Influence of Sparse Contact Point and Finger Penetration In Object on Shape Recognition

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Abstract—Making a virtual object shape recognizable using a haptic display is one of the major themes of haptic research. In previous works, multi-point haptic displays have been developed that had a high contact point density between the users' finger skin and the virtual object. However, the ideal contact point density that enables intuitive shape recognition has not been determined yet. Meanwhile, there is also a fundamental problem, that is, real fingers and virtual objects do penetrate, which cannot be solved with such wearable displays. This study investigated the influence of both contact point density and penetration on the shape recognition performance. We prepared a real testing environment where the user touched the real object, and where we could simulate both the sparse contact point and the penetration. Specifically, users' fingers wore thin film coated with glass particles and they touched the urethane foams that deformed flexibly. The result of experiments showed a broad trend where the sparseness of the contact and the softness of the object influenced the exploration time required to achieve recognition. In addition, the result suggested that the larger contact density could make up for the problem of penetration. We confirmed it by conducting two different tasks: (1) exploring the object surface with the index finger and (2) grasping the object surface with the thumb and the index finger.

Index Terms—Shape Recognition, Wearable Shape Display, Contact Point Density, Finger Penetration

1 INTRODUCTION

HUMANS are highly skilled in perceiving objects' shape even in the absence of visual information. They can sense the geometry of the real object's surface based solely on haptic cues, which comprise kinesthetic and cutaneous cues. Blindfolded people can allegedly perceive the shape of solid objects with an accuracy of 98% within a few seconds [1]. People also appear capable of distinguishing between twelve solid copies of bell peppers just from touch, with the same accuracy as if they used vision alone [2].

Thus, humans can reasonably be expected to recognize the shape of computer-generated objects in virtual environments if the haptic stimuli are replicated accurately. Researchers have developed various multiple-contact-point haptic displays to present the surface geometry of a virtual object to users. As one example of the multi-point display, pin-array displays raise pins against the human skin to render force. Traditionally, most devices have been mechanically grounded [3], [4]. They could present both kinesthetic and cutaneous cues using robustly grounded forces with users. However, these devices cannot display shapes in any position or location around users. In other words, the workspace and portability are constrained. A large interactive mobile workspace may be useful for the exploration of virtual spaces.

Recently, more haptic system designs have started appearing with wearability in mind, and in this context wearable, multiple contact point displays have been developed [5], [6]. The mechanical actuators employed usually include pneumatic arrays and shape memory alloy displays (SMA).

However, currently, the ability to recognize the shape of virtual objects when using these wearable devices is worse than when using a bare finger or hand. Tanabe et al. [7] developed vibrotactile whole hand glove with 52 vibrators. They evaluated the shape recognition performance for four different 3D virtual objects. The correct answer rate was approximately 70% and the response time was close to 20s. Taniguchi et al. [8] developed a pin array display for the whole hand as dense as the two-point threshold. The recognition time was close to 40s and the answering rate accuracy was approximately 70%. These results using current multi-point haptic displays are far inferior to the ones coming from the interaction between an actual finger and the actual objects, as obtained by [1].

To achieve a higher shape recognition performance, a promising approach is to implement a high contact point density to provide richer cutaneous cues. Though current multi-point displays apply contact forces in a sparse distribution (Fig.1 (b)), humans sense the local geometry of the actual object based on the dense distribution of the contact force (Fig.1 (a)). Thus, increasing the density of the human tactile spatial resolution is widely believed to lead to higher recognition performance. Thus, actuator integration technology to increase the contact point density has been developed actively, targeting a higher recognition performance. However, it is not even clear whether a larger contact point density truly contributes to better shape recognition. In addition, the exact contact point density enough to realize intuitive shape recognition has yet to be determined. These are still unknown in part because the shape recognition

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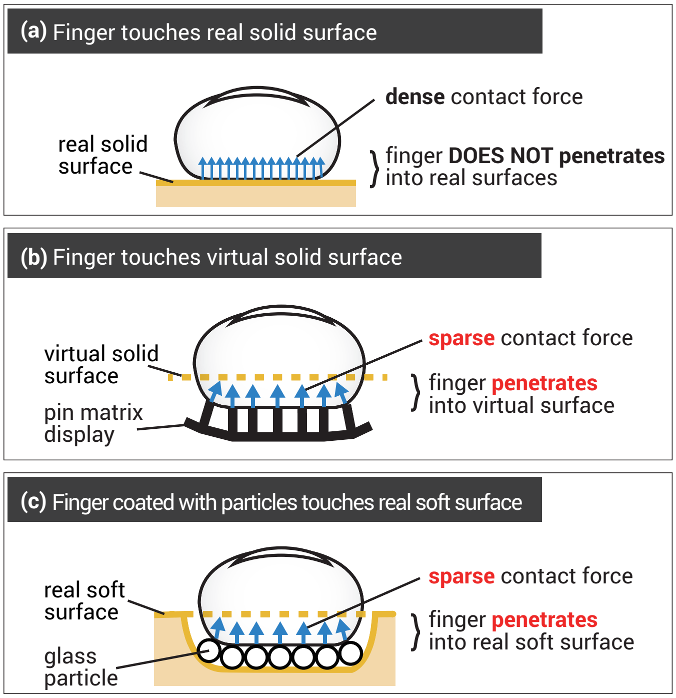

Fig. 1. (a) The ideal haptic feedback to represent the shape of a solid object. (b) Wearable pin matrix haptic feedback to represent the shape of a solid object. The pin's density defines the sparseness of the contact force from the virtual solid surface. (c) Simulating the wearable pin matrix haptic feedback. Users wear a thin finger cot covered with glass particles. The glass particle size defines the sparseness of the contact force from the actual soft surface. The softness of the object leads users to penetrate into the surface.

evaluation in previous studies was performed solely based on a specific contact point density of the developed device, hence evaluations across various contact point densities were lacking. Another reason is that the shape recognition evaluation beyond the maximum contact point density that can be developed with current technology is impossible.

Meanwhile, there is an insolvable problem specific to wearable display. Indeed, the user's actual finger moves into the surface of the virtual object (Fig.1 (b)). Even if the virtual contact forces are applied, users' fingers can nudge into the object. As a result, users can use small kinesthetic cues to explore surfaces, which would make recognition difficult. We consider that the problem of finger penetration into the object could influence the shape recognition.

Based on these considerations, this study investigated the effect of the sparse contact point and penetration on the recognition performance of the object shape. In particular, we had an interest in the impact of the contact point density when the penetration problem occurred. In order to investigate this, we used a real environment where we could gradually control the contact point density and penetration. Specifically, users' fingers wore an elastic film coated with glass particles. We refer to the film coated with particles as the "particulate glove" in this paper. The size of the particles in the particulate glove defined the contact point density. Because of the particulate glove, we could investigate the effect of higher contact point density that was impossible to investigate with current wearable multi-point display. Users touched the urethane foam with a variable softness that controlled the effect of the penetration (Fig.1 (c)).

We conducted shape recognition experiments to observe the effects of contact density and penetration. To broadly investigate these effects, we conducted the experiments assuming two different exploratory procedures [9]. In experiment 1, participants explored the object surface with the index finger. The exploration in experiment 1 corresponded to contour following among the exploratory procedure [9]. In experiment 2, participants grasped an object with the thumb and index fingers. The exploration in experiment 2 corresponded to the enclosure.

The contributions of this study are summarized here:

- We propose a method for preparing an actual testing environment where we can gradually control the sparseness of the contact point and the penetration of the finger in the object independently. To control the contact point density, we covered the actual user's finger with a particulate glove. In order to mimic penetration, we used urethane foams, which deform flexibly, as the target of touch.
- The result of the experiments demonstrated that both the sparseness of the contact point and the softness of the object contributed significantly to the longer exploration time. We confirmed that the exploration time decreased as the contact point became denser even when participants were exposed to the softest urethane form. It suggested that a higher contact density of wearable multi-point display could make up for the problem of the penetration.

2 Related Work

2.1 Human Shape Recognition

Various attempts were made to disentangle the contributions of the two primary sources of information in haptic shape recognition: kinesthetic and cutaneous [10]. Kinesthetic mechanoreceptors encode information on the state of muscles, tendons, and joints. Cutaneous mechanoreceptors respond to the deformation of the skin. Both kinesthetic and cutaneous cues are known to be important for shape recognition [11], [12], [13], [14]. The work in [11] showed that the addition of cutaneous cues to kinesthetic cues significantly improved the recognition of the orientation of a surface. Similarly, recent studies have shown the importance of cutaneous stimuli in addition to the kinesthetic stimuli in discerning curvature [15], [16]. As for the compliance perception, how kinesthetic and cutaneous cues contribute to the perception have been addressed in [17], [18], [19].

Previous work compared their observed data to two candidate models and investigated how two cues are integrated. The candidate models are Optimal Integration model [20], which shows how the means and variances of cues can be pooled, and a Sensory Capture model, in which the most reliable modality is the only one that is represented in the multi-sensory perception [21]. The work in [11], [22] showed that the obtained data in some case fit to the Optimal Integration model and data in other case fit to the Sensory Capture model.

2.2 Wearable Multi-point Haptic Display

Based on these findings, to improve the shape recognition performance using a wearable multi-point haptic display, increasing the contact density to provide more cutaneous cues is broadly viewed as important. Kim et al. [6] developed a wearable display composed of a 4×4 pin array on the fingertip. The diameter of the pin was 0.5 mm and pins were arranged in a 1.5 mm interval. The pin moved normally against the skin and normal indentation was achieved. Sarakoglou et al. [23] also proposed a compact 4×4 tactile array. Caldwell et al. [24] proposed a device that is able to combine normal indentation and shear stimuli. They used a 4×4 pin array with a spatial interval of pins of 1.75 mm.

Aside from pin arrays, another popular set of wearable systems providing multi-point stimuli is the one exploiting pneumatic jets. Kim et al. [25] developed a 5×5 array of air jets placed in direct contact with the fingertip and five additional air nozzles that are in direct contact with each side of the finger to produce the lateral force. Taniguchi et al. [8] developed a pin array display for the whole hand as dense as the two-point threshold.

Although in these studies custom displays were built with an increasing contact density, the contribution of this contact density to the shape recognition performance was still unclear. In addition, the shape recognition evaluation was restricted by the contact density achievable by the display. Recognition could only be evaluated within the contact density range of the developed displays. A wearable display with sub-millimeter-scale interval for contact points cannot be developed with current technology. As a guideline for the future development of multiple contact point displays, we would like to know more about the recognition performance under such sub-millimeter-scale contact density. Thus, it is still not clear what the ideal contact density is to achieve intuitive shape recognition.

2.3 Effect of Contact Density of Grounded Type Display

Although there are no previous studies on the impact of contact density using wearable displays, researchers have investigated these effects using grounded type pin array displays. The work of [26] studied participants' shape recognition performance using three passive arrays with distinct pin spacing values. Results showed that the smaller the pin spacing the better the shape recognition. Another work evaluated the recognition of shapes [27] and concave/convex surfaces [28]. The work [29] showed that a tactile array with a pin spacing of 1.8 mm and a pin array of size $1mm^2$ can accurately convey tactile information related to the inclination of an edge or even to simple tactile shapes. As in these studies, the effect of the density of the contact point has been well researched in the field of grounded-type pin array display.

However, the knowledge accumulated on these effects is not directly transferable to wearable displays. Indeed, there are little kinesthetic cues on wearable display although a robust kinesthetic cue exists on the grounded type display. The evaluation of the impact of the contact point density under the condition that there are little kinesthetic cues is required.

3 Hypotheses and Method

3.1 Hypotheses

We hypothesized that a denser contact point contributes to the shape recognition performance even when the finger penetrates into objects.

3.2 Method: Simulation of Sparse Contact Density and Finger Penetration

We prepared a real-world environment in which we mimicked the sparse contact point and the finger penetration and investigated the recognition performance of the object shape by the human. Specifically, by covering the actual finger with the particulate glove, we simulated a sparse contact point density with the object (Fig.1(c)).

We used objects made of deformable urethane foam as a target of exploration. When users pressed a finger against the deformable urethane foam, the users' fingers intruded into the original surface of the urethane foam. Under this condition, users could use minor kinesthetic cues to recognize the shape of the object. The softer the urethane foam users touch is, the more muted kinesthetic cues are; eventually they come closer to the condition where users' fingers penetrate the virtual object (Fig.1(c)). When the condition of kinesthetic cues are fixed the cutaneous cues in terms of the density of contact point can be controlled by the particulate glove.

3.2.1 *Particulate Glove*

In order to mimic the issue of a sparse contact point, we asked users to wear the particulate glove. The illustration in Fig.2 shows the cross section of the finger covered with two distinct particulate gloves. As the diameter of the glass particles becomes larger, the contact point becomes sparser. As the diameter of glass particles becomes smaller, the contact point becomes denser.

Overly large particles may lead to another effect, with the distance between the finger and the object increasing. However, we only used large objects in the experiments and thus the change of distance can largely be ignored.

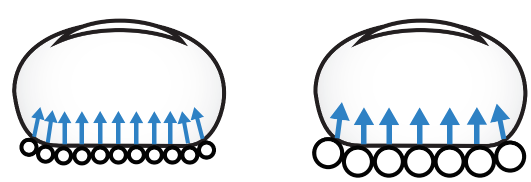

Fig. 2. As the diameter of the glass particles is larger, the contact point becomes sparser. The diameter of the left glass particles is half of that of the right ones. The contact density is also half according to the ratio between diameters.

We used the glass particles (KENIS Ltd.) and thin film for finger (Misumi ID:RTXY-CT-M). The glass particles were identical to the ones used in [30] to create a rough texture. The particles did not have any sharp edges on the surface of the sphere and did not generate unnecessary haptic stimuli. We followed [30], [31]'s approach which is to systematically make the texture plate reproducible. The glass particles were first arranged on the thin film using double-sided sticky tape. After arranging particles on the film, users wore them

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on fingers. The thin film's thickness was 0.1 mm and the film deformed easily by virtue of its elasticity.

We made five types of particulate gloves with distinct particle sizes and thus five distinct sparse conditions for the experiments. The diameters of the glass particles were 0.425, 1.194, 2, 3, and 4.3305 mm. The diameters were certified by the manufacturer (KENIS Ltd.). Fig.3 shows the index fingers with the specific gloves used in experiment 1. In experiment 2, participants wore the particulate gloves on the thumb and the index fingers.

Fig. 3. Five types of particulate gloves with distinct glass particles diameters

Though the uniformity of packing ratio, which is the proportion of area covered by glass particles, has been already assured by previous studies [30], [31], the specific value of the packing ratio has not been clarified yet. Thus, we measured the packing ratio of the glass particles attached to the thin films. This was calculated by counting the number of particles in certain areas using a microscope when we placed the glass particles on a flat plate in the same way. We took three photographs at different positions for each plate and measured the average packing ratio. Table.1 shows the packing ratio of each plate. These ratios ranged from 71 to 74. Although the attached curvature of the flat surface and on the curved surface of the finger is different or the curvature of finger slightly varies from person to person, this study considers that the packing ratio would remain identical across different particulate gloves.

TABLE 1
The measured packing ratio of glass particles attached to the flat plate for each particle diameter.

#	Particle diameter [mm]	Measured packing ratio [%]
d1	0.425	71.5 $\pm$ 0.022
d2	1.194	73.4 $\pm$ 0.016
d3	2.000	73.2 $\pm$ 0.025
d4	3.000	71.7 $\pm$ 0.027
d5	4.331	71.8 $\pm$ 0.063

3.2.2 *Urethane Foam Object*

In terms of soft material, we specifically used urethane foams. We used three types of urethane foam, with distinct levels in hardness. We call them s1 (INOAC CORP, ECZ), s2 (INOAC CORP, UEM-35G), and s3 (INOAC CORP, EMO) in ascending order of softness. The specification of the urethane foams is provided in Table.2. The hardness (25% ILD), density, and compression set described in the table were certified by the manufacturer. Fig.4 demonstrates the variability in the deformation of the foam based on hardness.

TABLE 2
The density of the urethane foam in this study.

	softness condition		
	s1	s2	s3
Density [kg/m^3]	16±1.5	35±3.0	50±5.0
Hardness (25% ILD) [N/314cm^3]	80	156.8	400.35
Compression set [%]	9	4.5	4

Fig. 4. The deformation of the three types of urethane foams when the same amount of force is applied.

4 Experiment 1: Exploring with Index Finger

Experiment 1 was conducted to test the effect of both the sparseness of the contact point and the penetration of the finger in the object on the recognition performance as participants explored surfaces with the index finger.

There were ten participants, seven males and three females, with ages ranging from 21 to 24. The participants were all right-handed. They were screened to ensure that they were not depressed nor excessively tired as perception would be altered by physical or emotional states. The University of Electro-Communications Ethics committee approved the data acquisition in this paper and written informed consent was obtained from all participants.

4.1 Experimental System

The participants' task in this experiment was to discern the shape of the actual object based solely on haptic information in the shortest time possible. Participants were seated on a chair (Fig.5). The object was placed approximately 30 cm in front of them on a desk. The base of the object in direct contact with the desk was always the same but the object was rotated randomly along the z-axis. Participants placed their dominant hands under a curtain and touched the object with their index finger.

Fig. 5. Appearance of the experimental system. (Left): Participants touch the object placed behind the curtain. They were asked to gauge the object shape based solely on haptic information. (Right): The object was placed in a certain position. The participants' finger was covered with the particulate gloves.

There were three object shapes. Their cross section was either square, an equilateral triangle, or trapezoid. The appearance and cross section of the object shapes are shown in Fig.6. Their height and depth were 50 mm. Their cross sections were distinct. We refer to the difference in object shapes as the shape condition.

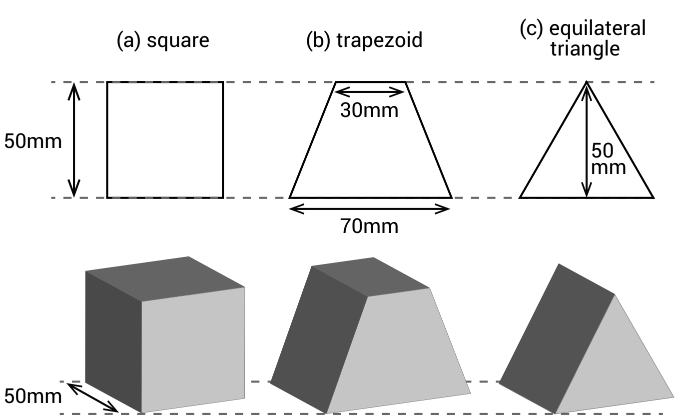

Fig. 6. The cross section and appearance of three different shapes.

As stated in section 3.2.2, there are three different softness conditions for the objects. Thus, participants touched the nine types of objects, which consisted of permutations in the three shape conditions and three softness conditions.

Participants wore one of the five particulate gloves on the index finger of their dominant hand as shown in Fig.3. Participants were only allowed to touch the object with the index finger area coated with glass particles.

4.2 Task Design

This experiment used a within-participants design. As we wanted to investigate the general effect of sparseness and penetration, there were no instructions on specific ways to touch the object or to distinguish between object shapes. The experiment comprised an initial phase and a test phase.

In the initial phase, participants saw the nine types of objects that were used in this experiment. The nine objects were different in softness and shape. Next, they touched the objects with a bare index finger for three seconds each for adaptation. The participants touched the objects one by one not only for haptic information but also for visual information. The participants then wore one of particulate gloves on their index fingers. Nine objects were placed behind the curtain sequentially and participants tried to distinguish their shape individually in one occurrence. After these completed, the test phase started.

During the test phase, participants distinguished the shape of the object by touch with the particle coated index finger in the shortest time possible. Let us describe the procedure of a trial in the test phase. The experimenter placed one of the objects in the designated position, randomly rotating it along the z-axis, and then told participants to start touching. Participants tried to distinguish the shape and answered a name in Fig.6 in a forced choice. The exploration time taken and the name of the shape answered by the participants were recorded by the experimenter. After the test phase, the participants were asked to clarify how to distinguish the three shapes and wrote free comments for the experiment.

There were five contact density conditions. For each contact density condition, the participants touched 27 objects (3 shape conditions $\times$ 3 softness conditions $\times$ 3 times). In aggregate, one participant touched 135 objects (27 objects $\times$ 5 contact density conditions). The presentation order of the contact density conditions was pseudo-randomly assigned across participants. The presentation order of the shape and softness condition for each contact density condition was also randomly assigned to be counter-balanced across participants.

4.3 Data Analysis

We performed a single round of 3 σ clipping to remove outliers. All the following analysis was performed on the data that did not include outliers. In order to identify there was a main effect of softness condition, contact density condition, or the interaction effect on the exploration time, we performed a two-way repeated ANOVA of factors of these two conditions. We conducted a Shapiro-Wilk test to check normality and a Mauchly's test to check the sphericity criteria in advance of the ANOVA test. If the sphericity assumptions were violated, Greenhouse-Geisser corrections were applied to the ANOVA test. As a result of the ANOVA test, when there was a significant interaction effect between the softness condition and contact density condition, Tukey-Kramer posthoc test for pairwise comparison of data for each combination of both conditions. Otherwise, and when there was a main effect of softness condition or contact density condition, the Tukey-Kramer post-hoc test was conducted for the pairs of condition that was found to be significant. If the sphericity assumptions were violated, the post-hoc test was conducted with bonferroni adjustment.

4.4 Results

Fig.7 shows the average exploration time for each participant across all conditions without removed outlier samples. We removed 25 outlier samples that were out of 3 σ range. All of the removed samples were the ones obtained from a certain participant (participant ID:J).

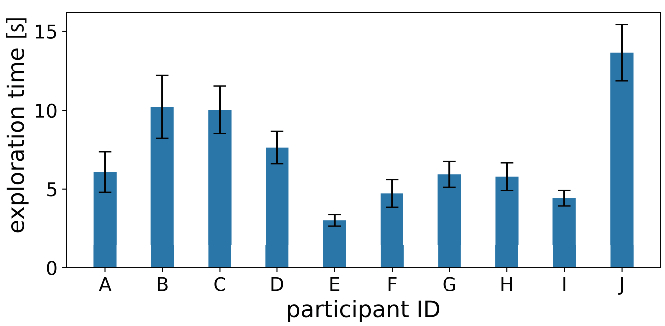

Fig. 7. The average exploration time for each participant across all conditions.

Fig.8 shows that from a matrix viewpoint. It shows the gradation of the exploration time along both the contact density and softness axes.

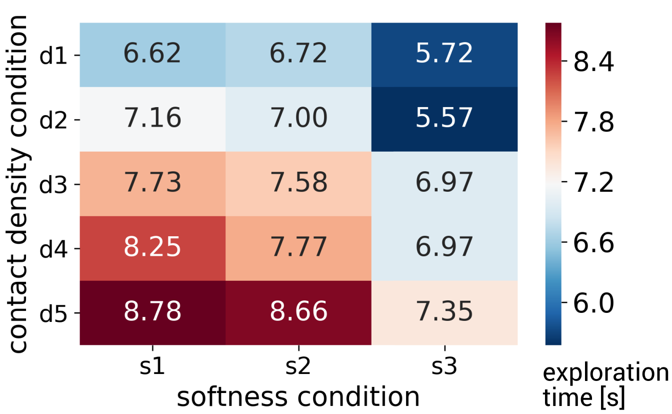

Fig. 8. The average exploration time for each softness and contact density condition.

The sphericity test's results indicated that the variance homogeneity assumption was violated for both conditions and interaction effect between them ($p < 0.01$). We performed a two-way repeated ANOVA with factors of softness condition ($s1, s2, s3$) and contact density condition ($d1, d2, d3, d4, d5$) on the exploration time. According to the ANOVA results, there was a significant main effect of the softness condition ($F(2, 1335) = 4.77, p = 8.5 \times 10^{-3}$) and a significant main effect of the contact density condition ($F(4, 1335) = 4.26, p = 1.9 \times 10^{-3}$). There was no significant interaction effect between the two factors ($F(8, 1335) = 0.11, p = 0.99$). Since there was no interaction effect, the effect of the softness condition and contact density condition were analyzed separately.

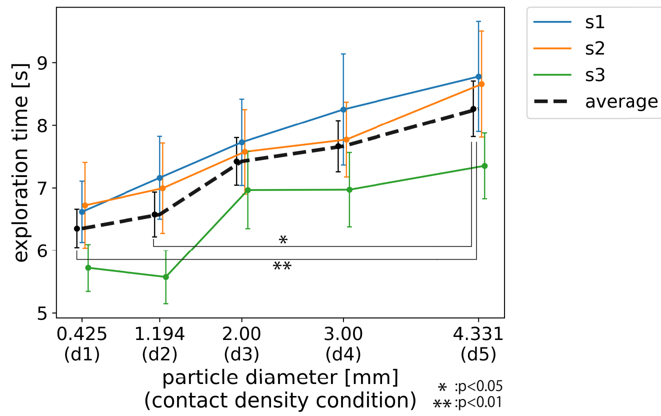

Fig. 9. The average exploration time across softness conditions with respect to contact density condition.

The black line in Fig.9 shows change in the average exploration time with standard error across softness conditions. We conducted post hoc test with bonferroni adjustment for pair-wise comparison of 5 contact density conditions. As a result, there were significant differences between $d1$ and $d5$ ($p < 0.01$),and $d2$ and $d5$ ($p < 0.05$).

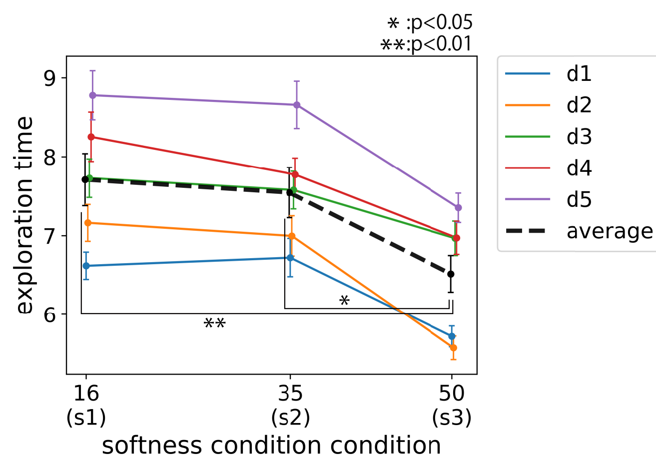

Fig. 10. The average exploration time across contact point density conditions with respect to softness condition.

The black line in Fig.10 shows change in the average exploration time across contact density conditions. We conducted post hoc test with bonferroni adjustment for pair-wise comparison of 3 softness conditions There were significant differences between $s1$ and $s3$ ($p < 0.01$),and $s2$ and $s3$ ($p < 0.05$).

The probability of correct responses for the softness and contact density condition are shown in Fig.11. We performed a two-way repeated ANOVA with factors of softness condition ($s1, s2, s3$) and contact density condition ($d1, d2, d3, d4, d5$) with the probability of correct responses and there was no significance on the main effect of both conditions and interaction effect.

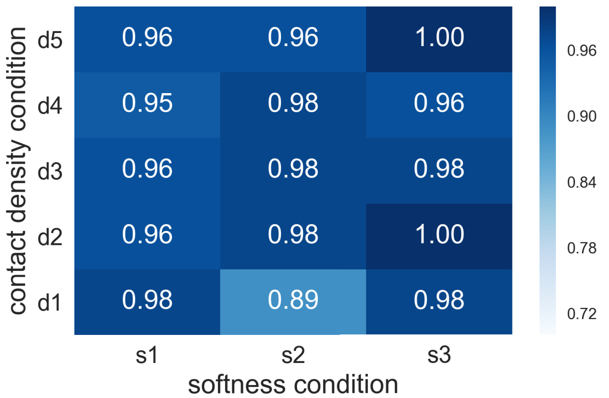

Fig. 11. The probability of correct answer for softness and contact density condition.

4.5 Discussion

The result of the ANOVA tests on the two factors of the softness and contact density conditions shows that these two factors had a significant effect on the exploration time. It suggested that if the contact point was sparse, it took longer for the participants to distinguish shapes. It also suggested that when the object was soft, it took longer to distinguish shapes. In addition, the gradation of the exploration time in Fig.8 and the significantly different pairs identified by the post-hoc test in Fig.9 and Fig.10 show that there seems to be a broad trend with a significant divide between the soft, small contact density condition and the hard, large contact density condition.

We observe the tendency that the average exploration time significantly went up with regard to the contact point density (shown in Fig.9). According to the post-hoc multiple comparison test, we confirm the significant difference in exploration time between $d1$ and $d5$. The average difference in exploration time between them was approximately 1.8 second. Also, we confirm the significant difference in exploration time between $d2$ and $d5$. The average difference in exploration time was approximately 1.5 second. Even if the object was softest ($s1$), the time required for discrimination was shortened when the contact point density is higher. Though there was no significant effect between the contact density conditions for $s1$, which was the softest condition, the average exploration time went up with regard to the contact point density (shown in Fig.9). Identical trends materialized in the lines of $s2$ and $s3$ in Fig.9). In addition, a comment from participants supports this analysis, as they suggested that it was easy to distinguish the square and trapezoid when the particles were small. We paid attention to the performance of softest condition $s1$ with denser density condition $d1$ or $d2$ were better than hardest condition $s3$ with sparser condition $d5$. This means that denser contact point density has a possibility of making up for the problem of the penetration.

On the other hand, we found the average exploration time plateau between $s1$ and $s2$ in Fig.10. As a quantitative evidence, there was not a significant difference between $s1$-$s2$ though there were not between $s1$-$s3$ and $s2$-$s3$. One of the possible explanations is that participants became to resort to the cutaneous cues to recognize the object shape when $s1$ and $s2$; thus, there was little influence from the difference of kinesthetic positional cue.

In this experiment, we did not restrict participants in the way they touched the object surface or distinguished the object shapes. Indeed, we wanted to confirm the impact of the contact density and the penetration while users freely explored the invisible objects. Fig.7 reports the variations in exploration time among participants. One of the probable reasons for the variance is that there were multiple methods for distinguishing objects and shapes per participant. Regarding how to distinguish among three shapes, participants commonly indicated in the comments that they easily distinguished the equilateral triangle from the other two shapes based on the presence or absence of an acute corner. In contrast, there were various methods to identify the square and trapezoid that were chosen freely by the participants. Four out of ten participants focused on the absolute inclination angle of the side area. They said that they ran their fingers on the side areas and looked for the side areas whose inclination were not vertical to the ground. Other four participants focused on the area of the top surface. They said that they sensed the area size of the top surface by pressing their fingertip onto the surface. These differences in identification methods could lead to the variance of exploration time. In addition, another factor could be the variability in the movement speed of the index finger as there were no instructions in that regard.

5 Experiment 2: Grasping with Thumb and Index Fingers

Experiment 2 was conducted to test the effect of both the sparseness of the contact point and the penetration while participants grasped objects with their thumb and index fingers. Although the exploring procedure, the position on which to attach the particulate gloves, and the object shapes were different from experiment 1, the task design and data analysis were identical.

There were six participants, five males and one female, and their ages ranged from 21 to 24. All participants were right-handed. They were screened to ensure that they were not depressed, overly tired as perception would be affected by their physical or emotional states. The University of Electro-Communications Ethics committee approved the data acquisition in this paper and written informed consent was obtained from all participants.

5.1 Experimental System

The experimental system was identical to experiment 1. Participants placed their dominant hands under a curtain and grasped the object with their thumb and index fingers (shown in Fig.12).

There were three object shapes. Their cross section was either a square, a rhombus, or an equilateral triangle. The appearance and cross section of the object shapes are shown in Fig.13. The cross sections from the top view were different

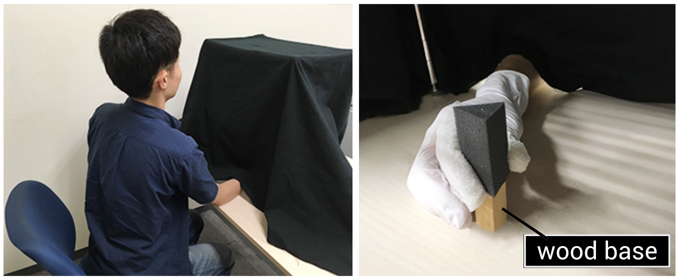

Fig. 12. Appearance of the experimental system. (Left): Participants touched the object placed behind the curtain. They were asked to gauge the object shape solely with haptic information. (Right): The object was placed in a certain position. Participants' fingers were covered with the particulate gloves.

from each other. On the cross section, the average length from the center to the corner was the same among all shapes, namely 17.5 mm. The height of the objects was 50 mm. We refer to the difference in object shapes as the shape condition. Participants grasped the side areas of the shape with their thumb and index fingers.

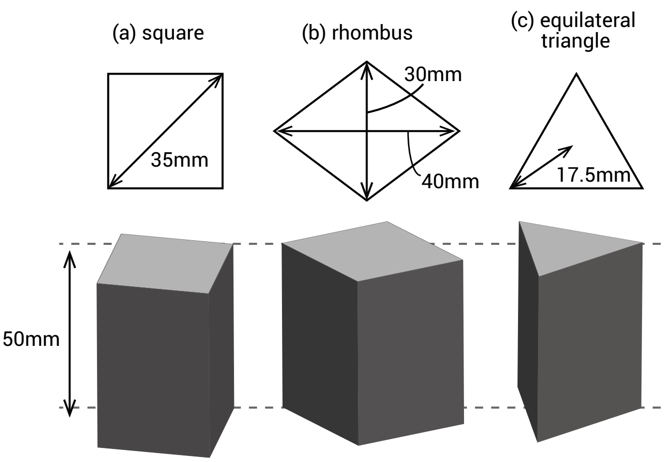

Fig. 13. The cross section and the appearance of three different shapes.

As stated in section 3.2.2, there were three different softness conditions on objects. Thus, participants grasped the nine types of objects, consisting of a permutation of the three shape conditions and three softness conditions.

We conducted informal experiments in advance and found that it took much longer to complete than the previous experiment. To avoid the participants' fatigue, we used three types of particulate gloves on the thumb and index fingers of their dominant hand as shown in Fig.14 rather than five types. The participants were only allowed to touch the object with their thumb and index fingers and the areas in the middle coated with glass particles. In order to prevent participants from taking a strategy other than grasping, we allowed participants to touch only the side areas and side corners of the objects.

The object was glued to the top surface on a wood base which was tightly attached to the table. The wood base was for height adjustment so that the object was aligned with the height of the subject's index finger and thumb. Because of the glue, the object's bottom surface did not rotate.

Fig. 14. Index and thumb fingers covered with particulate gloves. Three types of particle sizes were used in this experiment.

5.2 Task Design

The task design was almost identical, but the instructions on touching the object were different from experiment 1.

There were three contact density conditions. For each contact density condition, participants touched 27 objects (3 shape conditions $\times$ 3 softness conditions $\times$ 3 times). In aggregate, each participant touched 81 objects (27 objects $\times$ 3 contact density conditions). The presentation order of the contact density condition was randomly assigned to be counter-balanced across participants. The presentation order of the shape and softness condition for each contact density condition was also randomly assigned to be counter-balanced across participants.

Data analysis was performed as the same way as experiment 1.

5.3 Results

Fig.15 shows the average exploration time for each participant across all conditions without removed outlier samples. We performed a single round of 3 σ clipping to remove outliers as same as experiment 1. 12 outlier samples were removed and those were the ones obtained from a certain participant (ID:P).

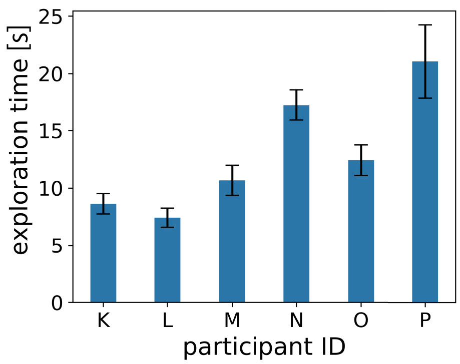

Fig. 15. The average exploration time for each participant across all conditions.

Fig.16 shows average exploration time for each softness and contact density condition from a matrix viewpoint.

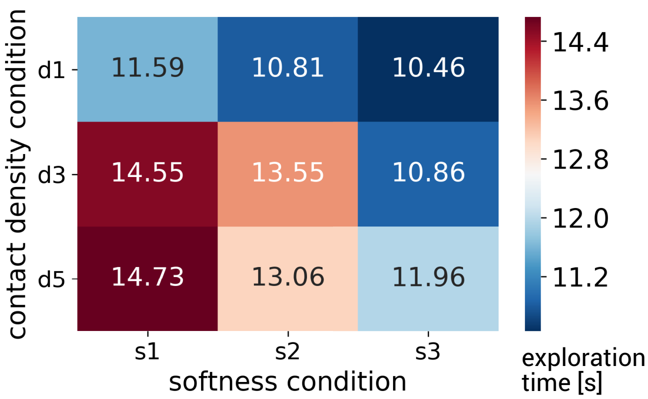

Fig. 16. The average exploration time for each softness and contact density condition.

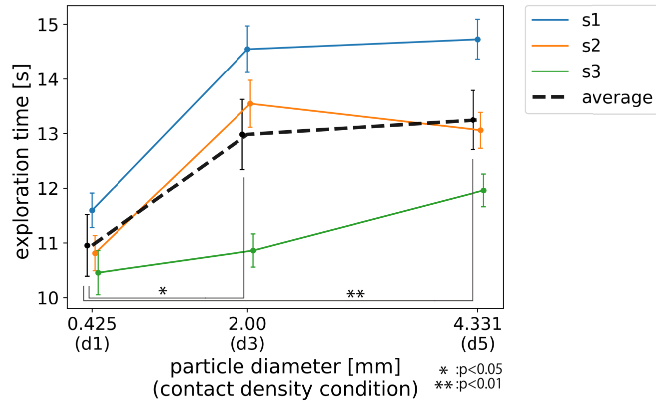

Fig. 17. The average exploration time across softness conditions with respect to contact density condition.

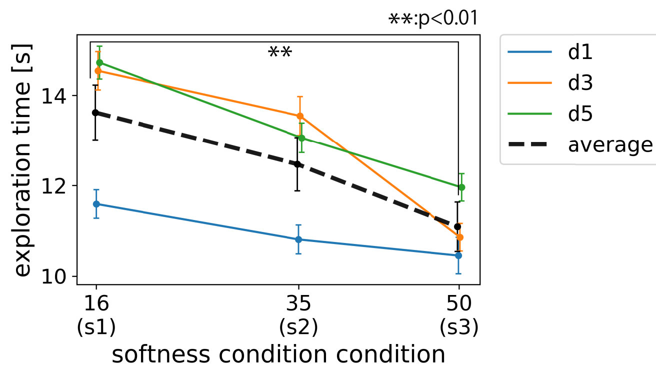

Fig. 18. The average exploration time across contact point density conditions with respect to softness condition.

The sphericity test ' s results indicated that the variance homogeneity assumption was violated for both conditions and interaction effect between them ($p < 0.01$). We performed a two-way repeated ANOVA with softness condition ($s1, s2, s3$) and contact density condition ($d1, d3, d5$) factors on the exploration time. According to the ANOVA results, there was a significant main effect of the softness condition ($F(2, 465) = 4.88, p = 7.0 \times 10^{-3}$) and a significant main effect of the contact density condition ($F(2, 465) = 4.70, p = 9.5 \times 10^{-3}$). There was no significant interaction effect between the two factors ($F(4, 465) = 0.55, p = 0.69$). Since there was no interaction effect, the effect of the softness condition and contact density condition were analyzed separately.

The black line in Fig.17 shows change in the average exploration time with standard error across softness conditions. We conducted post-hoc test with bonferroni adjustment for pair-wise comparison of 3 contact density conditions. As a result, there were significant differences between $d1$ and $d3$ ($p < 0.05$),and d1 and d5 ($p < 0.01$).

The black line in Fig.18 shows change in the average exploration time across contact density conditions. We conducted post hoc test with bonferroni adjustment for pair-wise comparison of 3 softness conditions. There were significant difference between $s1$ and $s3$ ($p < 0.01$).

The probability of finding correct responses for the softness and contact density condition are shown in Fig.19. We performed a two-way repeated ANOVA with softness condition ($s1, s2, s3$) and contact density condition ($d1, d3, d5$) factors on the probability of correct responses, and there was no significance on the main effect of both conditions and interaction effect.

5.4 Discussion

The result of the ANOVA tests on the softness and contact density conditions factors shows that these two factors had a significant impact on the exploration time. The gradation of the exploration time from Fig.16 and the post-hoc test's result in Fig.17 and Fig.18 supports that. These results are identical to experiment 1. According to the post-hoc multiple comparisons, differences in average exploration time between $d1$ and $d5$,and $d3$ and $d5$ were significant. There were comments from participants indicating that it was easy to recognize the corner when the particle size was small. Looking at Fig.17, the average performance softness condition $s1$ with denser density condition $d1$ was better than hardest condition $s3$ with sparser condition $d5$. This

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Fig. 19. The probability of a correct answer for softness and contact density condition.

means that denser contact point density has a possibility of making up for the problem of the penetration.

Regarding discrimination difficulty, it can be said that the task in experiment 2 had higher difficulty in discrimination than that in experiment 1. The lower discrimination accuracy and longer exploration time in experiment 2 support the difficulty of the task. According to Fig.19, it was more difficult for participants to discriminate. According to Fig.15, it took longer to discriminate. In experiment 2, the difference in exploration time between softness condition $s1$ and $s2$ are noticeable, though that was not in experiment 1. Because the task in experiment 2 was more difficult than experiment 1, the slight richness of kinesthetic cues influences the exploration time between condition $s1$ and $s2$.

6 General Discussion

6.1 Kinesthetic and Cutaneous Cues Integration

According to the results of the two series of experiments, we could confirm that the contact density and the softness of the object influenced the exploration time required for recognition. Though the exploration procedure was different between experiment 1 and 2, a similar influence was confirmed. The results also suggested that increasing the contact density facilitates shape recognition even when the finger penetrates into the object.

The previous research [11], [22] investigated the mechanism of sensory integration by fitting the results obtained in the experiment to sensory integration models such as Optimal Integration model and Sensory Capture model. However, from the viewpoint of the contact point density, it has not been discussed on the sensory integration of kinesthetic and cutaneous cues. If sensory capture model was adopted in our experimental environment and the kinesthetic cue dominated, it was speculated that exploration time would not decrease even if contact point density increased. However, in fact, whatever the condition of softness, the increase in contact point density reduced the exploration time. Thus, the kinesthetic cue did not dominate and the cutaneous cue was also integrated and used.

6.2 Design Guidelines for Future Multi-contact-point Haptic Display

Toward the future development of multi-point haptic display, our results suggested the importance of higher contact density. Let us pay attention to the transition with regard to the contact point density in Fig.9 and Fig.17. Lines of $s3$ condition in Fig.9 and Fig.17 show the effect of contact density when the more robust kinesthetic feedback is present. Lines of $s1$ and $s2$ conditions show the effect of contact density when there is little kinesthetic feedback. Fig.9 shows that the $s1$ with $d1$ or $d2$ performed better than $s3$ with $d5$. Similarly, Fig.17 shows that the $s1$ with $d1$ performed better than $s3$ with $d5$. This indicates that the lacking of kinesthetic cues could be compensated by the higher contact density. Because of the cost and workspace issues with kinesthetic devices, it would be nice to be able to make up for the lacking of kinesthetic cues with high contact density.

However, the exact density required for the multi-point display is still unknown, and additional experiments will be needed in the future. We plan to use particulate glove with higher contact density than that used in this study to know the minimum contact density sufficient to realize intuitive shape recognition. In such an experiment, we are able to evaluate shape recognition beyond the maximum contact density attainable using current multi-point displays, using the same method as presented in this study to simulate contact density and penetration. In addition, we also plan to make participants to touch soft urethan object with bare finger and use the exploration time as a benchmark.

7 Conclusion

This study proposed a method of preparing a real testing environment where we can control the density of the contact point and the penetration of the finger in the object independently. In order to control the density of the contact point, we covered the actual user's finger with particulate gloves. In order to mimic the penetration, we used urethane foam as a target of touch that deforms flexibly.

We conducted two series of experiments in which participants explored the object solely with the index finger or grasped with the index finger and thumb. The result of both experiments showed that both the sparseness of the contact point and the softness of the object had a significant impact on the longer exploration time. We confirmed that the exploration time decreased as the contact point became denser even when participants were exposed to the softest urethane foam.

As future work, we will study the discriminative threshold on more specific tasks while simulating the sparse contact density and the penetration.

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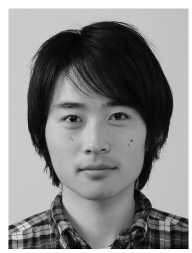

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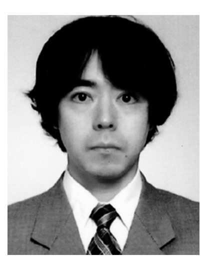

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