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Effect of Roughness, Compliance and Adhesion on Perception of Softness

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ABSTRACT

This paper concerns the perceived softness of objects, which is an important aspect of haptic perception. To design tactile displays, there are many unanswered questions about human touch perception and its relationship with material properties. This paper explores how the interaction of material properties affects perception of softness through the use of two psychophysical experiments. The first experiment used a set of nine stimuli representing three materials of different compliance, embossed with three different patterns to vary their surface roughness. The second used three materials of different compliance with three different coatings to vary their stickiness. Magnitude estimation was used to assess the perceived softness for the stimuli in both experiments under two conditions: pressing into the stimulus with the finger, and sliding the finger across the stimulus. The results indicated that compliance affected perception of softness when pressing the finger, but not when sliding; and that compliance, friction and thermal conductivity all influenced the perception of softness. This work is an essential step to understand interactions between compliance and other material properties. The new knowledge can be applied to the design of tactile displays for laparoscopic surgery.

Keywords: *human perception, softness, compliance, roughness, stickiness, tactile displays*.

1. Introduction

There are many situations in which being able to judge the softness or hardness of a surface is important. Surgery is one example, where tumours are detected by palpitation, looking for harder patches amongst softer, healthy tissue. Yet we know that mechanisms by which the body detects material properties can be influenced by other factors (Ottermo, 2006, Gersem, 2005). This can be important both in terms of determining how human judgements of material properties, such as softness, can be affected by other factors, and also in accurately reproducing sensations through tactile displays, which are proposed for use in situations such as laparoscopic surgery, where direct tactile feedback is not available (Ottermo, 2008). This paper investigates how subjective human perception of material softness, is affected by the compliance, roughness and adhesion of a given material.

A range of studies has explored the relationship between surface properties and human perception of them. (Hollins et al., 1993) identified hardness-softness as one of the main subjective responses used by humans to discriminate surfaces, the other being roughness-smoothness. However, subjective perception of roughness and softness can be affected by more than one physical parameter ((Bergmann Tiest and Kappers, 2006), Shao et al. (2009)). For example, Chen et al. (2009a) found that judgements of hardness-softness depended on both compliance and cooling rate. Perceptions of softness or hardness can also be affected by factors such visual feedback and the mode of interaction (static or dynamic touch, for example) (Koçak et al., 2011, Harper and Stevens, 1964, Srinivasan and LaMotte, 1995). Harper and Stevens (1964) were able to relate the objective measure (compliance) and the subjective sensation (perceived softness) by building a quantifiable model of compliance discrimination using numerical ranking of perceived softness. This study has one shortcoming, that compliance was quantified without control of surface texture. This means that the influence of texture for the different materials and surface properties on the subjective ranking of compliance is uncertain. The softness and hardness depended on the degree to which the object conforms to the body and to which the body conforms to the object respectively. This means that different kinds of sensory information are used to assess the soft versus hard objects (Friedman et al., 2008). The aim of this paper is to determine whether some of the interactions exist between the physical properties which effect the subjective perception. The same investigation was performed earlier (Shao et al., 2010), however, the experiments in this study were conducted with better experimental designed, and under more restricted control. This paper presents two experiments intended to further this exploration of the interaction between perceived softness and physical properties, by exploring the effect of roughness and stickiness on perceived softness.

2. Methodology

The goal of the first experiment (effect of surface roughness on perceived softness) was to determine whether surface roughness affected the perceived softness of a material. To do this, a set of experimental stimuli were created that represented different textures indented into different materials using magnitude estimation, and participants were asked to rate the softness of each texture by running their finger across it and by pressing their finger into it (as shown in Figure 1).

The second experiment (effect of adhesion and compliance on perception of softness) aimed at characterizing how surface adhesion and compliance affect the perception of softness. To accomplish this aim, there are several methods that could be used, but the method applied is magnitude estimation, which is fully explained later, by varying the level of stickiness of each sample.

2.1. Participants

Twenty four participants took part in each experiment (7 females and 17 males for first experiment and 11 females

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and 13 males for second experiment), their age ranged between 20 and 49. Through a handedness inventory questionnaire was adapted from the handedness questionnaire by Briggs and Nebes (1975). They completed at the laboratory, all of the participants were found to be right handed for each experiment but one the left handed participant was a male in his twenties in first experiment. None of the subjects reported any neurological or physical injury that affected sensitivity of the index figures of both hands. The experiments were approved by the Faculty Research Ethics Committee at University of Leeds.

2.2. Stimuli

For first experiment, nine stimuli were made for first experiment, representing all combinations of three different levels of compliance and three different levels of roughness. Stimuli were produced in square 100mm × 100mm plaques, 10mm thick. These were made using a hot pressing process from thermoplastic polyurethane material of varying hardnesses (IROGRAN A 60 E 4902, PS455-203, PS440-200). Samples of stimuli are shown in Figure 2. Three textured aluminium sheets with different surface roughness were used to impress the plaques with different textures as shown in Figure 3.

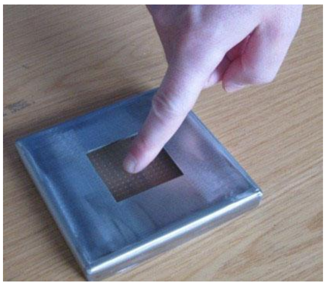

Fig. 1: Stimulus during touching.

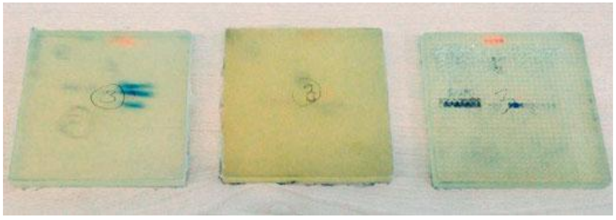

Fig. 2: Sample of stimuli made of thermoplastic polyurethane.

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

For the second experiment, a nine stimuli set representing all combinations of three levels of compliance and three levels of adhesion were created for each stimulus. Stimuli were varied by mixing platsil gel 10 parts A and B with different amounts of plasticizer. Moreover, platsil, plasticizer and toluene were mixed and applied in a thin layer of stickiness on the surface of softer blocks. A sample of stimuli is shown in Figure 4.

2.3. Method

In both experiments, the magnitude estimation procedure was used to quantitatively scale participants' perceptions of the softness of the different stimuli.

In the first experiment, the experimental approach used was to develop 3*3 general full factorial designs with the counterbalanced design for four conditions (Pressing and Sliding). These conditions requires 24 orders (4*3*2*1) in which they can occur (Field, 2010). So, Participants were divided into 2 groups to have an equal number of participants in each group; it means that12 participants were in each group. Within each block, the order of presentation of stimuli was randomised. The two-way repeated measures analysis of variance was carried out with the magnitude estimates of perceived softness as dependent variables and compliance levels and roughness levels, as independent variable, to explore relations between the perception of softness and roughness.

In the second experiment, the experimental approach used was to develop 3*3 randomized complete block factorial designs with the counterbalanced design for four conditions (rating softness through pressing, rating stickiness through pressing, rating softness through sliding, rating stickiness through sliding). These conditions requires 24 orders (4*3*2*1), that can occur (Field, 2010). So, participants were divided into 24 groups to have an equal number of participants in each group; it means one participant was in each group. Within each block, the order of presentation of stimuli was randomised. The two-way repeated measures analysis of variance was carried out with the magnitude estimates of perceived softness as dependent variables and softness levels and stickiness levels to explore relations between the perception of compliance and stickiness.

Fig. 4: Sample of stimuli made of silicone and deadener.

2.4. Procedure

Participants took part in this study individually, so that they did not influence each other in their responses. Participants were asked to rate eight of the stimuli against a reference stimulus (Stimulus E) under two different conditions: by pressing into the stimulus with their finger, and by sliding their finger across it. Textures were placed behind a curtain, so that participants could not see the stimuli, to prevent visual feedback interfering with the tactile perception. Two textures were presented at a time: the reference stimulus, and the test stimulus. These were always located in the same position, so that participants knew which was the reference and which was the test stimulus. The two touching conditions (pressing and

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sliding) were blocked and counterbalanced. Within each block, the order of presentation of stimuli was randomised.

The same reference stimulus was used in every case, and participants were asked to give a rating for the softness of the test stimulus using a magnitude estimation process (Lodge, 1981). The participant was told that the reference stimulus had a softness of 20, and asked to assign a rating to the test stimulus such that 40 would indicate twice as soft and 10 half as soft as the reference. Participants could go back and forth between the test and reference stimulus as often as desired before assigning a rating. Stimulus was presented three times for each participant, and the geometric mean was calculated for pressing and sliding condition.

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

The second experiment was carried out using a similar procedure to the previous experiment. During the experiment, participants touched the stimulus under four touch conditions: rating softness through pressing, rating stickiness through pressing, rating softness through sliding and rating stickiness through sliding. After each condition, the participants were allowed to rest for a period of time depending on the participant. The time ranged between (0-6) min. Participants could not see the stimuli during both experiments and rest period. The total experimental time per participant was between 18 minutes and 58 minutes (mean = 35.08 minutes and standard deviation = 9.71) and full study was performed within 8 days.

2.5. Material properties measurement

For each stimulus (for first and second experiments), material properties were measured: compliance was measured using Tribometer (measured using the tribometer presented in (Shao et al., 2010)). The artificial fingertip was replaced by a steel ball of 10 mm diameter. The ball was pressed into the surface of each compliant stimulus and the load was recorded against time, the load should reach around 3N.

The roughness of the stimuli (for first experiment) was measured by contact surface profilometry, using a Talysurf machine with a standard 0.8mm cut-off. Arithmetical roughness Ra (μm), is most popular measure of roughness of the surfaces.

The friction coefficient of each stimulus (for first and second experiments) was measured using a tribometer. For friction measurement, each sample was pressed and slid by forces Fy, Fx respectively were recorded against time. The force applied on each sample was 0.5N.

The thermal conductivity measurement (for first and second experiments) was also measured using the tribometer. The room temperature was recorded by running the program in LabVIEW system during one minute. The fingertip temperature was set up to be +10oC. After setting up the temperature, a force of 1N was applied to make fingertip contact with the stimulus.

In case of measuring stickiness (for second experiment), the artificial fingertip was attached. The contact force was 1N for stickiness.

All measurements were repeated three times at different points across the stimulus and the average obtained.

3. Results

3.1. Results of first experiment

A two-way repeated measure ANOVA was conducted using SPSS to explore relations between the human tactile perception and roughness and to find whether there is interaction between two factors within each condition; this section reviews the results for each condition in turn.

- *Pressing condition*

Mauchly's test [14] indicated that the assumption of sphericity is violated for the main effects of softness, $\chi^2(2) = 41.62$, $p<0.05$, roughness, $\chi^2(2) = 43.20$, $p<0.05$ and interactions between softness and roughness, $\chi^2(9) = 20.67$, $p<0.05$ and so correction of the F-ratio was required for the main effect of softness, roughness and the interactions. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.69$ for the main effect of softness, 0.69 for the main effect of roughness and 0.88 for main effect of interaction between softness and roughness) [14].

All effects are reported as significant at $p<0.05$. The two-way repeated measures ANOVA indicated that there was a significant main effect of compliance on the perception of softness, $F(1.38, 98.05) = 39.39$. This indicated that when the roughness level was ignored, the perception of softness were significant differenced according on the softness levels. There was a significant main effect of level of roughness on the perception of softness, $F(1.37, 97.23) = 26.11$. There was no significant interaction effect between the level of softness and the level of roughness used, $F(3.53, 250.50) = 2.45$, $p>0.05$.

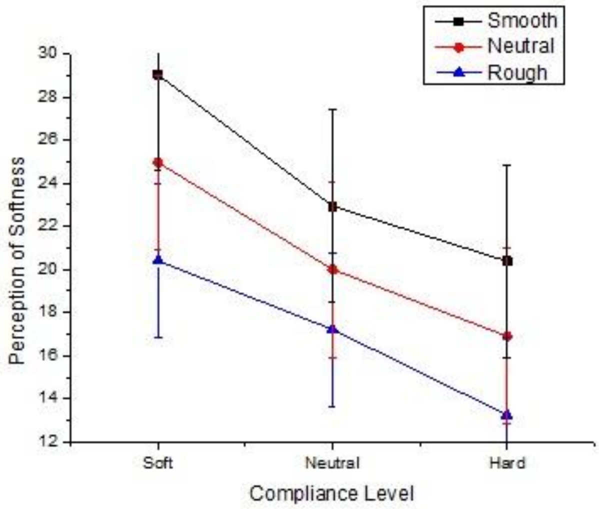

Fig.5: Perceived softness vs compliance at different levels of roughness during pressing condition.

Fig. 5 shows the geometric means for reported softness as a function of compliance in the pressing condition,

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standard deviation error bar and how this varied with the different roughness conditions.

- *Sliding condition*

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of softness, $\chi^2(2) = 9.37$, $p<0.05$. Moreover, it had been violated for the main effects of roughness, $\chi^2(2) = 12.40$, $p<0.05$; also for the main effects of interactions between softness and roughness, $\chi^2(9) = 43.89$, $p<0.05$. So correction of the F-ratio was required for the all effects of softness, roughness and their interaction. Therefore, the degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.89$ for the main effect of softness, 0.86 for the main effect of roughness and 0.76 for the main effect of interaction between softness and roughness).

From the tests of within subjects effects, there was a significant main effect of compliance on the perception of softness, $F(1.78, 126.19) = 11.57$. There was also significant main effect of level of roughness on the perception of softness, $F(1.72, 122.17) = 22.15$, to conclude that there was significant effect of roughness on perception of softness.

There was no significant interaction between the level of softness and the level of roughness used, $F(3.05, 216.33) = 1.84$ on perceived softness. This indicates that roughness had not different effects on perception of softness on different level of softness used for sliding condition.

Figure 6 shows the geometric means for reported softness as a function of compliance in the sliding condition, standard deviation error bar and how this varied with the different roughness conditions. Perceived softness against compliance for both conditions is shown in Figure 7.

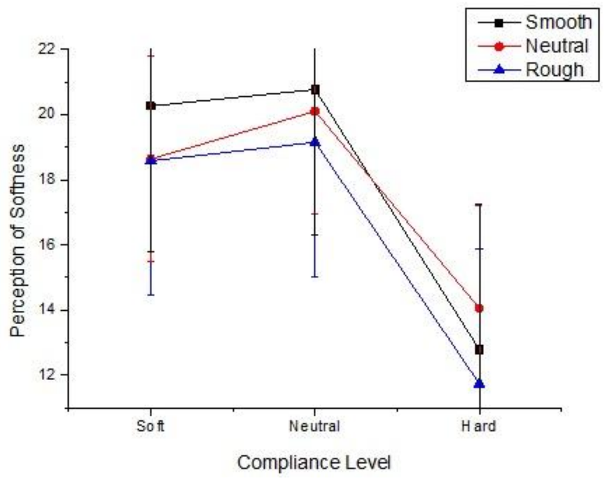

Fig.6: Perceived softness vs compliance at different levels of roughness during sliding condition.

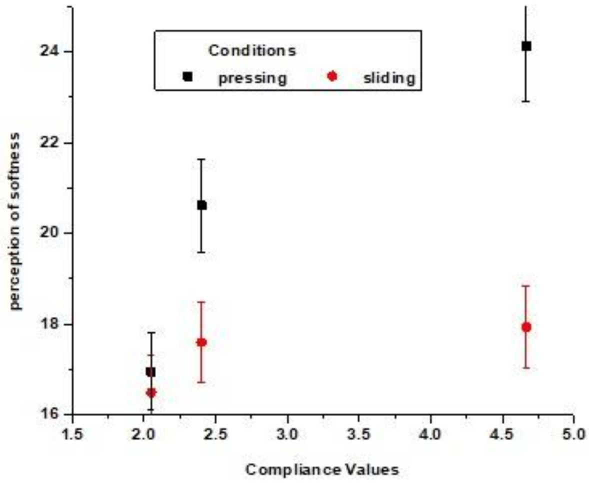

Fig.7: Perceived softness vs compliance.

To examine whether people could discriminate between different softness; the pairwise method was used to collect the data which compares between differences samples at same surface roughness. The results were analysed by Chi-square test to find out if there is any differences among samples. Since the significant value is 0 (which is less than 0.05), there is a significant difference between the levels of softness. It means that participants can distinguish between different compliance for all surface roughness. Table 1 shows the results of Chi-square test.

In order to examine the relationship between physical measurements and softness perception, a Pearson correlation coefficient was computed to assess the relationship between physical properties with perceived softness for both conditions, as shown in Table 2. Also, a regression analysis was used to draw this relationship between perceived softness and physical properties. The results showed that the perception of softness for pressing condition was contributed by compliance as found in previous studies (Shirado and Maeno, 2005, Bergmann Tiest and Kappers, 2006). This means that the perceived softness can be predicted by compliance and as being shown in Table 3.

A Pearson correlation coefficient was computed to assess the relationship between the physical properties with each other. There were not correlations between each physical property with other physical properties. Table 4 summarizes the results.

Table 1: Chi-square analysis for distinguish between softness of stimuli during pressing.

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

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Table 2: Correlations between physical properties and perceived softness during pressing and sliding

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

* Correlation is significant at the 0.05 level

Table 3. Beta coefficients of regression of perceived softness during pressing and sliding

Model	Perceived softness (pressing)	Model	Perceived softness (slidinging)
	Coefficient		Coefficient
Measured compliance	0.750	Friction coefficient	-0.736

Table 4: Correlations between physical properties

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

Correlation is significant at the 0.05 level

3.2. Results of second experiment

A two-way repeated measure ANOVA was conducted using SPSS to explore relations between the human tactile perception and stickiness and to find whether there is interaction between two factors within each condition; this section reviews the results for each condition in turn.

- *Perception of softness (through pressing condition)*

Mauchly's test indicated that the assumption of sphericity had been violated for the main effects of softness, $\chi^2(2) = 69.41$, $p<0.05$, stickiness $\chi^2(2) = 7.08$, $p<0.05$; and interactions between softness and stickiness, $\chi2(9) = 47.91$, $p<0.05$. so correction of the F-ratio was required for the main effect of softness, stickiness and the interactions stickiness. Therefore, degree of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.56$ for the main effect of softness, 0.88 for the main effect of stickiness and 0.66 for the main effect of interaction between softness and stickiness).

All effects are reported as significant at $p<0.05$. There was a significant main effect of compliance on perceived softness, F (1.12, 25.86) = 107.32. There was no significant main effect of level of stickiness on the perception of softness, F (1.75, 40.29) = 0.56. There was no significant interaction effect between the level of softness and the level of stickiness used, F (2.65, 60.88) = 2.57, $p>0.05$. Figure 8 shows the geometric means for reported softness as a function of compliance in the pressing condition, standard deviation error bar and how this varied with the different stickiness conditions.

In short, the analysis demonstrates that compliance and stickiness do not significantly affect perceived softness for this condition.

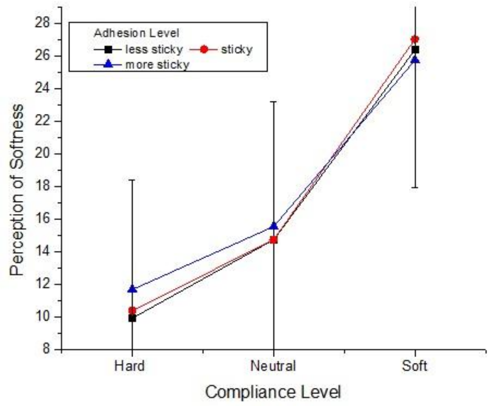

Fig8: Perceived softness vs compliance at different levels of adhesion during pressing conditions.

- *Perception of stickiness (through pressing condition)*

Mauchly's test indicated that the assumption of sphericity is met for the main effects of softness, χ^2 (9)= 2.02, $p>0.05$, but the assumption had been violated for the stickiness, χ^2 (9)= 10.13, $p<0.05$ and interactions between softness and stickiness, χ^2 (9) = 14.33, $p>0.05$ and so there is a need to correct F-ratio for these effect, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = 0.0.84 for the main effect of stickiness and 0.86 for the main effect of interaction between softness and stickiness).

From the tests of within subjects effects, there was no significant main effect of softness on the perception of stickiness, F (1.92, 90.13) = 2.82. There was also non-significant main effect of level of stickiness on the perception of stickiness, F (1.67, 78.49) = 2.38, to conclude that there was non-significant effect of stickiness on perception of softness.

There was no significant interaction between the level of softness and the level of stickiness used, F (3.46, 162.37) = 1.58. The geometric means for reported softness as a function of compliance in the pressing condition are shown in Figure 9.

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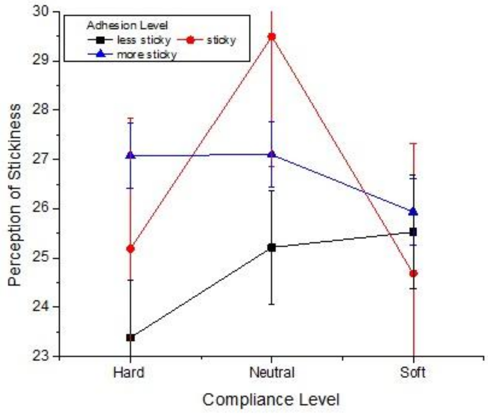

Fig. 9: Perceived stickiness vs compliance at different levels of adhesion during pressing conditions.

- *Perception of softness (through sliding condition)*

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

The results show that there was non-significant interaction effect between the level of softness and the level of stickiness used, F (2.42, 113.65) = 0.64, indicating that both softness and roughness had the same effects on participants' ratings. To sum up, there was no significant interaction between the levels of stickiness and level of softness for perceiving softness.

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

There was significant main effect of level of stickiness on the perception of Softness, F (1.84, 86.59) = 3.62 with stickiness level, to conclude that the main effects of stickiness do not perceive softness significantly (Figure 10).

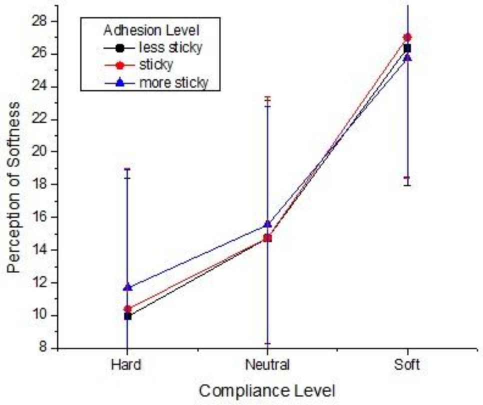

Fig. 10: Perceived softness vs compliance at different levels of adhesion during sliding conditions.

- *Perception of stickiness (through sliding condition)*

In the forth condition, Mauchly's test indicates that the assumption of sphericity had been violated for the main effects of softness, $\chi^2(9) = 25.48$, $p<0.05$, the main effects of stickiness, $\chi^2(9) = 54.20$, $p<0.05$ and interactions between softness and stickiness, χ^2 (9) = 45.51, $p<0.05$. Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.70$ for the main effect of softness, 0.54 for the main effect of stickiness and 0.74 for the main effect of interaction between softness and stickiness).

The results show that there was no significant interaction effect between the level of softness and the level of stickiness used, F (2.96, 139.18) = 1.60, indicating that a given level of softness, the perception of stickiness does not change significantly for all levels of stickiness. These interactions are shown in Figure 11 due to the interaction of the three lines. To sum up, there was non-significant interaction between the levels of stickiness and level of softness for perceiving softness. The perception of softness due to levels of softness compared to levels of stickiness is not affected by whether stimuli are soft or hard.

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

There was also a significant main effect of level of stickiness on the perception of stickiness, F (1.18, 55.55) = 27.99, To conclude that this effect revealed that if the different levels of softness were ignored, perception of stickiness of different levels of softness was different according to different levels of stickiness (Figure 11). Figure 12 shows Perceived softness against compliance for both conditions.

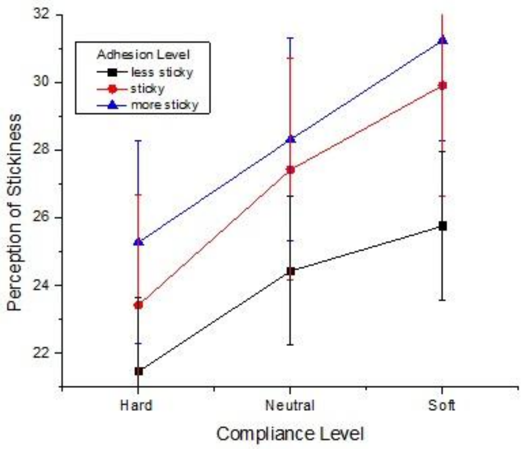

Fig. 11: Perceived stickiness vs compliance at different levels of adhesion during sliding conditions.

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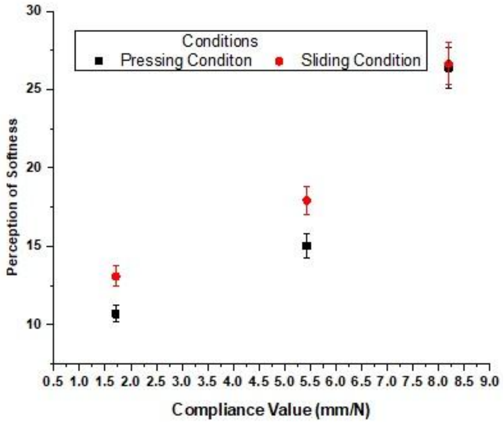

Fig. 12: Perceived softness vs compliance.

Further analysis is to determine whether, for each stickiness level, participants appeared to distinguish between the softness of the stimuli through both conditions, using One-way ANOVA analysis. The results show that the perception of softness was significantly affected by softness for all levels of stickiness. The values of F test and p values are shown in Table 5 for pressing and sliding conditions.

The results of correlation between physical properties and perception of softness and stickiness during two conditions (pressing and sliding) are shown in Table 6.This means that the perceived softness or stickiness can be predicted by these physical properties and it can be expressed as given in Table 7.

A Pearson correlation coefficient was computed to assess the relationship between the physical properties with each other. There were strong, negative correlations between compliance and friction coefficient and between compliance and heat transfer and no correlations between other physical properties with each other. Table 8 summarizes the results.

Table 5: One- Way ANOVA analysis for distinguishing between softness of stimuli during pressing and sliding condition.

Level of softness	Pressing condition		sliding condition	
	F(2,71)	P value	F(2,71)	P value
Stickiness level 1 compare different level of softness	38.43	0.00	26.31	0.00
Stickiness level 2 compare different level of softness	59.83	0.00	35.55	0.00
Stickiness level 3 compare different level of softness	55.58	0.00	37.93	0.00

Table 6: Correlations between physical properties and perceive softness and stickiness for pressing and sliding.

	Compliance	Stickiness	Friction coefficient (μ)	Heat transfer
Perceived softness (pressing condition)	0.932*	-0.14	-0.51	-0.89*
Perceived stickiness (pressing condition)	-0.01	-0.52	-0.44	0.28
Perceived softness (sliding condition)	0.94*	-0.09	-0.56	-0.87*
Perceived stickiness (sliding condition)	0.77*	-0.69*	-0.75*	-0.65

Table 7: Coefficients of regression of perceived softness and stickiness during pressing and sliding.

Model	Preceived softness (pressing)	Preceived softness (sliding)	Preceived stickiness (sliding)
	Coefficient	Coefficient	Coefficient
Measured compliance	0.656	0.801	0.575
Measured stickiness	0	0	-0.556
Friction coefficient	0	0	-0.172
Heat transfer	-0.312	-0.159	0

Table 8: Correlations between physical properties

	Compliance	Measured stickiness	Friction coefficient	Heat transfer
Compliance	1	-.14	-.69*	-.89**
Measured stickiness	-.14	1	.31	.06
Friction coefficient	-.69*	.31	1	.38
Heat transfer	-.89**	.06	.38	1

4. Discussion and conclusions

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

The main result of first experiment was that the compliance × roughness interaction had no significant effect on perceived softness; this was true for both pressing and sliding conditions. There was no evidence that interaction between compliance and roughness affected perceived softness. This may be because of frictional forces between the finger tips and the stimulus or because of small differences between compliance levels of samples. The amount of deformation that fingers undergo during pressing may be one reason, because it depends on the contact force and how stiff the material compared is to a finger.

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

Referring to Figure 9, the results of the sticky stimuli are presented. These results were completely unexpected; given that it is possible that participants cannot distinguish the stickiness by pressing. A possible explanation might be that stickiness seems to be detected through dynamic touch rather than a static touch. Bergmann Tiest et al. (2012) pointed out that people could detect stickiness through dynamic touch.

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

Nevertheless as first experiment shows, participants were able to distinguish between the compliance for each roughness level and for each stickiness level. This is in agreement with a previous study on the perception of softness (Srinivasan and LaMotte, 1995), which showed that perception of softness might depend on the objective compliance of the stimuli and people could discriminate softness easily through active touch. Our results are in agreement, since the compliance was largely determined by the influence of other material properties. The comparison of these results with previous findings shows very similar judgements on the relationship between perceived softness and physical hardness, as well as no significant effect between perception of softness and interaction between compliance and roughness surface as well as interaction between compliance and stickiness.

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

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

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

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

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

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

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

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

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to press the stimuli (Bergmann Tiest, 2010, Johnson et al., 2000, Friedman et al., 2008).

In addition, the data indicated that there is a correlation (r = -0.74, p<0.05) between the perceived softness and the friction coefficient during sliding conditions. In reviewing the literature, data were found on the association between perceived softness and friction coefficient (Chen et al., 2009c). However, the findings of the current study are inconsistent with those of Shao et al. (2010) who found that softness perception was related to compliance and thermal conductivity. Perhaps no correlation was found between softness perception and thermal conductivity because that condition was controlled, for example, dT/dt was made to be the same in every case.

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

Linear regression analysis was used to explore the relationship between perception of softness and physical material properties in both conditions. Correlations between physical measurements of compliance and psychophysical perceptions of softness and stickiness are presented in Figure 10. From the results, there is a significant relationship between the perceived softness during pressing conditions and measured compliance which is highly correlated with each other and with heat transfer. Moreover, perceived softness during sliding conditions was significantly related to measured compliance and heat conductivity (p<0.05). In addition, there was a significant correlation between perceived stickiness, compliance, adhesion and friction coefficient during sliding conditions (p<0.05). However, perceived stickiness during pressing conditions was not significantly correlated with any physical properties. The results seem to be consistent with findings by Shao et al. (2009).

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

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

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

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

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

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

5. Conclusion

Experiments were conducted to explore whether perception of softness is affected by interaction between compliance and surface roughness or interaction between compliance and adhesion. As a result from the experiments, it was found that the interaction between compliance and surface roughness do not significantly affect perceived softness for sliding or pressing conditions, indicating that both compliance and surface roughness had the same effects on participants' ratings. Also, interaction between compliance and adhesion does not significantly influence perceived softness for sliding and pressing conditions, indicating that both compliance and adhesion had the same effects on participants' ratings. Results from the first experiment, which used polyurethane stimuli to determine the effects of roughness and compliance on the perception of softness, confirm that perceived softness was related to compliance alone in the pressing condition, and friction coefficient alone in the sliding condition. However, in the second experiment, which used silicone stimuli to determine the effects of adhesion and compliance on the perception of softness, the perception of softness correlated with compliance, thermal conductivity and friction coefficients for both the pressing and sliding conditions. An explanation for this result could be because it was not possible to control the physical properties of the silicone stimuli independently; both thermal conductivity and friction coefficient correlated with the materials' compliance. For the polyurethane stimuli, it was possible to control the physical properties independently. The difference in results could also be because the silicone stimuli were similar in compliance to the human finger, and the polyurethane stimuli were somewhat harder, and that perception of softness does indeed also depend on thermal and friction properties.

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

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References

[1] Beierholm Et Al., B., U., Kording, K., Shams, L., Ma, W.J., (2007). Comparing Bayesian Models For Multisensory Cue Combination Without Mandatory Integration. Advances in Neural Information Processing Systems, ed.^eds.

[2] Bensmaïa, S. & Hollins, M. (2005). Pacinian Representations of Fine Surface Texture. Attention, Perception, & Psychophysics, 67, 842-854.

[3] Bergmann Tiest, W. M. (2010). Tactual Perception Of Material Properties. Vision Research, 50**,** 2775-82.

[4] Bergmann Tiest, W. M. & Kappers, A. M. (2006). Analysis of Haptic Perception of Materials By Multidimensional Scaling And Physical Measurements of Roughness And Compressibility. Acta Psychol (Amst), 121**,** 1-20.

[5] Briggs, G. & Nebes, R. (1975). - Patterns Of Hand Preference In A Student Population. Cortex, 11**,** 230-8.

[6] Beierholm Et Al., B., U., Kording, K., Shams, L., Ma, W.J., (2007). Comparing Bayesian Models For Multisensory Cue Combination Without Mandatory Integration. Advances In Neural Information Processing Systems, Ed.^Eds.

[7] Bensmaïa, S. & Hollins, M. (2005). Pacinian Representations of Fine Surface Texture. Attention, Perception, & Psychophysics, 67**,** 842-854.

[8] Bergmann Tiest, W. M. (2010). Tactual Perception of Material Properties. Vision Research, 50**,** 2775-82.

[9] Bergmann Tiest, W. M. & Kappers, A. M. (2006). Analysis of Haptic Perception of Materials By Multidimensional Scaling And Physical Measurements of Roughness And Compressibility. Acta Psychol (Amst), 121**,** 1-20.

[10] Chen, X., Shao, F., Barnes, C., Childs, T. & Henson, B. (2009a). Exploring Relationships Between Touch Perception And Surface Physical Properties. International Journal Of Design 3**,** 67-76.

[11] Chen, X., Shao, F., Barnes, C., Childs, T. A. & Henson, B. (2009b). Exploring Relationships Between Touch Perception And Surface Physical Properties. International Journal of Design 3**,** 67-76.

[12] Field, A. (2010). Discovering Statistics Using Spss Introducing Statistical Methods Series, United Kingdom, Sage Publications Ltd.

[13] Friedman, R. M., Hester, K. D., Green, B. G. & Lamotte, R. H. (2008). Magnitude Estimation of Softness. Exp Brain Res, 191**,** 133-42.

[14] Gersem, G. D.(2005). Kinaesthetic Feedback And Enhanced Sensitivity In Robotic Endoscopic Telesurgery. Ph.D., Katholieke Universiteit Leuven.

[15] Harper, R. & Stevens, S. S. (1964). Subjective Hardness of Compliant Materials. Quarterly Journal of Experimental Psychology, 16**,** 204 - 215.

[16] Hollins, M., Faldowski, R., Rao, S. & Young, F. (1993). Perceptual Dimensions of Tactile Surface Texture: A Multidimensional Scaling Analysis. Percept Psychophys, 54**,** 697-705.

[17] Hollins, M. & Risner, S. R. (2000). Evidence For The Duplex Theory of Tactile Texture Perception. Perception & Psychophysics, 62**,** 695-705.

[18] Johnson, K., Yoshioka, T. & Vega-Bermudez, F. (2000). Tactile Functions of Mechanoreceptive Afferents Innervating The Hand. J Clin Neurophysiol, 17**,** 539-58.

[19] Koçak, U., Palmerius, K., Forsell, C., Ynnerman, A. & Cooper, M. (2011). Analysis of The Jnd of Stiffness In Three Modes of Comparison. In: Cooper, E., Kryssanov, V., Ogawa, H. & Brewster, S. (Eds.) Haptic And Audio Interaction Design. Springer Berlin Heidelberg.

[20] Lodge, M. (1981). Magnitude Scaling: Quantitative Measurement of Opinions, Sage.

[21] Ottermo, M. S., Ø. And Johansen, T. (2008). Design And Performance of A Prototype Tactile Shape Display For Minimally Invasive Surgery. The Electronic Journal of Haptics Research 4**,** 1-13.

[22] Ottermo, M. V. (2006). Virtual Palpation Gripper. Ph.D Degree, Norwegian University of Science And Technology.

[23] Petrie, H., King, N. & Tomlins, P. (2004). Investigations Into Sensation of 'Softness' And Perception of The Tactile Properties of 'Soft Touch' Thermoplastic Elastomers. . National Physical Laboratory.

[24] Shao, F., Chen, X. J., Barnes, C. J. & Henson, B. (2010). A Novel Tactile Sensation Measurement System For Qualifying Touch Perception. Proceedings of The Institution of Mechanical Engineers, Part H: Journal of Engineering In Medicine, 224**,** 97-105.

[25] Shao, F., Childs, T. H. C. & Henson, B. (2009). Developing An Artificial Fingertip With Human Friction Properties. Tribology International, 42**,** 1575-1581.

[26] Shirado, H. & Maeno, T. (2005). Modeling of Human Texture Perception For Tactile Displays And Sensors. Proceedings of The First Joint Eurohaptics Conference And Symposium On Haptic Interfaces For Virtual Environment And Teleoperator Systems. Ieee Computer Society.

[27] Skedung, L., DanerlãV, K., Olofsson, U., Michael Johannesson, C., Aikala, M., Kettle, J., Arvidsson, M., Berglund, B. & Rutland, M. W. (2011). Tactile Perception: Finger Friction, Surface Roughness And Perceived Coarseness. Tribology International, 44**,** 505-512.

[28] Srinivasan, M. A. & Lamotte, R. H. (1995). Tactual Discrimination of Softness. J Neurophysiol, 73**,** 88-101.

[29] Wouter, M. B. T. (2009). Cues For Haptic Perception of Compliance. Ieee Transactions On Haptics, 2**,** 189-199.