen an avocado before. They tried to replicate what they were feeling for the first time having no prior knowledge of the object. In general the pattern I can deduce from this data set and the clusters formed is that some participants (best clustering) felt the avocado as being of medium to high static friction, low to medium stiffness and low dynamic friction. Overall, the largest portion of the participants gave answers that allowed no pattern to rise from their data sets.

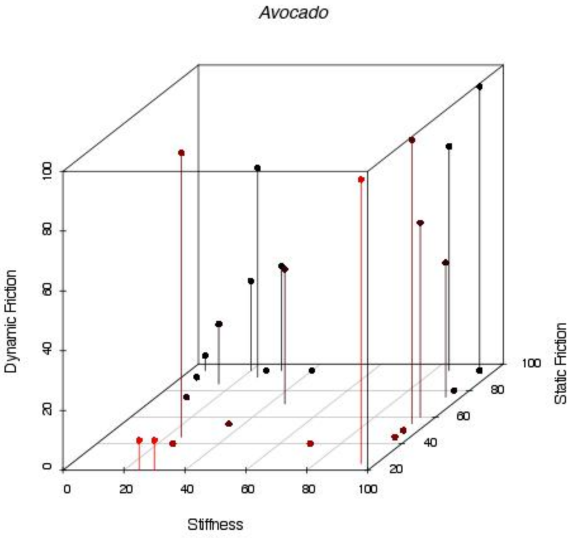

Figure 26 Three-dimensional scatter plot for the avocado

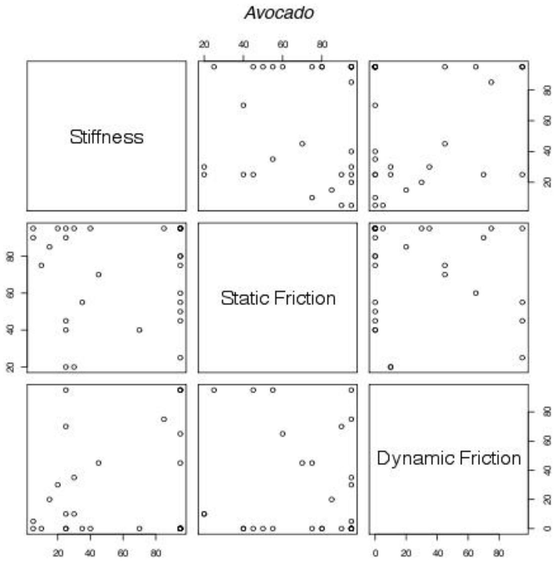

Figure 27 Matrix plot for the avocado

Billiards Ball

A billiards ball was probably the easiest object to analyse, but also gave some of the most interesting results. Even though the billiard ball is the object with the highest stiffness out of the five I was testing, most of my participants (17/30 or 56.67%) gave a very low value for stiffness.

The rest of the values given had both static and dynamic friction being at a very low level.

It is interesting to note that one participant gave high value for static friction also gave high dynamic friction value. This can mean that the two may be cancelling each other out. The same can be told by stiffness and static friction since at very low values of stiffness some participants would give values for the static friction as high as 40%.

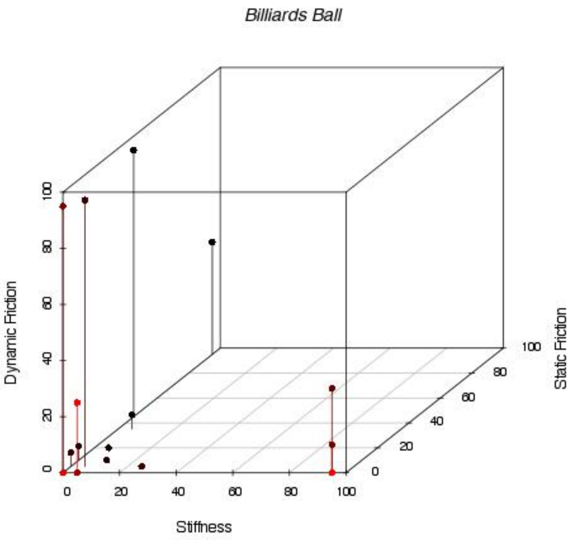

Figure 28 Three-dimensional scatter plot for the billiard ball

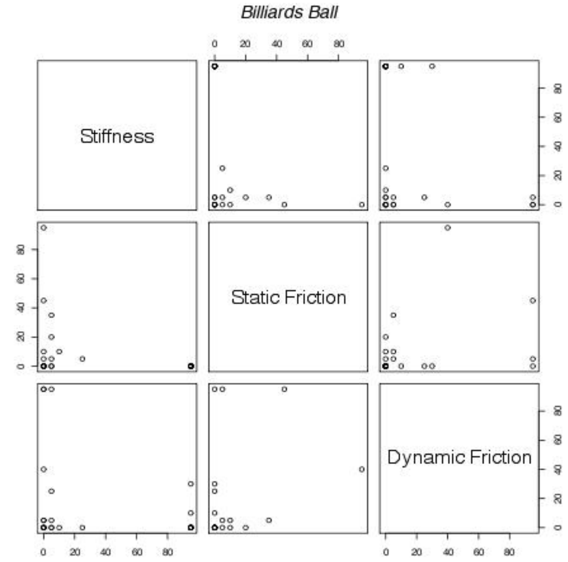

Figure 29 Matrix plot for the billiard ball

Orange

Data from the orange show a distinct split of the data, in a similar fashion as the data from the mandarin did. The difference with the mandarin is that in the case of the orange, the data seem to be clustered together much more cleanly, especially when only considering the stiffness-static friction plane. Again, there are no values in the diagonal of this plane, meaning the participants felt the orange as being either of low to medium stiffness and low to medium static friction or high stiffness and high static friction with no in-between values.

Having this in mind and looking how this data look like in a three dimensional space, adding the dynamic friction plane I could see that the cluster appearing at the lower end had low to medium (mostly low) values whereas it was higher in the other cluster (of high stiffness and static friction values). This may mean, that the three variables affect each other and in some cases they may even cancel each other out. More specifically, in this case, high dynamic friction seems like it is cancelling the effect of static friction at a level where high static friction feels almost the same as low to medium static friction.

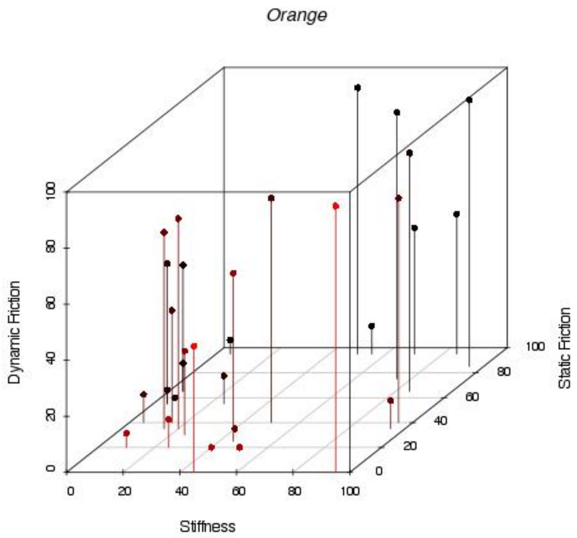

Figure 30 Three-dimensional scatter plot for the orange

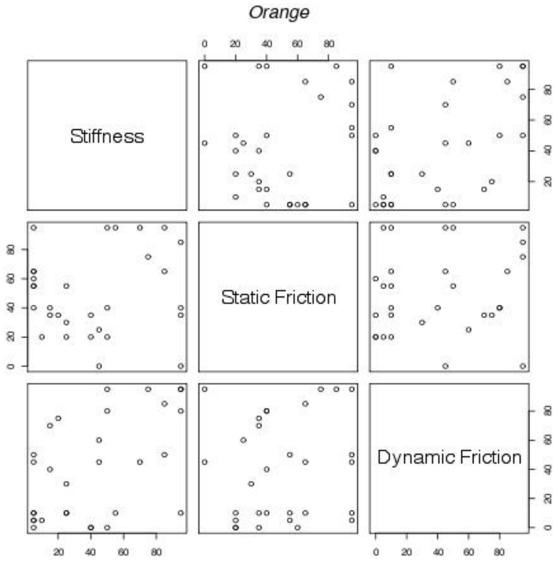

Figure 31 Matrix plot for the orange

Apple

The apple gave me the cleanest results of all five objects. A factor contributing to this nice clean dataset may had been that it was the last object the participants had to try and replicate, therefore they had a lot of experience in using the OMNI device and got used to the experimental procedure. Another factor affecting this may have been the simple shape and familiar texture of the apple and how recognizable it was from all my participants.

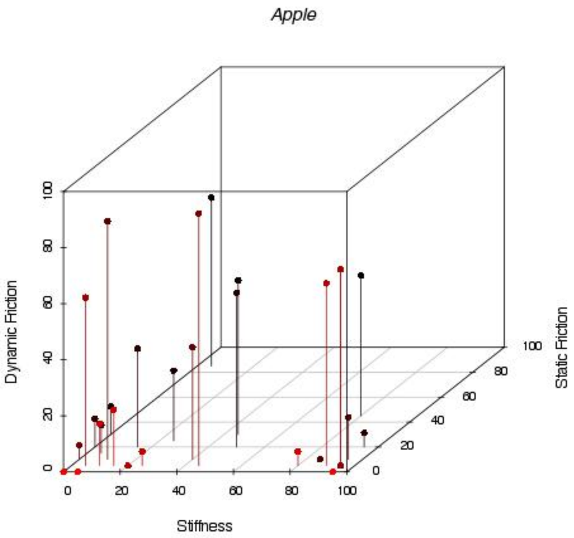

Figure 32 Three-dimensional scatter plot for the apple

The data seem to cluster in two main groups. One located in the corner where all three attributes (stiffness, static and dynamic friction) are medium to low, and the other where the static and dynamic friction are medium to low but stiffness is high. This separation may indicate a misunderstanding from the participants on what the control changing stiffness was doing (they did not know what each control as changing) or they did not feel the stiffness of the virtual ball changing; it was not as important as feeling the friction changing.

It is interesting to also note that all the values recorded are in the medium to low range for all attributes, except stiffness.

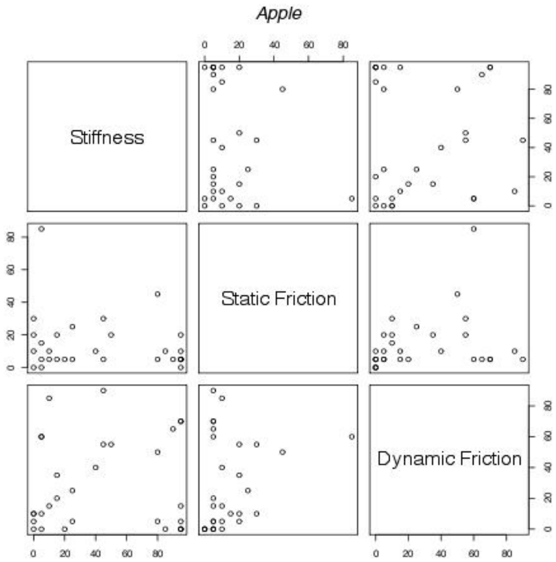

Figure 33 Matrix plot for the apple

Also, when considering only the stiffness and the dynamic friction plane, I was able to observe a positive correlation pattern emerging. This may be because of noise in the data and the relatively small data sample.

6.3.5 Cluster Analysis

The scatter plots produced showed clustering or grouping of data. This is an indication that even though the "distance" between the values is big in statistical terms, they may have a relationship when you see them together. Cluster analysis was then performed in each set of data to prove the existence of these clusters. The method used for this cluster analysis was a non-hierarchical cluster analysis technique, which uses k-means clustering.

Using a non-hierarchical method, the dataset can be classified by partitioning, giving a set of non-overlapping groups, or clusters, with no hierarchical relationships between them.

K-means clustering was used via the kmeans() function in R. It is a method of cluster analysis aiming to partition a number of observations into a number (k) of clusters in which each observation belongs to the cluster with the nearest mean.

Finding the number of clusters (k) is a frequent problem in all cluster analyses. A variety of techniques exist for finding k and they span from the simple rule of thumb as proposed by Mardia et al. [37] using the following equation:

$$k \approx \sqrt{n/2} \quad (1)$$

where k is the number of clusters and n is the number of data points. This method was considered unreliable and the "elbow method" was used. This method of defining the cluster numbers can be traced back to Thorndike in 1953 [38]. Via this method, the percentage of variance is considered as a function of the number of clusters and plotted on a graph with the percentage of variance against the number of clusters. The most suitable number is chosen at the point where any marginal gain in variance will cause a gain or a drop to the graph's gradient, giving an angle in the graph. The number of clusters is chosen at this point, hence the "elbow" name. Figure 34 is an example of this plot. Here we can observe that the greatest change in variance, and hence the "elbow" shape starts to appear at the point where the "number of groups" is 4, therefore we can conclude that the data used for plotting this graph can form 4 clusters.

Then the k-means function was used and a graph containing the clusters was drawn. The graphs obtained are presented in the sections below. The line plot indicating the elbow effect used for determining the number of clusters to be used accompanies all graphs. These graphs do not present anything different from the scatter plots above but are used to strengthen the descriptions and analysis of the scatter plots and are used for giving further proof of the existence of clusters in the dataset of every object.

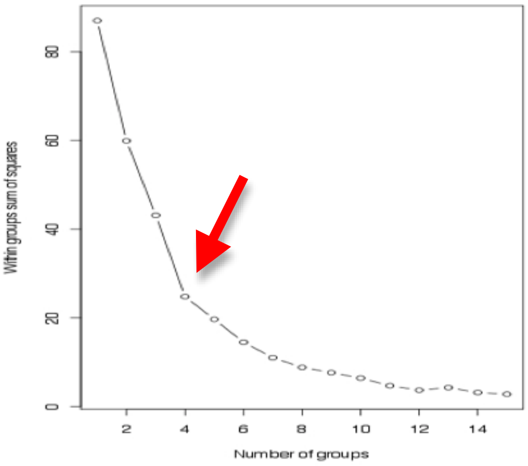

Figure 34 Example of the "elbow method" plot

6.3.6 Cluster plot analysis

The first plot (Figure 35) represents the data obtained from the mandarin. The elbow effect begins to occur at the point defined by 6 in the “Number of groups” axis, giving a total number of 6 clusters. These clusters can be seen in the next plot. The arrangement of these clusters is identical to the arrangement of the clusters in the scatter plot analysed above, confirming the existence of clusters in the dataset.

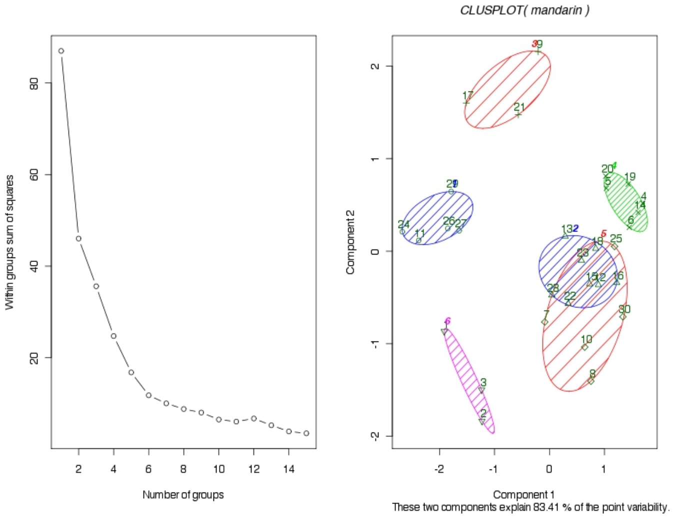

Figure 35 Cluster analysis for the mandarin

The same observations can be made for the cluster analysis performed on the avocado dataset values (Figure 36). The elbow effect starts to become more obvious at k number of 4 clusters. These clusters are arranged in a way that occupies most of the area available, not giving a definite pattern of data distribution or cluster arrangement. It is just confirming the existence of data clusters. The arrangement of these clusters (occupying most of the cluster plot area) is very similar to what was observed in the scatter plots produced for avocado. Therefore it is now proven that even though data appear to be scattered over a wide range of values, clusters of data exist and therefore they are not random.

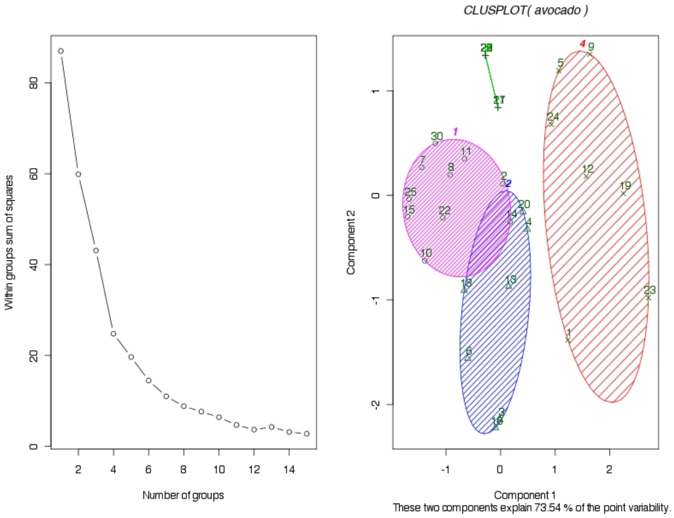

Figure 36 Cluster analysis for the avocado

For the billiard ball (Figure 37), even though there was a small anomaly at k=13 point, the elbow effect appeared to be more visible at k=4. Even though 4 clusters were present, there was only one holding the majority of points, while the other three were just small clusters of no more than 5 data points each. This is similar to what was observed in the scatter plots above (see Figure 29) where majority of data points are clustered together.

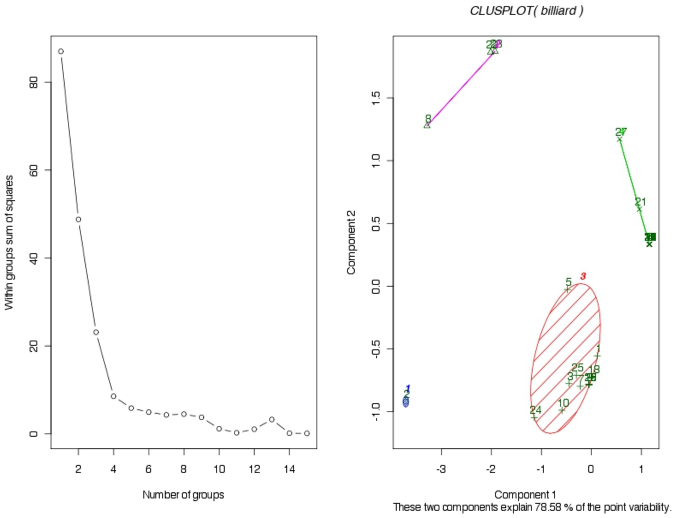

Figure 37 Cluster analysis for the billiards ball

The cluster analysis on the data obtained for the orange (Figure 38), yielded similar results to those of the mandarin. Five clusters were formed, with three being very close to each other and the other being in the opposite size, all arranged in a similar way to what was visible from the scatter plots above (Figure 31).

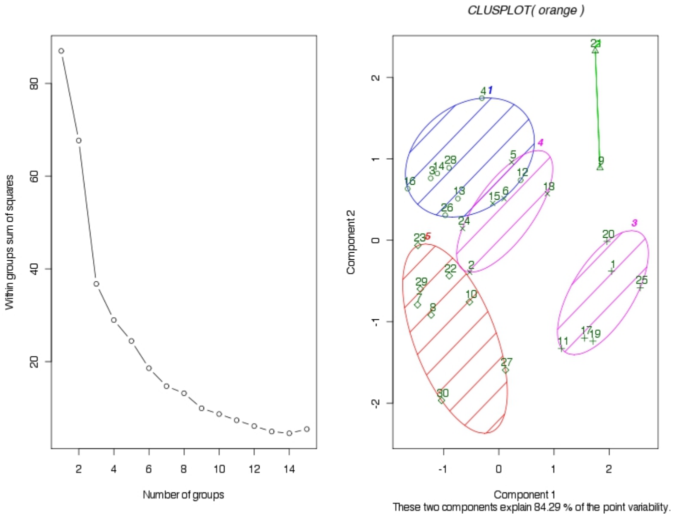

Figure 38 Cluster analysis for the orange

Finally, the cluster analysis for the apple (Figure 39) showed the existence of seven clusters. Again, these seven clusters are grouped together in a similar fashion as what was observed in the scatter plot diagram above (see Figure 33). Data are grouped together in a cluster that is made up of a number of smaller clusters.

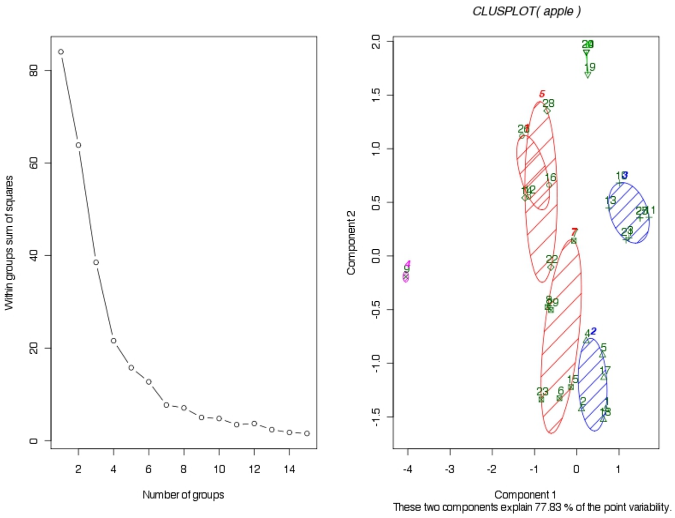

Figure 39 Cluster analysis for the apple

6.4 Discussion

Using the results from this experiment, I could safely reject my initial hypothesis that there would be a definite set of numbers, obtained from the mean values of each haptic attribute, that would describe the unique haptic properties of each object tested. The reason for rejecting the mean values is mainly because of their high standard deviation values that render them unreliable. Having a high standard deviation for the mean values indicates that the data points are spread out over a large range of values. This makes the mean value not being representative for the whole data set, and therefore it cannot be used for defining the object the mean was obtained from.

This led me in looking for relationships between the haptic attributes (stiffness, static and dynamic friction) of each object. Ratios between them were also rejected as a valid method since all objects had a large number of ratios that would lead to infinity and had to be removed from the study. Even though the ratio values left showed some interesting trends and exponential growth between some attributes, they could not be considered as valid due to the high number of values that had to be rejected. This introduced statistical noise[5] within the data sample. One form of statistical noise is what is known as the residual, which is a more casual estimate of the anticipated outcome. In general, statistical noise exists when a set of data is not necessarily precise and might not be able to be replicated if the same information was collected and analysed again.

Performing a correlation analysis on the data obtained from the experiment did not show any strong correlations between them either. This just came to confirm that there is not a single relationship that can definitely describe any pair of attributes. The correlation analysis not returning strong correlations also may help to confirm that the relationships found when ratios were considered may just be products of statistical noise.

After seeing that means and ratios gave too high standard deviation and statistical noise I wanted to see how the three attributes related to each other when considered together. So far I only considered each attribute for each object on its own (by taking means) and saw if there was a relationship between two of them (ratios and correlations). The next step was to investigate if there was a relationship between all three attributes when considered together, that could describe an object. One-way was via plotting a three-dimensional scatter plot for each object containing the values of all three haptic attributes (stiffness, static and dynamic friction).

These three-dimensional scatter plots showed some clustering for all objects. These clusters help to explain why means failed to work, since there seem to be more than one relationship between the haptic attributes of each object. In the data, gathered for orange for example (see Figure 30 and Figure 31) there are two distinct clusters of data points at opposite sides of each other, with no values in between them. Even though, by the definition of 'mean' it is accurate, in this situation it is not representative and would give an extremely misleading mean value.

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[5] 'Statistical noise' is here used to describe unexplained variation or randomness found within the data.

On the other hand there can be correlation of values in the clusters formed. Unfortunately, the sample size was too small for any accurate correlation analysis to be made.

Overall, this experiment was set to explore how people perceive and describe physical objects using only their sense of touch, giving non-verbal descriptions. The results showed that there is a much more complex relationship of the haptic attributes involved for recognising textures. Haptic attributes cannot be described via the use of a simple mean value mainly because the existence of this more complex relationship.

This made the data produced to appear to have very little consistency and in their raw format seemed to be almost random, but, as mentioned above, upon further investigation and cluster analysis techniques showed the data was clustering in some meaningful patterns. At this point I can only speculate as to why this clustering occurred. One possible assumption is that haptic perception is a very individualistic attribute of humans. It seems likely that everyone feels the world slightly differently, focusing on different haptic attributes or allowing better domination of one sense over the other when more than one is available (e.g. vision and touch). Therefore, the uniqueness of each person should also be considered as the sense of touch is a much more personal feeling [27]. It is hard to compare different people's perception, but it seems likely that every person feels the world around them slightly differently, focussing on a different haptic attribute more than others (e.g. focus on the object's stiffness more than its surface static surface).

Another theory trying to describe this clustering effect, is what was mentioned through the work of Klatzky and her colleagues [6], [29], [28] stating that indirect touch or indirect tactile input has a much lower resolution since exploration and recognition is based entirely on vibrations. These vibrations depended on the speed and exploratory procedure (EP). Therefore, different EPs may have given data in different clusters. Nonetheless, at this point these are just early theories in development and further experiments need to be designed for further investigation of what may have caused this data clustering.

This experiment also builds on the study performed by Sulaiman et al. [33] where haptic drawing tablets were investigated in a similar way. The experiment in this project tried to avoid limitations Sulaiman and her colleagues had in their studies by allowing the participants to change the whole range of every haptic attribute instead of confining them in just three value groups ("low", "medium" and "high").

In addition, intermodal relationships may have been an important factor in the recognition of the surface texture while exploring it with the probe [17]. Vision, as mentioned above is a dominant sense, and when two senses are available, they may work together or dominate one over the other. There is no way to know if any intermodal relationships existed and if they did, if they played any role, making some participants explore the object's surface more "with their eyes" than with their sense of touch.

In conclusion, this part of the experiment confirmed that there is not a single set of definite numbers that can be used for accurately describing the haptic properties for an object. On the contrary, there is a much more complex relationship, involving all three haptic attributes I was testing for. Further work needs to be done to isolate some conditions (such as intermodality and intermodal relationships) and see what really affects the sense of touch, in both feeling and describing the objects we come in contact with.

7. Conclusion

This project was set to explore how people perceive touch and how they can describe what they feel through the sense of touch using non-verbal descriptions. Verbal description was so far the norm in similar experiments (e.g. Klatzky and Lederman work [29]). Describing the objects haptically rather than verbally was considered more accurate since it eliminates a big part of the language and cultural barrier of the participants taking part on the experiments.

In summary, the results of this project indicate that when people have an unknown texture, which they have to recognize via indirect touch, they tend to use similes of rubber, man-made objects. This finding rejects the initial hypothesis that people use fruit similes to describe texture haptically, in a similar way they do in linguistics. The results from this experiment also show that multimodality and multimodal relationships were not important factors in the object's recognition and description of an abstract object, since the answers given did not change even when the visual cue given (colour of virtual sphere) was changing.

In addition, it was confirmed what Lederman and Klatzky mention through their work [30,28] on how accuracy of object recognition is affected when indirect touch is used solely, with no other external cues from other senses. What seemed to further hinder recognisability in some extend was the cultural and sometimes language barrier that existed between the participants. This strengthens the reasoning behind my choice to use haptic descriptions instead of verbal ones when trying to get the values for haptic properties describing each object.

In this project, participants' perceptions of haptic interaction with textured surfaces was also investigated when they were asked to change three haptic attributes in a virtual object and make it feel as similar to the real object as they could. Not knowing what each of the three attributes was they could only explore for a relationship between the three that would give them the desired haptic result.

The results showed that a more complex relationship existed than the one initially anticipated. The haptic attributes for each object did not cluster together in any group that could be used for defining each object but, on the contrary, they appeared to have very little consistency and in their raw format seemed to be almost random. However, upon further investigation and cluster analysis the data seemed to be clustering in some meaningful patterns. There are a number of possible reasons that account for this observed clustering but at the moment they are all just speculations based on existing literature and possible limitations of the force feedback device used.

Overall, most of the current haptic technologies are still relatively primitive in comparison to other input and output technologies available. The PHANToM OMNI, for example, has a single point of contact, and generates motor noise, which may affect the user's haptic perception. The OMNI also has a relatively very low haptic resolution if we compare it to what humans are capable to sense or what the real world can produce. These limitations of the force feedback device used can be the reason for the relatively wide spread of data obtained for the haptic attributes of every object tested and the clustering observed. Nevertheless, this project was able to provided some evidence on how people haptically perceive the objects they are in contact with and managed to get some haptic, instead of verbal descriptions of objects.

The sense of touch is undoubtedly a very complex sense, with many interconnected sensory systems and sensory processors [14]. These results can be used for better understanding the physical and psychophysical factors that affect the feeling of touch as a sense.

Having this in mind, along with the psychophysical implication of multimodality and prior knowledge of sense, we can move forward to a better understanding of touch as a sense. This will help us move to the creation of better and more accurate haptic interfaces; and progress from the abstract representation of objects, that has been the norm so far in haptic rendering, to more accurate representations of haptic objects, as they exist in the real world.

8. Further Work

The analysis of the results obtained through this project, allowed another set of hypotheses to come into view. The first one comes from the results where the biggest percentage of participants taking part in the experiments, described the abstract objects as being made out of rubber or having a rubbery feel. The arising hypothesis that abstract objects are described using rubber similes should be further investigated.

The first thing to do is gather non-verbal descriptions of actual rubber balls, such as basketball ball, grass hockey ball and a variety of squash balls (examples taken from answers given as qualitative data in experiments of this project). This data can then be compared with the random numbers used for the virtual haptic sphere in the experiment conducted in this project, to see if the random numbers accidentally described an actual rubber ball or if rubber was indeed a haptic perception for an abstract texture.

The second field that would be interesting to investigate further is that of multimodality and how it effects texture perception. One possible way of doing this is by using the virtual space and combine different modalities. An example could be to have a three-dimensional model of an orange, with a correct set of haptic properties (correct meaning a set that resembles an real world orange) but have it making a metallic sound during exploration and see how sound affects texture perception. This could be further extend the research if there is a “McGurk” effect where an auditory stimulus can change what a person feels in a similar way it does with sound perception [39].

Lastly, in this project I have mentioned in a number of occasions the exploratory procedures (EP) as defined by Klatzky and her colleagues [6]. Their work can be extended as a part of further work of this project and study if these exploratory procedures exist when exploration is done in the virtual world with a force feedback device. During the experiments of this project, I was recording a video of participants exploring a set of objects in the real world using indirect touch (a probe). Three-dimensional models can be used to replicate these objects in the virtual world and investigate if people use similar or identical techniques to explore these virtual objects as they do in the real world.

Works Cited

[1] S. A. Brewster, "Using non-speech sound to overcome information overload," *Displays*, vol. 17, no. 3, pp. 179-189, May 1997.

[2] S. Brewster and V. Raty, "Earcons as a method of providing navigational cues in a menu hierarchy," in *In Proceedings of BCS HCI'96*, 1996, pp. 169-183.

[3] S. Kettebekov and S. Rajeev, "Toward Natural Gesture/Speech Control of a Large Display.," in *8th IFIP International Conference on Engineering for Human-Computer Interaction*, Toronto, 2001, pp. 221-234.

[4] A. M. Okamura, "Methods for haptic feedback in teleoperated robot-assisted surgery," *Industrial Robot: An International Journal*, vol. 21, no. 6, pp. 499 - 508, 2004.

[5] J. E. Anderson and P. Sanderson, "Sonification Design for Complex Work Domains: Dimensions and Distractors," *Experimental Psychology: Applied*, vol. 15, no. 3, pp. 183-198, September 2009.

[6] R. L. Klatzky and S. J. Lederman, "Touch," *Experimental Psychology*, vol. 4, no. 1, pp. 147-176, 2002.

[7] R. L. Klatzky, S. J. Lederman, and V. A. Metzger, "Identifying objects by touch: An "expert system."," *Perception & Psychophysics*, vol. 37, no. 4, pp. 299-302, 1985.

[8] R. L. Klatzky, S. J. Lederman, and C. Reed, "There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision.," *Journal of Experimental Psychology: General*, vol. 114, no. 4, pp. 359-369, December 1987.

[9] American Foundation for the Blind. (2012, July) Helen Keller Biography and Chronology. [Online]. http://www.afb.org/section.aspx?SectionID=1&TopicID=129

[10] E. W. Bushnell and P. J. Boudreau, "The development of haptic perception during infancy," in *The Psychology of Touch*, Morton A. Heller and William Schiff, Eds. Hullsdale, United States of America: Lawrence Erlbaum Associates, Publishers, 1991, pp. 139-167.

[11] P. A. Andersen and K. Leibowitz, "The development and nature of the construct touch avoidance," *Journal of nonverbal behavior*, vol. 3, no. 2, pp. 89-106, 1978.

[12] S. A. Rose, A. W. Gottfried, and W. H. Bridger, "Cross-modal transfer and information processing by the sense of touch in infancy.," *Developmental Psychology*, vol. 17, no. 1, pp. 90-98, January 1981.

[13] T. Striano and E. W. and Bushnell, "Haptic perception of material properties by 3-month-old infants," *Infant Behavior and Development*, vol. 28, no. 1, pp. 266–289, 2005.

[14] E. R. Kandel, J. H. Schwartz, and T. M. Jessel, *Principles of neural science*, 4th ed.: McGraw-Hill, 2000.

[15] G. C. Burdea, *Force and Touch Feedback for Virtual Reality*. New York, United States of America: Wiley-Interscience, 1996.

[16] G. Böttcher, *Haptic Interaction with Deformable Objects*, 1st ed. Hannover, Germany: Springer, 2011.

[17] D. H. Warren and M. J. Rossano, "Intermodality relations: Vision and Touch," in *The Psychology of Touch*, Morton A. Heller and William Schiff, Eds. Hillsdale, United States of America: Lawrence Erlbaum Associates, publishers, 1991, pp. 119-137.

[18] G. L. Poling, J. M. Weisenberger, and T. Kerwin, "The Role of Multisensory Feedback in Haptic Surface Perception," in *Proceedings of the 11th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, Washington, 2003, p. 187.

[19] V. J. Manyam, "A psychophysical measure of visual and kinesthetic spatial discriminative abilities of adults and children," *Perception*, vol. 15, no. 3, pp. 313-324, 1986.

[20] M. A. Heller, "Visual and tactual texture perception: Intersensory cooperation," *Attention, Perception & Psychophysics*, vol. 31, no. 4, pp. 339-344, 1982.

[21] H. Pietry, Psychophysics and haptic perception, 2011, Understanding Users Session 3 Lecture Slides.

[22] T. Yoshioka, S. J. Bensmaïa, J. C. Craig, and S. S. Hsiao, "exture perception through direct and indirect touch: an analysis of perceptual space for tactile textures in two modes of exploration.," *Somatosens Mot Res*, vol. 1, no. 2, pp. 53-70, March 2007.

[23] I. Oakley, M. R. McGee, S. Brewster, and P. Gray, "Putting the Feel in 'Look and Feel'," in *SIGCHI conference on Human factors in computing systems*, Hague, Netherlands, 2000, pp. 415-422.

[24] D. Katz and L. E. Krueger, "The World of Touch," *The American Journal of Psychology*, vol. 104, no. 1, pp. 147-150, Spring 91.

[25] R. L. Klatzky, S. J. Lederman, C. Hamilton, M. Grindley, and R. H. Swendsen, "Feeling textures through a probe: effects of probe and surface geometry and exploratory factors," *Perception & Psychophysics*, vol. 65, no. 4, pp. 613-631, May 2003.

[26] A. Chang and C. O'Sullivan. (2005, April) Glasgow Interactive Systems Group. [Online]. http://www.dcs.gla.ac.uk/haptic/haptics%20web%20pages_files/Chang%20and%20Sullivan.pdf

[27] C. Classen, *The Book of Touch*, 1st ed., Constance Classen, Ed.: Berg Publishers, 2005.

[28] R. Klatzky and S. Lederman, "Perceiving Texture through a probe," in *Touch in Virtual Environments*, M. L. McLaughlin, J. P. Hespanha, and Sukhatme, Eds. Upper Saddle River, United States of America: Prentice Hall PTR, 2002, pp. 180-193.

[29] R. L. Klatzky and S. J. Lederman, "Identifying objects from a haptic glance.," *Perception & Psychophysics*, vol. 57, no. 8, pp. 1111-1123, November 1995.

[30] S. J. Lederman and R. L. Klatzky, "Haptic identification of common objects: Effects of constraining the manual exploration process," *Perception &*

Psychophysics, vol. 66, no. 4, pp. 618–628, 2004.

[31] K. E. MacLean, "Designing with haptic feedback," in *Haptic Feedback in the Proceedings of IEEE Robotics and Automation*, San Francisco, 2000, pp. 783-788.

[32] J. H. Clark, "The Ishihara Test for Color Blindness," *American Journal of Physiological Optics*, vol. 5, pp. 269-276, 1924.

[33] S. Sulaiman, A. Blandford, and P. Cairns, "Haptic experience and the design of drawing interfaces," *Interacting with Computers*, vol. 22, no. 3, pp. 193–205, May 2010.

[34] S. Scali, A. M. Shillito, and M. Wright, "Thinking in space: concept physical models and the call for new digital tools," in *Craft in the 21st Century*, Edinburgh, 2002.

[35] SensAble Technologies Inc., *PHANTOM Omni User Manual*. Woburn, United States of America: SensAble Technologies Inc., 2008.

[36] A. Field, *Discovering Statistics Using SPSS*, Second Edition ed. London, United Kingdom: SAGE Publications LTD, 2005.

[37] K. V. Mardia, J. T. Kent, and J. M. Bibby, *Multivariate analysis*. London, England: Academic Press, 1979.

[38] R. L. Thorndike, "Who Belong in the Family?," *Psychometrika*, vol. 18, no. 4, pp. 267-276, December 1953.

[39] H. McGurk and J. MacDonald, "Hearing lips and seeing voices," *Nature*, vol. 264, pp. 746 - 748, December 1976.

Appendix 1.

Experiment answer form

Age:________________________.   Participant Number:________.

Sex: Male / Female

Left-Right handed: LEFT / RIGHT

Ever used a haptic device before? Yes/No .____________________________________.

Department my Bachelor's degree belongs in:________________________________ _______________.

Department my Mater's degree belongs in:___________________________________ _______________.

Part 1:

Training Object

.____.

Part 2:

Multiple Objects

.________. - .____.

.________. - .____.

.________. - .____.

.________. - .____.

.________. - .____.

Part 3

Virtual Objects

.________.   -   .________.   .________.   .________.

.________.   -   .________.   .________.   .________.

.________.   -   .________.   .________.   .________.

.________.   -   .________.   .________.   .________.

.________.   -   .________.   .________.   .________.

Consent Form

Participant Number:_______.

Participant consent

Your participation in this experiment is entirely voluntary; there will be no remuneration for the time you spend evaluating it. All data gathered from this study will be treated in a confidential fashion: It will be archived in a secure location. When your data are reported or described, all identifying information will be removed. There are no known risks to participation in this experiment, and you may withdraw at any point. Please feel free to ask the researcher if you have any other questions; otherwise, if you are willing to participate, please sign this consent form and proceed with the experiment.

Date: _____________________ Signature: ____________________

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Appendix 2.

Experiment Part 1 – Raw Data

Participant no.	Answer
1	Wooden table
2	Rubber ball
3	Plastic ball
4	Deflated football
5	Tennis ball
6	Basket ball
7	Ping pong ball
8	Metallic sphere
9	Deflated basket ball
10	Rubber bouncy ball
11	Golf ball
12	Rubber ball
13	Basket ball
14	Ping pong paddle skin
15	Ping pong ball
16	Iron sphere
17	Rubber ball
18	Tennis ball
19	Stress ball
20	Tennis ball
21	Beach ball
22	Track ball
23	Tennis ball
24	Metallic sphere
25	Rubber ball
26	Rubber ball
27	Squash ball
28	Rubber ball
29	Golf ball
30	Rubber ball

Table 11 Raw data from Experiment part 1

Experiment Part 2 – Raw Data

Object	**Mandarin**	**Avocado**	**Billiards Ball**
Participant number			
1	Orange	Scale weight	Egg
2	Mandarin	Basketball	Trackball
3	Orange	NR	Glass ball
4	NR (fruit)	Hard plastic toy/statue	Glass ball
5	Plasteline ball	Orange	Glass ball
6	Grass hockey ball	Peach	Billiard ball
7	Tennis ball	Plastic ball	Ping pong ball
8	Rubber sphere	Lemon	Glass ball
9	Orange	Orange	Glass ball
10	Rubber toy	Mini basket ball	Glass ball
11	Plastic toy	Basketball	Billiard ball
12	Rubber ball	Basketball	Billiard ball
13	Doll head (solid plastic)	Small basketball	Billiard ball
14	Orange	Basketball piece	Billiard ball
15	Orange	Avocado	Glass ball
16	Orange	Orange	Glass ball

17	Orange	Muskmelon	Glass ball
18	Bouncy ball	NR (rubber sphere)	Solid plastic sphere
19	Mandarin	Avocado	Trackball
20	Mandarin	Melon	Billiard ball
21	Orange	NR (plastic)	Billiard ball
22	Orange	Golf ball	Glass ball
23	Orange	NR (rough plastic)	Billiard ball
24	NR (plastic sphere)	NR (plastic)	Plastic globe
25	NR (rubber sphere)	Lemon	Wooden sphere
26	Small basketball	NR (plastic)	Glass ball
27	Orange	NR (leather)	Hard plastic ball
28	Tennis ball	Rough plastic toy	Glass ball
29	Rubber ball	Plastic ball	Solid plastic sphere
30	Rubber ball	Avocado	Glass ball

Table 12 Raw data from Experiment part 2 (Mandarin, Avocado and Billiard ball)

Object	**Orange**	**Apple**
Participant number		
1	Orange	Tomato
2	Orange	Apple
3	Orange	Apple
4	NR (plastic)	Apple
5	Plastic ball	Apple
6	Mango	Apple
7	NR (rubber object with petal top)	NR (rubber object with petal top)
8	Lemon	NR (something plastic)
9	Orange	Apple
10	Basket ball	NR (something plastic)
11	Orange*	Fake tomato
12	Plasteline ball	Blue tag ball
13	Ping pong paddle skin	Apple
14	Orange	Apple
15	Orange	Apple
16	Grass hockey ball	Apple
17	Orange	Apple
18	Bouncy ball	NR (leather)
19	Orange	Apple
20	Orange	Apple
21	Orange	Apple
22	Orange	Apple
23	Orange	Apple
24	Large lime stone	NR (wooden)

25	Orange	Apple
26	NR (plastic)	NR (paper or cloth)
27	Orange	Apple
28	Orange	Half rubber ball
29	Orange	Iron ball
30	Orange	Apple

Table 13 Raw data from Experiment part 2 (Orange and Apple)

Experiment Part 3 – Raw Data

Object	**Mandarin**		
Participant no	Stiffness	Static Friction	Dynamic Friction
1	0.45	0.95	0.95
2	0	0.95	0.95
3	0.15	0.95	0.85
4	0.25	0.1	0.1
5	0.3	0.05	0.4
6	0.1	0.05	0.35
7	0.4	0.9	0.2
8	0.05	0.85	0.1
9	0.95	0	0.55
10	0.05	0.65	0.3
11	0.9	0.95	0.85
12	0.05	0.3	0.45
13	0.3	0.3	0.55
14	0.25	0.15	0.1
15	0.1	0.35	0.45
16	0.05	0.3	0.3
17	0.95	0.25	0.95
18	0.1	0.15	0.55
19	0.35	0.1	0.15
20	0.4	0.1	0.3
21	0.95	0.35	0.45
22	0.1	0.45	0.55
23	0.05	0.15	0.7
24	0.95	0.95	0.95

25	0.35	0.45	0
26	0.9	0.9	0.65
27	0.8	0.8	0.7
28	0.15	0.45	0.65
29	0.95	0.75	0.7
30	0.05	0.5	0.1

Table 14 Raw data from Experiment part 3. Haptic attributes for Mandarin

Object	**Avocado**		
Participant no	Stiffness	Static Friction	Dynamic Friction
1	0.25	0.45	0.95
2	0.25	0.9	0.7
3	0.3	0.2	0.1
4	0.95	0.45	0
5	0.85	0.95	0.75
6	0.25	0.4	0
7	0.25	0.95	0
8	0.2	0.95	0.3
9	0.95	0.95	0.95
10	0.1	0.75	0
11	0.3	0.95	0.35
12	0.95	0.6	0.65
13	0.7	0.4	0
14	0.45	0.7	0.45
15	0.05	0.9	0
16	0.25	0.2	0.1
17	0.95	0.8	0
18	0.35	0.55	0

19	0.95	0.55	0.95
20	0.95	0.5	0
21	0.95	0.8	0
22	0.15	0.85	0.2
23	0.95	0.25	0.95
24	0.95	0.75	0.45
25	0.05	0.95	0.05
26	0.95	0.95	0
27	0.95	0.95	0
28	0.95	0.95	0
29	0.95	0.95	0
30	0.4	0.95	0

Table 15 Raw data from Experiment part 3. Haptic attributes for Avocado

Object	**Billiard ball**		
Participant no	Stiffness	Static Friction	Dynamic Friction
1	0.25	0.05	0
2	0	0.95	0.4
3	0	0.1	0.05
4	0.95	0	0
5	0.05	0	0.25
6	0.95	0	0
7	0.1	0.1	0
8	0	0.45	0.95
9	0	0	0
10	0.05	0.2	0
11	0.95	0	0
12	0.95	0	0

13	0.95	0	0
14	0.95	0	0
15	0	0	0
16	0	0	0
17	0.95	0	0
18	0.05	0	0
19	0	0	0
20	0.95	0	0
21	0.95	0	0.1
22	0.05	0.05	0.95
23	0	0	0.95
24	0.05	0.35	0.05
25	0	0.05	0.05
26	0	0	0
27	0.95	0	0.3
28	0.95	0	0
29	0.95	0	0
30	0.95	0	0

Table 16 Raw data from Experiment part 3. Haptic attributes for Billiards ball

Object	**Orange**		
Participant no	Stiffness	Static Friction	Dynamic Friction
1	0.75	0.75	0.95
2	0.05	0.55	0.5
3	0.25	0.2	0.1
4	0.45	0	0.45
5	0.45	0.25	0.6
6	0.2	0.35	0.75
7	0.05	0.6	0
8	0.05	0.65	0.1
9	0.95	0.4	0.8
10	0.05	0.65	0.45
11	0.7	0.95	0.45
12	0.95	0.35	0.1
13	0.25	0.3	0.3
14	0.4	0.2	0
15	0.15	0.35	0.7
16	0.1	0.2	0.05
17	0.85	0.95	0.5
18	0.5	0.4	0.8
19	0.5	0.95	0.95
20	0.85	0.65	0.85
21	0.95	0	0.95
22	0.25	0.55	0.1
23	0.05	0.4	0.1
24	0.15	0.4	0.4

25	0.95	0.85	0.95
26	0.4	0.35	0
27	0.55	0.95	0.1
28	0.5	0.2	0
29	0.05	0.55	0.05
30	0.05	0.95	0.05

Table 17 Raw data from Experiment part 3. Haptic attributes for Orange

Object	**Apple**		
Participant no	Stiffness	Static Friction	Dynamic Friction
1	0.1	0.05	0.15
2	0.05	0	0
3	0	0.1	0.05
4	0.8	0.05	0.05
5	0.15	0.05	0.2
6	0.25	0.05	0.05
7	0	0.2	0.1
8	0.4	0.1	0.4
9	0.15	0.2	0.35
10	0.05	0.85	0.6
11	0.95	0.1	0.15
12	0.95	0	0
13	0.45	0.3	0.55
14	0.95	0.2	0.05
15	0.1	0.1	0.85
16	0.05	0.15	0.1
17	0.5	0.2	0.55
18	0.2	0.05	0

19	0	0	0
20	0.9	0.05	0.65
21	0.95	0.05	0.7
22	0.85	0.1	0
23	0.05	0.05	0.6
24	0	0.3	0.1
25	0.95	0.05	0.7
26	0.95	0.05	0
27	0.8	0.45	0.5
28	0.95	0.05	0
29	0.45	0.05	0.9
30	0.25	0.25	0.25

Table 18 Raw data from Experiment part 3. Haptic attributes for Apple

Appendix 3.

Programs made for this project

Random Sequence Generator

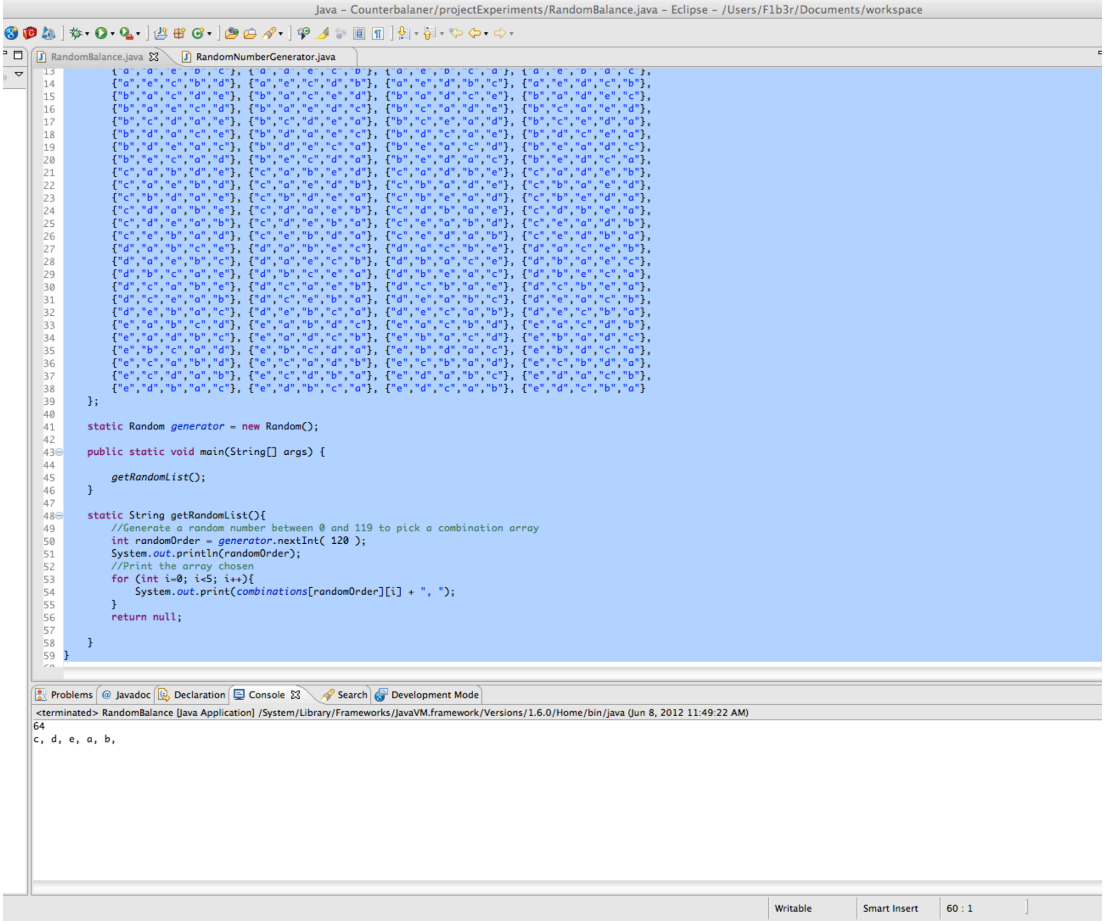
Generate random list of objects for counterbalancing

Used once to determine order of real objects when felt through a probe and when participant needs to replicate them

Used only ONCE at the very beginning

```
package projectExperiments;


import com.sun.tools.javac.code.Attribute.Array;

import java.util.Random;


public class RandomBalance {

//list obtained from:

http://www.mathsisfun.com/combinatorics/combinations-permutations-
calculator.html


static String[][] combinations = {

{"a","b","c","d","e"},{"a","b","c","e","d"},{"a","b","d","c","e"},
{"a","b","d","e","c"},{"a","b","e","c","d"},{"a","b","e","d","c"},
{"a","c","b","d","e"},{"a","c","b","e","d"},{"a","c","d","b","e"},
{"a","c","d","e","b"},{"a","c","e","b","d"},{"a","c","e","d","b"},

{"a","d","b","c","e"},{"a","d","b","e","c"},{"a","d","c","b","e"},
{"a","d","c","e","b"},{"a","d","e","b","c"},{"a","d","e","c","b"},
{"a","e","b","c","d"},{"a","e","b","d","c"},{"a","e","c","b","d"},
{"a","e","c","d","b"},{"a","e","d","b","c"},{"a","e","d","c","b"},

{"b","a","c","d","e"},{"b","a","c","e","d"},{"b","a","d","c","e"},
{"b","a","d","e","c"},{"b","a","e","c","d"},{"b","a","e","d","c"},
{"b","c","a","d","e"},{"b","c","a","e","d"},{"b","c","d","a","e"},
{"b","c","d","e","a"},{"b","c","e","a","d"},{"b","c","e","d","a"},

{"b","d","a","c","e"},{"b","d","a","e","c"},{"b","d","c","a","e"},
{"b","d","c","e","a"},{"b","d","e","a","c"},{"b","d","e","c","a"},
{"b","e","a","c","d"},{"b","e","a","d","c"},{"b","e","c","a","d"},
{"b","e","c","d","a"},{"b","e","d","a","c"},{"b","e","d","c","a"},

{"c","a","b","d","e"},{"c","a","b","e","d"},{"c","a","d","b","e"},
{"c","a","d","e","b"},{"c","a","e","b","d"},{"c","a","e","d","b"},
{"c","b","a","d","e"},{"c","b","a","e","d"},{"c","b","d","a","e"},
{"c","b","d","e","a"},{"c","b","e","a","d"},{"c","b","e","d","a"},

{"c","d","a","b","e"},{"c","d","a","e","b"},{"c","d","b","a","e"},
{"c","d","b","e","a"},{"c","d","e","a","b"},{"c","d","e","b","a"},
{"c","e","a","b","d"},{"c","e","a","d","b"},{"c","e","b","a","d"},
{"c","e","b","d","a"},{"c","e","d","a","b"},{"c","e","d","b","a"},

{"d","a","b","c","e"},{"d","a","b","e","c"},{"d","a","c","b","e"},
{"d","a","c","e","b"},{"d","a","e","b","c"},{"d","a","e","c","b"},
```

```
{"d","b","a","c","e"},{"d","b","a","e","c"},{"d","b","c","a","e"},
{"d","b","c","e","a"},{"d","b","e","a","c"},{"d","b","e","c","a"},

{"d","c","a","b","e"},{"d","c","a","e","b"},{"d","c","b","a","e"},
{"d","c","b","e","a"},{"d","c","e","a","b"},{"d","c","e","b","a"},
{"d","e","a","b","c"},{"d","e","a","c","b"},{"d","e","b","a","c"},
{"d","e","b","c","a"},{"d","e","c","a","b"},{"d","e","c","b","a"},

{"e","a","b","c","d"},{"e","a","b","d","c"},{"e","a","c","b","d"},
{"e","a","c","d","b"},{"e","a","d","b","c"},{"e","a","d","c","b"},
{"e","b","a","c","d"},{"e","b","a","d","c"},{"e","b","c","a","d"},
{"e","b","c","d","a"},{"e","b","d","a","c"},{"e","b","d","c","a"},

{"e","c","a","b","d"},{"e","c","a","d","b"},{"e","c","b","a","d"},
{"e","c","b","d","a"},{"e","c","d","a","b"},{"e","c","d","b","a"},
{"e","d","a","b","c"},{"e","d","a","c","b"},{"e","d","b","a","c"},
{"e","d","b","c","a"},{"e","d","c","a","b"},{"e","d","c","b","a"}
};


static Random generator = new Random();


public static void main(String[] args) {
	getRandomList();
}
static String getRandomList(){
//Generate a random number between 0 and 119 to pick a combination array
	int randomOrder = generator.nextInt( 120 );
	System.out.println(randomOrder);
	//Print the array chosen
	for (int i=0; i<5; i++){
		System.out.print(combinations[randomOrder][i] + ", ");
	}
	return null;
	}
}
```



```
        {"a","e","c","b","d"}, {"a","e","c","d","b"}, {"a","e","d","b","c"}, {"a","e","d","c","b"},
        {"b","a","c","d","e"}, {"b","a","c","e","d"}, {"b","a","d","c","e"}, {"b","a","d","e","c"},
        {"b","a","e","c","d"}, {"b","a","e","d","c"}, {"b","c","a","d","e"}, {"b","c","a","e","d"},
        {"b","c","d","a","e"}, {"b","c","d","e","a"}, {"b","c","e","a","d"}, {"b","c","e","d","a"},
        {"b","d","a","c","e"}, {"b","d","a","e","c"}, {"b","d","c","a","e"}, {"b","d","c","e","a"},
        {"b","d","e","a","c"}, {"b","d","e","c","a"}, {"b","e","a","c","d"}, {"b","e","a","d","c"},
        {"b","e","c","a","d"}, {"b","e","c","d","a"}, {"b","e","d","a","c"}, {"b","e","d","c","a"},
        {"c","a","b","d","e"}, {"c","a","b","e","d"}, {"c","a","d","b","e"}, {"c","a","d","e","b"},
        {"c","a","e","b","d"}, {"c","a","e","d","b"}, {"c","b","a","d","e"}, {"c","b","a","e","d"},
        {"c","b","d","a","e"}, {"c","b","d","e","a"}, {"c","b","e","a","d"}, {"c","b","e","d","a"},
        {"c","d","a","b","e"}, {"c","d","a","e","b"}, {"c","d","b","a","e"}, {"c","d","b","e","a"},
        {"c","d","e","a","b"}, {"c","d","e","b","a"}, {"c","e","a","b","d"}, {"c","e","a","d","b"},
        {"c","e","b","a","d"}, {"c","e","b","d","a"}, {"c","e","d","a","b"}, {"c","e","d","b","a"},
        {"d","a","b","c","e"}, {"d","a","b","e","c"}, {"d","a","c","b","e"}, {"d","a","c","e","b"},
        {"d","a","e","b","c"}, {"d","a","e","c","b"}, {"d","b","a","c","e"}, {"d","b","a","e","c"},
        {"d","b","c","a","e"}, {"d","b","c","e","a"}, {"d","b","e","a","c"}, {"d","b","e","c","a"},
        {"d","c","a","b","e"}, {"d","c","a","e","b"}, {"d","c","b","a","e"}, {"d","c","b","e","a"},
        {"d","c","e","a","b"}, {"d","c","e","b","a"}, {"d","e","a","b","c"}, {"d","e","a","c","b"},
        {"d","e","b","a","c"}, {"d","e","b","c","a"}, {"d","e","c","a","b"}, {"d","e","c","b","a"},
        {"e","a","b","c","d"}, {"e","a","b","d","c"}, {"e","a","c","b","d"}, {"e","a","c","d","b"},
        {"e","a","d","b","c"}, {"e","a","d","c","b"}, {"e","b","a","c","d"}, {"e","b","a","d","c"},
        {"e","b","c","a","d"}, {"e","b","c","d","a"}, {"e","b","d","a","c"}, {"e","b","d","c","a"},
        {"e","c","a","b","d"}, {"e","c","a","d","b"}, {"e","c","b","a","d"}, {"e","c","b","d","a"},
        {"e","c","d","a","b"}, {"e","c","d","b","a"}, {"e","d","a","b","c"}, {"e","d","a","c","b"},
        {"e","d","b","a","c"}, {"e","d","b","c","a"}, {"e","d","c","a","b"}, {"e","d","c","b","a"}
    };

    static Random generator = new Random();

    public static void main(String[] args) {

        getRandomList();
    }

    static String getRandomList(){
        //Generate a random number between 0 and 119 to pick a combination array
        int randomOrder = generator.nextInt( 120 );
        System.out.println(randomOrder);
        //Print the array chosen
        for (int i=0; i<5; i++){
            System.out.print(combinations[randomOrder][i] + ", ");
        }
        return null;

    }
}
```

```
<terminated> RandomBalance [Java Application] /System/Library/Frameworks/JavaVM.framework/Versions/1.6.0/Home/bin/java (Jun 8, 2012 11:49:22 AM)
64
c, d, e, a, b,
```

Figure 40 Output of Random Sequence Generator after running once

Random Number Generator

Generate random attributes for training (abstract object)

Used only ONCE at the very beginning

```
package projectExperiments;

import java.util.Random;

public class RandomNumberGenerator {

      static Random generator = new Random();

      public static void main(String[] args) {

            int stiffness = generator.nextInt( 10 );
            System.out.println("Stiffness: 0." + stiffness);

            int staticFriction = generator.nextInt( 10 );
            System.out.println("Static Friction: 0." + staticFriction);

            int dynamicFriction = generator.nextInt( 10 );
            System.out.println("Dynamic Friction:0."+ dynamicFriction);

      }
}
```

R script

Three dimensional scatter plots script

```
#Directory independence code
frame_files <- lapply(sys.frames(), function(x) x$ofile)
frame_files <- Filter(Negate(is.null), frame_files)
thisPath <- dirname (frame_files[[length(frame_files)]])

setwd(thisPath);

library(rgl);
library(scatterplot3d) ;

object <- read.csv(file="values.csv",header=TRUE,sep=",");

Stiffness<-vector();
Static<-vector();
Dynamic<-vector();

Stiffness<-apple[[object_stiffness_column]];
Static<-apple[[object_static_friction_column]];
Dynamic<-apple[[object_dynamic_friction_column]];

plot3d(Stiffness,Static,Dynamic, main="Object", type="s", radius =
"2");

text3d(Stiffness+5,Static,Dynamic,text=object[[object_label_column]]);

jpeg(object.jpg');
pairs(~Stiffness+Static+Dynamic, main="Object",
labels=c("Stiffness","Static Friction","Dynamic Friction"));
scatterplot3d(Stiffness,Static,Dynamic, highlight.3d=TRUE, type="h",
pch=16, main="Object", xlab="Stiffness", ylab="Static Friction",
zlab="Dynamic Friction");
dev.off();
```

*Note: substitute all Bold italic words with the appropriate ones for each object

OMNI control code

```
#include <stdlib.h>

#include <math.h>
#include <assert.h>
#include <iostream>
#include <fstream>

#if defined(WIN32)
#include <windows.h>
#endif

#if defined(WIN32) || defined(linux)
#include <GL/glut.h>
#elif defined(__APPLE__)
#include <GLUT/glut.h>
#endif

#include <HL/hl.h>
#include <HDU/hduMatrix.h>
#include <HDU/hduError.h>

#include <HLU/hlu.h>
#include <string.h>
#include <iostream>

/* Haptic device and rendering context handles. */
static HHD ghHD = HD_INVALID_HANDLE;
static HHLRC ghHLRC = 0;

/* Shape id for shape we will render haptically. */
HLuint gShapeId;

#define CURSOR_SIZE_PIXELS 20
static float STIFFNESS = 0.8;
static float DAMPING = 0.1;
static float STATIC_FRICTION = 0.1;
static float DYNAMIC_FRICTION = 0.4;
char stiffnessCounter[1024] = "Stiffness:";
char staticCounter[1024] = "Static:";
char dynamicCounter[1024] ="Dynamic:";
char timestamp[1024];

int shape = 1;

static double gCursorScale;
static GLuint gCursorDisplayList = 0;

/* Function prototypes. */
void glutDisplay(void);
void glutReshape(int width, int height);
void glutIdle(void);
void glutMenu(int);
void keyUp(unsigned char key, int x, int y);
bool* keyStates = new bool[256];
```

```
void exitHandler(void);

void setup();
void initGL();
void initHL();
void initScene();
void drawSceneHaptics();
void drawSceneGraphics();
void drawCursor();
void updateWorkspace();
void getShape();
void drawString(const char* string);


/***************************************************************
****************
 Initializes GLUT for displaying a simple haptic scene.
****************************************************************
***************/
int main(int argc, char *argv[])
{
    glutInit(&argc, argv);

    glutInitDisplayMode(GLUT_DOUBLE | GLUT_RGB | GLUT_DEPTH);

    glutInitWindowSize(1024, 768);
    glutCreateWindow("Haptic Objects");
    setup();

    // Set glut callback functions.
    glutDisplayFunc(glutDisplay);
    glutReshapeFunc(glutReshape);
    glutIdleFunc(glutIdle);
    glutKeyboardUpFunc(keyUp);

    glutCreateMenu(glutMenu);
    glutAddMenuEntry("Wire Sphere", 1);
    glutAddMenuEntry("Solid Sphere", 2);
    glutAddMenuEntry("Tetrahedron", 3);
    glutAddMenuEntry("Dodecahedron", 4);
    glutAddMenuEntry("Quit", 0);
    glutAttachMenu(GLUT_RIGHT_BUTTON);
    // Provide a cleanup routine for handling application exit.
    atexit(exitHandler);

    initScene();

    glutMainLoop();

    return 0;

}

/***************************************************************
****************
```

```
 GLUT callback for redrawing the view.
****************************************************************
***************/
void setup() {
       glClearColor(0.3f, 0.0f, 1.0f, 0.0f);
}

void glutDisplay()
{
    drawSceneHaptics();

    drawSceneGraphics();

    glutSwapBuffers();
}

/***************************************************************
****************
 GLUT callback for reshaping the window.  This is the main place
where the
 viewing and workspace transforms get initialized.
****************************************************************
***************/
void glutReshape(int width, int height)
{
    static const double kPI = 3.1415926535897932384626433832795;
    static const double kFovY = 40;

    double nearDist, farDist, aspect;

    glViewport(0, 0, width, height);

    // Compute the viewing parameters based on a fixed fov and
viewing
    // a canonical box centered at the origin.

    nearDist = 1.0 / tan((kFovY / 2.0) * kPI / 180.0);
    farDist = nearDist + 2.0;
    aspect = (double) width / height;

    glMatrixMode(GL_PROJECTION);
    glLoadIdentity();
    gluPerspective(kFovY, aspect, nearDist, farDist);

    // Place the camera down the Z axis looking at the origin.
    glMatrixMode(GL_MODELVIEW);
    glLoadIdentity();
    gluLookAt(0, 0, nearDist + 1.0,
              0, 0, 0,
              0, 1, 0);

    updateWorkspace();
}

/***************************************************************
```

```
****************
 GLUT callback for idle state.  Use this as an opportunity to
request a redraw.
 Checks for HLAPI errors that have occurred since the last idle
check.
****************************************************************
***************/
void glutIdle()
{
    HLerror error;

    while (HL_ERROR(error = hlGetError()))
    {
        fprintf(stderr, "HL Error: %s\n", error.errorCode);

        if (error.errorCode == HL_DEVICE_ERROR)
        {
            hduPrintError(stderr, &error.errorInfo,
                "Error during haptic rendering\n");
        }
    }

    glutPostRedisplay();
}

/***************************************************************
***************
 Popup menu handler.
****************************************************************
**************/
void glutMenu(int ID)
{
    switch(ID) {
        case 0:
            exit(0);
            break;
      case 1:
            shape = 1;
            break;
      case 2:
            shape = 2;
            break;
      case 3:
            shape = 3;
            break;
      case 4:
            shape = 4;
            break;
    }
}

/***************************************************************
****************
 Initializes the scene.  Handles initializing both OpenGL and
HL.
```

```
***************************************************************
**************/
void initScene()
{
    initGL();
    initHL();
}

/**************************************************************
***************
 Sets up general OpenGL rendering properties: lights, depth
buffering, etc.
***************************************************************
**************/
void initGL()
{
    static const GLfloat light_model_ambient[] = {0.3f, 0.3f,
0.3f, 1.0f};
    static const GLfloat light0_diffuse[] = {0.9f, 0.9f, 0.9f,
0.9f};
    static const GLfloat light0_direction[] = {1.0f, -0.0f,
0.4f, 0.0f};

    // Enable depth buffering for hidden surface removal.
    glDepthFunc(GL_LEQUAL);
    glEnable(GL_DEPTH_TEST);

    // Cull back faces.
    glCullFace(GL_BACK);
    glEnable(GL_CULL_FACE);

    // Setup other misc features.
    glEnable(GL_LIGHTING);
    glEnable(GL_NORMALIZE);
    glShadeModel(GL_SMOOTH);

    // Setup lighting model.
    glLightModeli(GL_LIGHT_MODEL_LOCAL_VIEWER, GL_FALSE);
    glLightModeli(GL_LIGHT_MODEL_TWO_SIDE, GL_FALSE);
    glLightModelfv(GL_LIGHT_MODEL_AMBIENT, light_model_ambient);
    glLightfv(GL_LIGHT0, GL_DIFFUSE, light0_diffuse);
    glLightfv(GL_LIGHT0, GL_POSITION, light0_direction);
    glEnable(GL_LIGHT0);
}

/**************************************************************
***************
 Initialize the HDAPI.  This involves initing a device
configuration, enabling
 forces, and scheduling a haptic thread callback for servicing
the device.
***************************************************************
**************/
void initHL()
{
```

```
    HDErrorInfo error;

    ghHD = hdInitDevice(HD_DEFAULT_DEVICE);
    if (HD_DEVICE_ERROR(error = hdGetError()))
    {
        hduPrintError(stderr, &error, "Failed to initialize
haptic device");
        fprintf(stderr, "Press any key to exit");
        getchar();
        exit(-1);
    }

    ghHLRC = hlCreateContext(ghHD);
    hlMakeCurrent(ghHLRC);

    // Enable optimization of the viewing parameters when
rendering
    // geometry for OpenHaptics.
    hlEnable(HL_HAPTIC_CAMERA_VIEW);

    // Generate id for the shape.
    gShapeId = hlGenShapes(1);

    hlTouchableFace(HL_FRONT);
}

/****************************************************************
****************
 This handler is called when the application is exiting.
Deallocates any state
 and cleans up.
*****************************************************************
***************/
void exitHandler()
{
    // Deallocate the sphere shape id we reserved in initHL.
    hlDeleteShapes(gShapeId, 1);

    // Free up the haptic rendering context.
    hlMakeCurrent(NULL);
    if (ghHLRC != NULL)
    {
        hlDeleteContext(ghHLRC);
    }

    // Free up the haptic device.
    if (ghHD != HD_INVALID_HANDLE)
    {
        hdDisableDevice(ghHD);
    }
}

/****************************************************************
****************
 Use the current OpenGL viewing transforms to initialize a
```

```
transform for the
 haptic device workspace so that it's properly mapped to world
coordinates.
*************************************************************
***************/
void updateWorkspace()
{
    GLdouble modelview[16];
    GLdouble projection[16];
    GLint viewport[4];

    glGetDoublev(GL_MODELVIEW_MATRIX, modelview);
    glGetDoublev(GL_PROJECTION_MATRIX, projection);
    glGetIntegerv(GL_VIEWPORT, viewport);

    hlMatrixMode(HL_TOUCHWORKSPACE);
    hlLoadIdentity();

    // Fit haptic workspace to view volume.
    hluFitWorkspace(projection);

    // Compute cursor scale.
    gCursorScale = hluScreenToModelScale(modelview, projection,
viewport);
    gCursorScale *= CURSOR_SIZE_PIXELS;
}

void drawString(const char* string)
{
    for (;*string != '\0';++string)
    {
        glutBitmapCharacter(GLUT_BITMAP_HELVETICA_18, *string);
    }
}

/************************************************************
****************
 The main routine for displaying the scene.  Gets the latest
snapshot of state
 from the haptic thread and uses it to display a 3D cursor.
*************************************************************
***************/
void drawSceneGraphics()
{
    glClear(GL_COLOR_BUFFER_BIT | GL_DEPTH_BUFFER_BIT);

    // Draw 3D cursor at haptic device position.
    drawCursor();

    glEnable(GL_COLOR_MATERIAL);

    glColor3f(1.0f, 0.0f, 1.0f);
    getShape();
    //glRasterPos2f(-1.8, 1.3);
    //drawString("Touch an object and press button to drag.\n" +
```

```
STIFFNESS);
}

/****************************************************************
****************
 The main routine for rendering scene haptics.
*****************************************************************
***************/
void drawSceneHaptics()
{
    // Start haptic frame.  (Must do this before rendering any
haptic shapes.)
    hlBeginFrame();

    // Set material properties for the shapes to be drawn.
    hlMaterialf(HL_FRONT_AND_BACK, HL_STIFFNESS, STIFFNESS);
    hlMaterialf(HL_FRONT_AND_BACK, HL_DAMPING, DAMPING);
    hlMaterialf(HL_FRONT_AND_BACK, HL_STATIC_FRICTION,
STATIC_FRICTION);
    hlMaterialf(HL_FRONT_AND_BACK, HL_DYNAMIC_FRICTION,
DYNAMIC_FRICTION);

    // Start a new haptic shape.  Use the feedback buffer to
capture OpenGL
    // geometry for haptic rendering.
    hlBeginShape(HL_SHAPE_FEEDBACK_BUFFER, gShapeId);

    // Use OpenGL commands to create geometry.
    getShape();

    // End the shape.
    hlEndShape();

    // End the haptic frame.
    hlEndFrame();

}

void getShape (){
    if (shape == 1) return glutSolidSphere(0.5, 100, 100);
    if (shape == 2) return glutSolidCube(0.5);
    if (shape == 3) glutSolidTetrahedron();
    if (shape == 4) {
     glPushMatrix();
        glScalef(0.5,0.5,0.5);
        glutSolidDodecahedron();
        glPopMatrix();
    }
}



/****************************************************************
****************
 Draws a 3D cursor for the haptic device using the current local
```

```
transform,
 the workspace to world transform and the screen coordinate
scale.
****************************************************************
***************/
void drawCursor()
{
    static const double kCursorRadius = 50;
    static const double kCursorHeight = 50;
    static const int kCursorTess = 15;
    HLdouble proxyxform[16];

    GLUquadricObj *qobj = 0;

    glPushAttrib(GL_CURRENT_BIT | GL_ENABLE_BIT |
GL_LIGHTING_BIT);
    glPushMatrix();

    if (!gCursorDisplayList)
    {
        gCursorDisplayList = glGenLists(1);
        glNewList(gCursorDisplayList, GL_COMPILE);
        qobj = gluNewQuadric();

        gluSphere(qobj, 1, kCursorRadius, kCursorHeight);
        glTranslated(0.0, 0.0, kCursorHeight);

        gluDeleteQuadric(qobj);
        glEndList();
    }

    // Get the proxy transform in world coordinates.
    hlGetDoublev(HL_PROXY_TRANSFORM, proxyxform);
    glMultMatrixd(proxyxform);

    // Apply the local cursor scale factor.
    glScaled(gCursorScale, gCursorScale, gCursorScale);

    glEnable(GL_COLOR_MATERIAL);
    glColor3f(0.0, 0.5, 1.0);

    glCallList(gCursorDisplayList);

    glPopMatrix();
    glPopAttrib();
}

void keyUp(unsigned char key, int x, int y)
{
    keyStates[key] = false;
    switch (key) {
    case 27: //escape
      exit(0);
      break;
```

```
    case '#': //reset
     STIFFNESS = 0.05;
     STATIC_FRICTION = 0.05;
     DYNAMIC_FRICTION = 0.05;
     break;

    case 'q':
     if (STIFFNESS<0.95) STIFFNESS = STIFFNESS+0.05;
     printf("Stiffness: %4.2f \n", STIFFNESS);
     strcat_s(stiffnessCounter, "Up, ");
     break;

    case 'w':
     if (STIFFNESS>0.05) STIFFNESS = STIFFNESS-0.05;
     printf("Stiffness: %4.2f \n", STIFFNESS);
     strcat_s(stiffnessCounter, "Down, ");
     break;

    case 'a':
     if (STATIC_FRICTION<0.95) STATIC_FRICTION = 
STATIC_FRICTION+0.05;
     printf("Static Friction: %4.2f \n", STATIC_FRICTION);
     strcat_s(staticCounter, "Up, ");
     break;

    case 's':
     if (STATIC_FRICTION>0.05) STATIC_FRICTION = 
STATIC_FRICTION-0.05;
     printf("Static Friction: %4.2f \n", STATIC_FRICTION);
     strcat_s(staticCounter, "Down, ");
     break;

    case 'z':
     if (DYNAMIC_FRICTION<0.95) DYNAMIC_FRICTION = 
DYNAMIC_FRICTION+0.05;
     printf("Dynamic Friction: %4.2f \n", DYNAMIC_FRICTION);
     strcat_s(dynamicCounter, "Up, ");
     break;

    case 'x':
     if (DYNAMIC_FRICTION>0.05) DYNAMIC_FRICTION = 
DYNAMIC_FRICTION-0.05;
     printf("Dynamic Friction: %4.2f \n", DYNAMIC_FRICTION);
     strcat_s(dynamicCounter, "Down, ");
     break;

    case 'p':

    printf("\n**************************************************
***********************\n");
     printf("*\tStiffness\t Static Friction\t Dynamic 
Friction\t*\n");
     printf("*\t%4.2f\t\t %4.2f\t\t\t %4.2f\t\t\t*\n", 
STIFFNESS, STATIC_FRICTION, DYNAMIC_FRICTION);
```

```
    printf("****************************************************
*********************\n");
      std::ofstream fs("text.txt");
      fs<< ("%s",stiffnessCounter);
      fs<<std::endl;
      fs<< ("%s", staticCounter);
      fs<<std::endl;
      fs<< ("%s", dynamicCounter);
      fs<<std::endl;
      break;
    }
}


/***************************************************************
***************/
```