Analysis of the JND of Stiffness in Three Modes of Comparison

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Abstract. Understanding and explaining perception of touch is a non-trivial task. Even seemingly trivial differences in exploration may potentially have a significant impact on perception and levels of discrimination. In this study, we explore different aspects of contact related to stiffness perception and their effects on the just noticeable difference (JND) of stiffness are surveyed. An experiment has been performed on non-deformable, compliant objects in a virtual environment with three different types of contact: Discontinuous pressure, continuous pressure and continuous lateral motion. The result shows a significantly better discrimination performance in the case of continuous pressure (a special case of nonlinearity), which can be explained by the concept of haptic memory. Moreover, it is found that the perception is worse for the changes that occur along the lateral axis than the normal axis.

Keywords: Perception, stiffness, exploratory procedures, JND

1 Introduction

Research in haptics has extensively grown in the last decade within different disciplines. In addition to improvements in hardware and software solutions, the way we, as human beings, perceive objects by the act of touching has also been under focus in the psychophysics branch. Understanding our perception mechanism as well as our limitations has the potential to guide the development of more effective haptic hardware and software solutions.

Various physical and geometrical properties of objects have been surveyed under the concept of perception. Perception of touch, however, is not easy to explain considering that several factors play a role in the process. The perception of an object is tightly bound to the nature of the contact, which may include one or more different exploratory procedures [5]. Static contact, lateral motion, contour following and pressure are among the various ways of touch providing different kinds of perception cues [5]. Some studies have proven that the choice of exploratory procedures has a significant effect on the perception of the object. For example, [4, 12] showed that the type of sensory requirements for an optimal softness discrimination differ between exploring with a tool and exploring with fingers.

One of the most frequently surveyed material properties is stiffness (or compliance) since it refers to hardness/softness, which is one of the major components to understand the type of the material. Several studies have been conducted on just noticeable difference (JND) with different scenarios and ranges. The effects of exploratory procedures on stiffness perception, however, has not been shown as much interest. There are a few studies [2, 4, 12] surveying different aspects of contact on perception.

We suspect that understanding the effects of exploratory procedures on perception has the potential to affect our choices of exploration in real life by helping us choose better exploration techniques for different purposes. In this study, therefore, we explore the effects of some aspects of exploratory procedures on stiffness perception. We start by identifying and discussing different stiffness transitions which may occur in real situations such as surgery and clinical palpation. We explore whether touching continuously or discontinuously affects the stiffness discrimination. In the case of continuous contact, the discrimination of stiffness along lateral and normal axis are also compared. The unique aspect of the study is the comparison of the JNDs of stiffness for three different types of contact. The dependency of stiffness JND on the nature of the contact has been surveyed by an experiment performed with the subjects in a virtual environment. The results show that JND is significantly affected by the way we touch.

2 Related Work

Numerous perception studies have considered the various physical and geometrical properties of objects as well as the effects of different modalities and ways of grasping. Stiffness (or compliance) is one of the most studied properties, representing the hardness or softness of an object. The most common means to explore stiffness perception is to present a measure showing how well humans can perceive the varying levels of hardness or softness; to present this in the form of a JND. The results found vary depending on the differences between the methods employed. Effects of other factors such as multi-modality, cutaneous, kinaesthetic cues are also being surveyed.

There are a number of studies (e.g [14]) which have examined the JND in the stiffness. The effects of force and work cues on compliance discrimination were surveyed in [13] and the significant effect of force cues on discrimination was emphasized. In [15], the effect of surface deformation cues was examined and it was shown that the subjects' ability to discriminate the difference in stiffness was reduced by a factor of more than three without deformation cues.

The effect of visual information on stiffness perception was explored in the studies [11, 16]. A dominance of visual feedback over kinaesthetic sense of hand position was demonstrated in [11]. Compliant objects that are further away were perceived to be softer in the case of haptic feedback alone [16], while the addition of the visual information reduced the bias.

Further studies [2, 4, 12] have examined the effects of exploratory procedures on stiffness perception. These exploratory procedures directly affect which properties of the object can be observed and how we perceive them. In [12], the contribution of tactile and kinaesthetic cues were explored for deformable and non-deformable objects. It was shown that the tactile information alone is sufficient for discrimination capacity of deformable objects while additional kinaesthetic feedback is necessary for non-deformable compliant objects. When a tool was used for exploration, additional kinaesthetic cues were found to be necessary for all types of objects [4]. Squeezing a deformable object between thumb and index finger was explored in [2, 9]. Tactile information was found to be negligible for the scenario of squeezing objects between thumb and index finger [9]. These findings in the literature demonstrate the importance of the exploratory procedure in perception.

Some of the studies mentioned above explore different aspects of exploratory procedures but none of them compare the stiffness perception during different modes of transition, which we anticipate will be important in both real situations and computer simulated environments.

3 Modes Of Transition

There are various ways of exploring an object including poking, contour following, squeezing, tapping with a tool, etc. Mainly the style of the motion, how we move our hands (or a tool), results in different exploratory techniques. If exploration is considered from the surface point of view, there are two principle directions: Normally directed and lateral motion. The movement along the normal direction refers to pushing into an object by applying a pressure, providing a sense of hardness [5]. The term "lateral motion" is mostly used for the exploration technique to obtain information about the texture of a surface [5], however we will consider the "lateral motion", as in [1], as the movements of the haptic device performed to perceive the topography of a surface like in the case of contour following. This type of lateral motion is common in real life situations such as palpation, surgical cuts, drawing or painting.

In addition to the direction of movement we also consider how the transition occurs between two different stiffnesses during comparison. One type would be comparison of two objects with different stiffnesses by separately touching the objects, which we call discontinuous contact. Another way of comparison is to discriminate a stiffness change during exploration without taking the probe away from the object. We call the latter one continuous the contact.

The combination of the two concepts of touch—continuity and the motion axis—creates different exploration scenarios as illustrated in figure 1. We aim to survey stiffness perception under these concepts by finding the JND of stiffness. The different conditions of the experiment are named depending on the type of contact.

DP-Discontinuous Pressure Comparison : In *Discontinuous Pressure Comparison* the contact refers to applying a pressure normal to the surface of

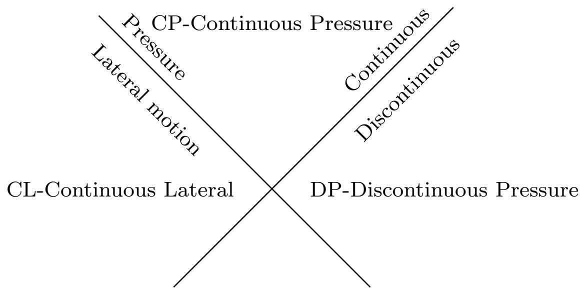


Fig. 1. Two aspects of contact during stiffness change: Continuity and Axis of Motion. The discontinuity during touch refers to touching discrete objects separately in order to discriminate the stiffness difference between them. While continuity corresponds to stiffness change during contact with the same object. The continuous stiffness change has been surveyed as two types: Lateral stiffness change and stiffness change along the surface normal axis during applied pressure, which is a special case of nonlinearity.

an object and separately touching different objects in order to compare their hardness. In other words, the subject experiences a pause in the time domain between exploration of different stiffness values. This is the most common procedure followed in perception studies (e.g [12, 4, 11]).

CP-Continuous Pressure Comparison : When one is applying palpation to a surface, it is common in real life that the ratio of stress to strain changes with strain resulting in a stiffness that changes during contact. One can wonder how sensitive human beings are to these changes or whether we perceive or react differently than the previous condition (*Discontinuous Pressure (DP)*).

Similarly to visual memory, our minds can remember the perceived touch information for a limited period of time after a haptic exploration. The perceived information in the brain decays with time, which shows the limitation of the haptic memory. For instance in [10], the representation of object mass was found to be short-lived (two seconds). In the case of stiffness comparison, the interruption during discontinuous contact forces us to remember the pervious representation while touching an object. Discrimination of the changes during continuous contact has no such memory demand since the change occurs at a transition point during contact and perceiving the transition itself is sufficient for discrimination, instead of explicit comparison of stiffnesses. The case of *Continuous Pressure Comparison* can be thought of as detecting a transition instead of a memory task. Therefore it would be reasonable to expect better performance in the discrimination when the change occurs continuously allowing exploration without interruption.

In addition to the differences in the nature of *Continuous Pressure Comparison* and *Discontinuous Pressure Comparison*, the rarity of pure linear stiffnesses in real life scenarios also makes it interesting to survey the discrimination that occurs during palpation. Tumours underneath a tissue, bone structure under a fat layer, feeling veins during needle insertion are some cases with stiffness varying with strain. In addition, most soft tissues are also known to show nonlinear behaviour, but to the authors' knowledge there has been very little work on the perception of nonlinearity in stiffness. In [6] the perception of nonlinearity and in [8] the effects of shear and normal forces of nonlinear tissues on perception were explored. In neither of these studies, however, was the JND explored. In the *Continuous Pressure Comparison* condition we are surveying a special case of nonlinearity.

CL-Continuous Lateral Comparison : During *Continuous Lateral Comparison*, the stiffness is to be discriminated continuously but a change occurs with respect to lateral motion over the surface. This condition should not be confused with the use of lateral motion of fingers touching a texture for tactile information. The movement of the haptic device resembles contour following, possibly providing kinaesthetic cues, however, we include no contour change in our study, but instead, survey the discrimination of stiffness across a flat surface.

The concept of kinaesthetic height cues from varying stiffness over lateral motion was surveyed in [1]. Instead of the stiffness perception, Choi et al. focused on how hand movement is affected by the stiffness changes during lateral motion over the surface and came up with the force constancy theory. It was shown that during exploration of a virtual surface by a haptic probe, the user has a tendency to keep the applied force constant. This results in a change in the height of hand position due to a stiffness change during exploration of a flat surface. In our case of lateral motion, we are interested in perception of the stiffness changes, therefore visual cues about the height of hand position were eliminated during the experiment.

The fourth possible combination (Discontinuous-Lateral) describes discrimination between the stiffness of two separate objects under lateral motion with a pause between each palpation. This scenario is not considered in this survey since we see no important applications to real life situations.

4 Evaluation

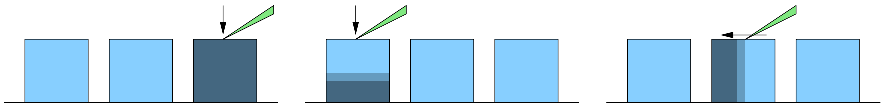
To explore the effect of the three different contact types (hereafter referred to as conditions) on stiffness perception as described above, we performed an experiment. The following section describes the method applied.

4.1 Method

The experiment was performed in a virtual environment and a Desktop Phantom and a semi-transparent framework were used as the equipment, as illustrated in figure 2(a). Each stimulus was composed of three virtual boxes (providing force feedback depending on *Hooke's law*) that were visually rendered as in figure 2(b). The orientation of the boxes was adjusted such that the palpation occurs on the axis perpendicular to the desk. The boxes were not visually changing due to the compression and the haptic probe was rendered as a sphere which disappeared in the boxes during contact in all situations to prevent the visual cues about the

(a) The experiment framework (b) A screenshot of the experiment

Fig. 2. (a) A 3D virtual image registered with the real hand position is obtained with the help of a semi-transparent mirror and stereo glasses. (b) The type of the experiment and the question number was rendered at the top of the view.



(a) Condition DP (b) Condition CP (c) Condition CL

Fig. 3. Three virtual boxes were presented to the subjects during each individual trial. The subjects were asked to find the single harder box among the three and the location of the harder box was randomized during the experiment. The way the harder box differed from the others depended on the type of the experiment. Interpolation is applied around the transition region in condition CP and CL to prevent an obvious discontinuity in stiffness.

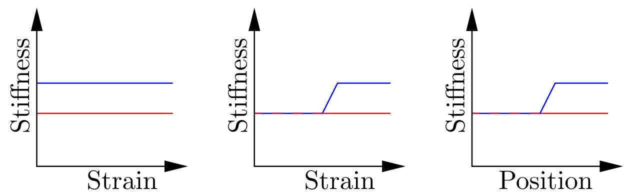
strain applied. The subject was also prevented from seeing the real hand position under the semi-transparent mirror by setting the background color to bright white. In each individual trial the subjects were thus presented with three boxes. Two of the boxes were identical while one of them was harder in different ways depending on the specific condition, see description below. The force feedback from the boxes was evaluated by multiplying the stiffness and the depth of probe from the surface of the box, based on Hooke's Law.

Three different conditions were designed: DP, where the subjects were presented with three different boxes with linear stiffness, one of which was harder than the other two which had the reference stiffness, (figure 3(a)). The second condition, CP, included two boxes with reference stiffness and a third one which has a nonlinear stiffness as illustrated in figure 3(b). The nonlinearity was modelled as two piece-wise linear stiffnesses. The first linear region had the same stiffness as the other two boxes while the second linear region was always harder. In the third condition, CL, one of the three boxes had the reference stiffness on the right half while the left side was set to a harder stiffness, (figure 3(c)). The subjects were asked to make a lateral motion over the surface for CL and to apply a downward palpation for the other two conditions. The higher stiffness in each condition was changed depending on the subjects' responses, while the reference stiffness was kept constant. The relationship between the higher stiffness and the reference stiffness for each condition is illustrated in figure 4.

For all three conditions the height of the boxes were set to 3 cm. In the literature a wide range of reference stiffnesses, varying from 100 N/m to 16900 N/m [2], have been surveyed. During several pilot studies various stiffness values had been tried out. It was observed that the continuous use of the haptic device with higher stiffness values can result in overheating of the motors, requiring a break for the system to cool down. Finally, 100 N/m was determined as a reference stiffness.

In *CP*, which models nonlinearity as two piece-wise linear functions, the first linear region was active for strains less than 2 cm and the second for larger strains. In *CL* the subjects were told to make ‘sweeping’ movements sideways (left-to-right-to-left) across the surface. The horizontal position of the change was kept constant in the middle. In these two conditions which include a transition point, linear interpolation was applied across a neighbourhood of the transition point in order to prevent an obvious discontinuity. This interpolation region, however, was chosen small enough (0.5 cm) during pilot studies such that only two different stiffness values would be perceived.

To establish the just noticeable difference (JND) of stiffness a one-up two-down adaptive staircase procedure was used [7]. An adaptive staircase starts with an initial difference and, depending on an individual subject’s responses, it changes the magnitude of the difference such that it converges to the perception limit of discrimination for that subject. In the case of a one-up two-down staircase, the magnitude is decreased following two consecutive correct responses and increased after each single incorrect response. This procedure converges to a stimulus level at which participants can make accurate responses with a certainty of 70.7%. In our case each session started with a stiffness difference of 20 N/m (20% of the reference stiffness value). Initially, the stiffness difference was changed by increments of 9 N/m and then by 4.5 N/m after the third reversal and by 2.25 N/m after the sixth reversal. A reversal occurred when the stiffness changed from increasing to decreasing, or vice versa. The session was



(a) Condition DP (b) Condition CP (c) Condition CL

Fig. 4. The stiffness changes for the conditions. The blue and red lines refer to the reference and the harder stiffnesses respectively. In condition DP, the act of touching for distinguishing between different levels of stiffness occurs discontinuously, while in condition CP and CL the subjects were to feel the difference during continuous contact. Interpolation results in a smoother change around the transition region for conditions CP and CL.

terminated after nine reversals and the average of the peaks and valleys of the last six reversals were calculated to be the JND.

Twelve subjects took part in the experiment, 10 male and 2 female. They were all undergraduate or graduate students aged between 27 and 40 years (mean age was 30). 8 of the subjects had tried a haptic device a few times previous to the experiment, 3 had used it quite often, and 1 had never tried it before. All subjects had normal or corrected to normal vision. They received no compensation for taking part in the experiment.

The evaluation was performed as a within-subjects design with one independent variable (stiffness) having three levels (DP vs. CP vs. CL) or conditions. The experiment was performed over three separate sessions where each condition was carried out once. The presentation order of the conditions for each subject was balanced by using a Latin-square procedure. The placement of the harder box was randomized for each trial.

Before the experiment began background information was obtained from each subject. They then reviewed written instruction material and were instructed about the equipment and the tasks to be performed. Before each of the three separate sessions they also completed a set of practice trials. For each individual trial the task was to identify the harder box, out of the three, and give a response by pressing a button placed on the haptic device while pointing to that box. They were told to make a sweeping movement across the surface of the boxes for the CL session, to apply a downward palpation for the other two sessions. Total participation time lasted 30–40 minutes (including the introductory part).

5 Results

The values of each subject for all three conditions were analyzed for the 12 participants. Since the data deviated from normality according to the Kolmogorov-Smirnov and Shapiro-Wilks tests, non-parametric tests were used. A Friedman ANOVA by ranks with a decision criterion of 0.05 showed that there was a significant difference between the three conditions, Chi-Square (N=12 , df=2) = 12.667 p= 0.001.

To determine which conditions significantly differ, Wilcoxon signed-rank tests were used for post-hoc testing and a Bonferroni correction was applied meaning that all effects are reported at a 0.0167 (0.05/3) level of significance. There was a significant difference between condition DP and condition CP, Z=-3.061 $p<0.001$ and between CL and CP, z=-4.71 p=0.003 but no significant difference was observed between conditions DP and CL, Z=-2,746 p=0.677.

The analysis of the results shows that the discrimination performance due to nonlinearity of stiffness is much better than the other two conditions: the stiffness change along lateral motion and comparing objects with different stiffness. The mean value of the JND for the nonlinearity case (*Continuous Pressure*) is $5.23\pm3.01\%$, while the *Discontinuous Pressure* and *Continuous Lateral* contacts have a mean JND of $12.91\pm6.93\%$ and $15.77\pm9.59\%$ respectively.

6 Discussion and Conclusions

The aim of the study was to compare the stiffness discrimination for different scenarios representing different exploration techniques. Some studies [2, 4, 5, 12] and the variance of the results of JND studies support that the perception is not trivial to explain and is affected by several factors including the exploratory procedure. Creating a scenario including all factors affecting perception is a challenging task, however we performed an experiment considering two aspects of touch: continuity and the axis of motion.

An experiment was performed to find the JND of stiffness for three different scenarios of contact: *Discontinuous pressure*, *Continuous pressure* (nonlinearity) and *Continuous lateral*. Instead of comparing the numerical JND values one by one with previous perception studies, we compared the JND performances between these different types of contact. Our main reasoning being that the studies [2, 4, 5, 12] support the idea that perception is affected by several factors, therefore the numerical values depend on the experiment design. The comparison between the three contact scenarios shows that the discrimination performance is significantly better for the nonlinearity case than the others.

The significant difference between the results of *Continuous Pressure* and *Discontinuous Pressure* was expected due to the concept of haptic memory: the reason for the difference between the JNDs then being the interruption between exploring different stiffnesses. One interesting fact, however, is the substantial difference between the *Continuous Pressure* and *Continuous Lateral* showing the effect of the motion axis on discrimination, which brings us to the second outcome of the study: better discrimination along normal axis than lateral axis.

The only difference between the conditions *Continuous Pressure* and *Continuous Lateral* is that the stiffness change occurs along a different axis. A possible reason for a worse discrimination along the lateral axis might be the *force constancy* principle [1] which states that a user will subconsciously absorb changes in the normal directed force during lateral surface exploration.

The choice of exploratory procedures is related to the aim of the exploration and the type of object. In addition to quantification of our sensitivity to force and stiffness, it is also important to understand how it is affected by the exploratory procedures we choose. This knowledge has the potential to affect our choices of exploration in real life. For instance, the scenarios surveyed in this study, contact including nonlinearity and lateral motion is commonly observed in some medical procedures such as diagnosing a tumour, surgery, needle insertions etc. Knowing our limitations for different types of exploration could help us choose better exploration techniques for different aims. The limitation of our study is the difference between the tested and real life scenarios. For instance, observing nonlinearity in the form of two piecewise linear functions in real life is not so common. The significant results, however, are promising to continue exploring the topic with more realistic scenarios.

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