Multi Primitive Tactile Display Based on Suction Pressure Control

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Abstract

In this paper we propose a new method for displaying touch sensation by controlling suction pressure. We discovered a tactile illusion that pulling skin through a hole with suction pressure causes a feeling as if a stick is pushing the skin. This illusion is considered to be caused by the insensitivity of our mechanoreceptors to signs of stress (negative or positive) that are sensitive to the strain energy. Our tactile display is based on the key concept of this illusion and that of "multi-primitive stimulation." We show that a simple structure of a sparse stimulator array produces various tactile sensations from a sharp edge to a smooth plane surface.

1. Introduction

Until now, many tactile displays have been proposed for producing various tactile sensations using pin arrays [1] [2], electrical stimulation for firing nerve fibers [3], and radiation pressure of ultrasound [4]. These stimulators are intended to be applied on fingers and therefore are not feasible to stimulate a large area. Our goal of the study is to realize a tactile display that can produce various touch sensations in a large area like a whole palm. A problem in realizing a large-area-covering tactile display is that we have to prepare a large number of stimulators for producing tactile sensations varying from fine textures to smooth plane surfaces.

A method of "Multi Primitive Tactile Stimulation (MPTS)" was proposed in a previous work [5] although it had not been named in the paper. The paper suggested that applying two degree-of-freedom stress distributions (2 DOF primitives) with intervals of two-point-discrimination threshold (TPDT) creates equivalent cutaneous sensations that are generated by normal stress distributions. Since TPDT in palm is about 10mm, this method shows a possibility to make the stimulator array sparse. However, it turned to be infeasible due to one problem of the method that we had to control the primitives independently with precise intensity. Similar difficulty of pressure control has also been seen in traditional tactile displays using pin arrays as Fig. 1 shows. That is, when a large displacement is given to a pin in an array, the neighboring pins will lose contact with the skin. This interference impedes precise control of the contact pressure.

In this paper we propose a new tactile stimulation method by controlling suction pressure. This method is based on our discovery of a tactile illusion that we feel as if something like a stick pushes up the skin surface when we pull skin through a hole by lowering the air pressure. This illusion indicates that our tactile mechanoreceptors detects strain energy but can not discriminate positive or negative of stress.

Using the Suction Pressure Stimulation (SPS), we can control the pressure of stimulators independently and precisely since skin surface is constrained on a tactile display plate even when we apply an intense stimulation. The SPS method with a sparse array of suction holes makes MPTS feasible to produce various touch feelings.

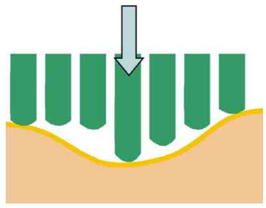


Figure 1: Displacement of a pin in a tactile display array interferes with the contacts between the neighboring pins and the skin.

2. Suction pressure stimulation

Figure 2 shows a cross-section of a skin put on a rigid plate with a suction hole. When we asked 10 subjects "what do you feel this stimulation is like?" lowering the air pressure in the hole of 6 mm in diameter to pull the skin surface, 9 of 10 subjects replied that they felt as if the skins were pushed by a stick like a pencil's bottom-end.

This illusion suggests that the mechanoreceptors are insensitive to the signs of the stress (positive or negative), which agrees with a prevailing belief that human's mechanoreceptors detect not stress or strain tensor directly but strain energy [6].

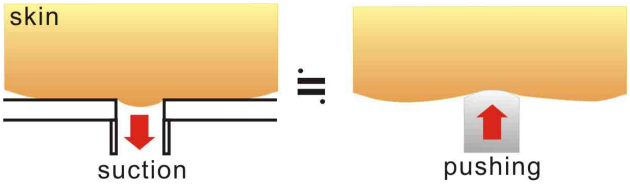


Figure 2: Schematic illustration of suction pressure stimulation. Drawing air causes a sensation as if something like a stick is pushing up.

We examined the strain energy in the skin by Finite Element Methods (FEM) to confirm this idea. The graphics in Fig. 3 (a) and (b) show the strain energy distributions in the skin under air suction (a) and pushing by a real stick (b). Physical parameters of Young's modulus, Poisson's ratio and depths of the mechano-receptors were based on a previous study by Maeno [7].

The 3-D distributions at skin surface are quite different between the two cases. On the other hand, the two cases give similar strain-energy distributions at the mechano-receptor level (approximately 0.7 mm below a skin surface) as Fig. 4 shows. These numerical results explain that our skin is insensitive to the difference between the two stimulations.

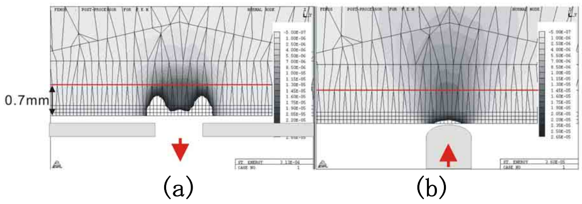


Figure 3: 3-D distributions of strain energy by suction pressure (a) and positive pressure caused by sticklike object (b). The distributions on skin surface are different from each other.

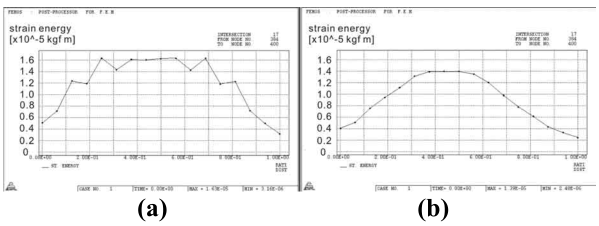


Figure 4: Distributions of strain energy near the receptors. Suction pressure (a) and positive pressure caused by stick-like object (b). The distributions are similar to each other.

One of the advantages owing to SPS is that the skin deforms locally around the suction hole being constrained by a tactile display plate while the skin feels an intense stimulation. Hence the stimulators do not interfere with each other unlike traditional pin arrays. Another advantage is that use of air pressure enables us to integrate stimulators easily with remote valves. These advantages are particularly useful to realize MPTS described in the next section.

3. Multi primitive tactile stimulation

The two-point-discrimination threshold (TPDT) is a classical parameter of tactile resolution. TPDT is the minimum distance with which we can correctly distinguish two point contacts as two. Pin arrays with their intervals of TPDT, however, does not suffice covering all possible tactile sensations, because we easily discriminate plural patterns of stress inside a TPDT circle. For example, we never take a top-end of a pencil for the bottom-end of it though the both of the diameters are smaller than the TPDT on a palm.

This fact shows that we have to prepare multi DOF stress-distribution patterns in a TPDT circle. We call these basic patterns as primitives. Then next question is how many primitives we should prepare. The former paper [5] suggested that the minimum number of primitives to cover tactile sensations is very small though it is not one. A relationship between TPDT and primitives are similar to one between visual resolution and RGB. As yellow is produced by green and red, we expect applying one primitive and another one produces a medium tactile feeling. An advantage of MPTS is that the method requires dramatically smaller density of stimulators than that would be required in single-primitive stimulation. Regarding a palm, the TPDT is about 10 mm [8] and it seems easy to place stimulators with intervals of 10 mm.

In a previous study [9], following two primitives, a smooth surface (S1) and a pin tip (S2) were examined as the primitives (see Fig. 5). These two primitives S1 and S2 present extremely small and large surface curvatures, respectively. The paper reported that the subjects felt medium curvatures when these two primitives were given simultaneously. But it lacked reproducibility because interference between S1 and S2 made the ratio of the stimulations unstable. In SPS method we expect interference between stimulators is small, which will make MPTS feasible.

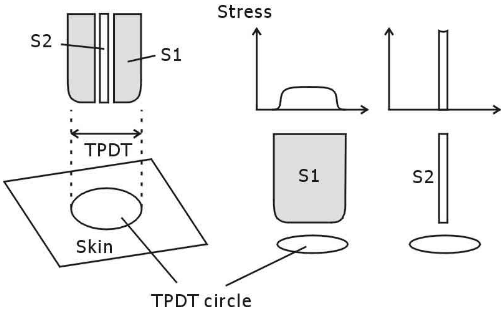


Figure 5: Two primitives described in [9]. The S1 gives smooth pressure distribution and the S2 gives concentrated pressure distribution.

4. Structure of the Display and Experiments

Our final goal is to realize a large-area-covering tactile display which gives various touch sensations from a fine texture to a smooth plane surface based on MPTS method. The overall structure of the tactile display is shown in Fig. 6. The display also has two kinds of primitives S1 and S2 as proposed in the previous study though the structures are different from those in the previous study. The hole S1 has an elastic rounded edge that generates a pressure distribution with a smooth profile while the hole S2 has a rigid sharp edge that generates a concentrated pressure distribution.

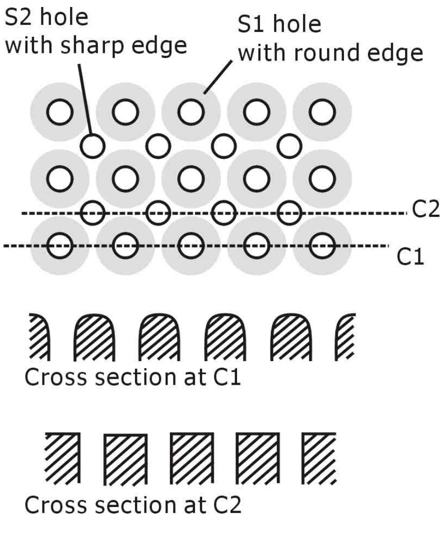


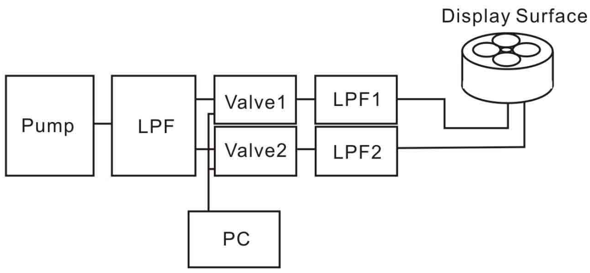
Figure 6: A MPTS tactile display with S1 and S2 suction holes. The S1 hole with a soft rounded edge gives smooth pressure distribution while the S2 hole with a rigid sharp edge gives a concentrated pressure distribution.

In this section we confirm following two things. One is whether we feel a medium curvature surface by combination of two primitives S1 and S2. If we feel an object with a medium sharpness, we can expect that the display produces most of touch sensations within TPDT. The other thing that we have to ascertain is whether arraying S1 (smooth surface primitive) can create a touch sensation on a perfectly smooth flat surface. Since the stress distribution by S1 holes is periodical, it is not self-evident if it can produce a large smooth surface.

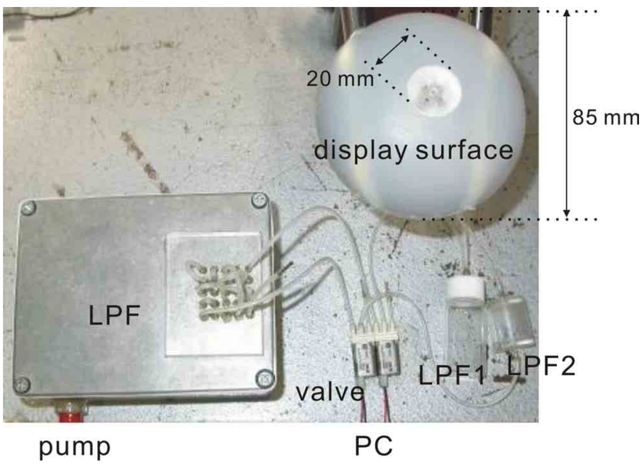
In this research that clarifies the feasibility of the display system, we examine the two problems by using a different device for each.

4.1 Experimental system

Figure 7 shows the block diagram and a photo of the experimental system for the following two experiments. We control the suction pressure with small valves that can operate 50 Hz. The LPF is realized by a fine tube and a cavity placed between the pump and valves to eliminate vibration caused by pump.



(a)



(b)

Figure 7: Block diagram of the system (a) and the photo (b). We control the suction pressure by the length of open time of each valve.

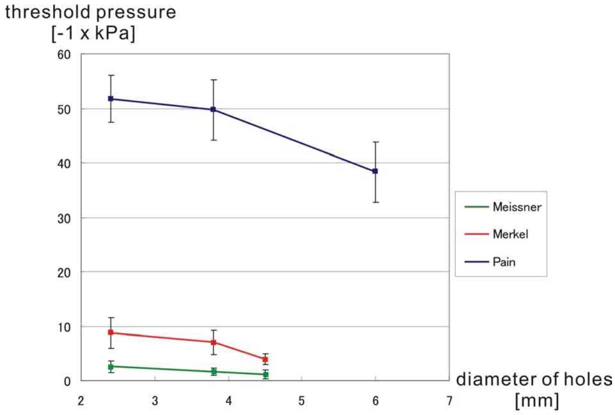


Figure 8: The minimum thresholds of suction pressure. The lowest green line shows the sensible minimum amplitude of vibratory 40 Hz pressure. The middle red line is the thresholds for slowly decreased pressure with time-constant 0.5 seconds. Blue line indicates thresholds of pain.

4.2 Measurement of Threshold

At first, we examined minimum thresholds of SPS. We chose two kinds of signal patterns. One is a slowly changing air pressure that reaches the minimum value (the most intense negative pressure) in 0.5 seconds, and the other is a vibratory stimulation. The vibratory stimulation was generated by the valve without the LPF1or LPF2 in Figure 7 (a). These two stimulations were chosen to evaluate the response of two kinds of mechanoreceptors of Meissner corpuscle and Merkel's Cell, individually. Meissner corpuscles (FA I) is said to have a high sensitivity around 40 Hz vibrations and Merkel's Cells (SA I) respond to low frequency stimulation. As we showed in Figure 3, the stress does not reach the deep part of the skin. Another important threshold is that of pain. The pain by nociceptors is easily distinguished from feeling by mechanoreceptors because its sensation follows the physical stimulation with a time rag of more than one second. Intense stimulation that excites nociceptors induces strange sensation as if we are pinched on the skin surface. Figure 8 shows the experimental results for four kinds of suction-hole-diameters. Six subjects were tested to determine a threshold. The lowest green line in the figure indicates the minimum amplitude of the 50 Hz vibratory stimulation that can be sensed by the subjects. The middle red line shows the threshold to the slowly decreased pressure. In both cases each threshold decreases as the suction holes diameter increases. It is also seen that the threshold of the vibratory stimulation that is mainly intended to excite FA I is lower than that of quasi-static stimulation mainly to excite SA I. We can give a wide range of stimulation intensity because the pain threshold is about ten times larger than the SA I threshold and fifty times larger than the F A I threshold, respectively.

4.3 Experiment I: Producing a medium curvature by two primitives

We examine whether we feel a virtual object with medium sharpness by synthesized stimulation of two primitives. Figure 9 shows the stimulation unit made of acrylic that we used in this experiment. The four S1 holes with the center-to-center interval of 6.0 mm surround the S2 hole. The edge of the S1 hole is rounded in order to prevent stress concentration. On the other hand, the central small hole S2 with the diameter of 2.4 mm has a sharp edge. The bottoms of the holes are connected to the valves with fine tubes with the inner diameter of 1.0 mm.

We apply three kinds of stimulations illustrated in Fig. 10 with pressure profiles shown in Fig. 11.

1) Plane surface (the left pattern in Fig. 10)

To show a plane surface contact we pull the skin from four S1 holes. The final pressure of every hole is -23 kPa and it takes 120 ms to reach the pressure ("S1 only" in Fig. 11).

2) Concentrated pressure (center)

For displaying concentrated pressure, we activate the central small hole. The pressure reaches -60 kPa in 120 ms ("S2 only").

3) Medium curvature (right)

All holes are activated to produce medium curvature stimulation. The final pressure is -14 kPa for each S1 hole and -37 kPa for S2 hole. All holes need 60 ms to reach respective pressures ("S1+S2").

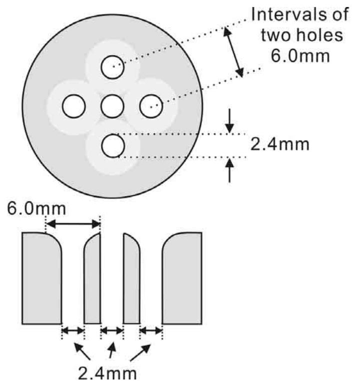


Figure 9: A shape of stimulation unit. The S1 edge is rounded in order to prevent stress concentration, while the S2 edge is not rounded for producing sharp pin like sensation.

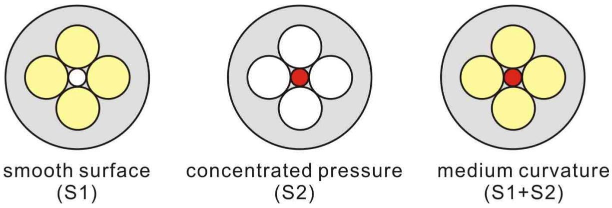


Figure 10: We apply three kinds of stimulations to subjects. The suction patterns correspond to a smooth surface (S1 only: left), a pin-like object (S2 only: center), and medium curvature by combination of two primitives (S1+S2: right).

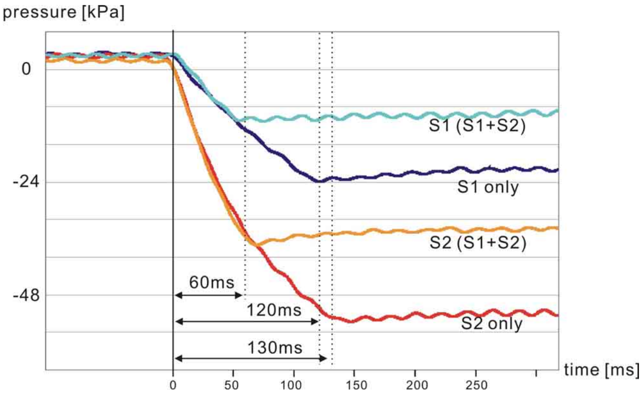


Figure 11: Pressure transition of three stimulations for producing a medium curvature.

We evaluated perceived curvature of SPS by comparing it with actual objects. We provided suction stimulation to the left hand of a subject and then an actual object is pushed on the right hand. After that, subjects were asked which stimulation was sharper. The actual reference objects were three cylinders made of acrylic whose contact curvature radiuses were A: 0.7 mm, B: 1.5 mm, and C: 3.0 mm respectively. We categorized perceived curvature into 7 classes shown in Table 1. For example, if someone answered suction pressure stimulation felt sharper than reference object B and flatter than object A, we evaluate the perceived curvature as class 3. Six subjects (5males and 1female) compared 5 times for each stimulation (S1 only, S2 only, and S1+S2) randomly without visual and auditory information. Totally 15 trials were done for each subject.

Table 1: Relationship between reference objects and evaluated classes

Curvature radius	⇦	A 0.7mm	⇔	B 1.5mm	⇔	C 3.0mm	⇨
Evaluation	1	2	3	4	5	6	7

Figure 12 shows the result of the evaluation on perceived curvature by SPS. Horizontal axis indicates evaluated curvature class (from 1 to 7) of the virtual surfaces following Table 1. Vertical axis exhibits the number of the answer.

It shows that S2 stimulation (blue) is evaluated to be sharper than the other two stimulations. It was also estimated to be equivalent to 0.7 mm curvature radius (object A). Subjects answered that S1 (yellow) was the flattest one and its radius was evaluated about 3.0 mm (object C). For S1+S2 combined stimulation (red), the subjects felt as if it has a medium curvature.

The results suggest that by controlling the suction pressure, we can produce any curvature stimulations in a TPDT circle when we prepare two kinds of primitives.

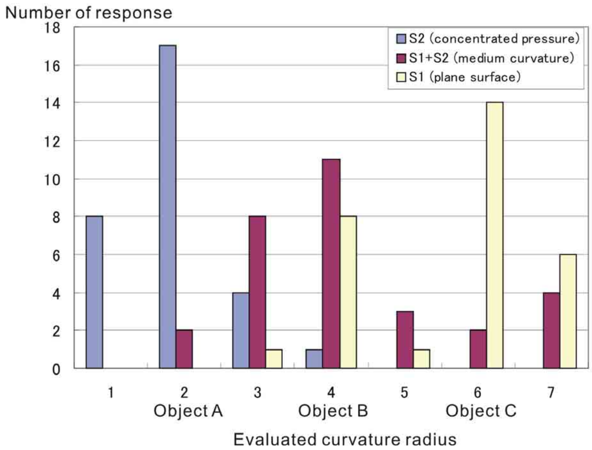


Figure 12: The results of curvature comparison. It shows that S1+S2 (red) is evaluated as medium curvature stimulation between plane surface (yellow) and concentrated pressure (blue).

4.4 Experiment II: Displaying a large plane surface

Another problem that we have to examine is whether we feel a smooth large plane surface by the array of S1 holes. To ascertain this we fabricated a display plate shown in Fig. 13. We rounded the edge of every hole and they were covered with a silicone rubber in order to prevent stress concentration on the edges. Each hole with a round edge is placed with their intervals of 5 mm.

To produce a large plane sensation, we drove each hole as follows for synthesizing a realistic contact. The central-hole-pressure is lowered to -46 kPa (it takes about 190ms). 10 ms after the central-hole-pressure drop, the surrounding 6 holes start to be activated, and 110 ms later they reach -28 kPa. 30 ms after the start of the central hole, the outmost 12 holes start to be activated and the pressure of each hole reaches -7 kPa after 40 ms (Fig. 14). These spatial and temporal suction patterns are intended to create a realistic feeling of a contact with a smooth object. The virtual force caused by air suction felt comparable to a real contact with a cylinder whose diameter is 20 mm with contact force 30 gf.

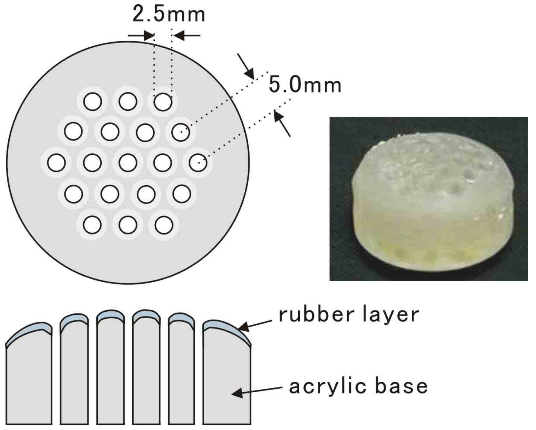


Figure 13: A configuration of the display device to stimulation unit to express large smooth surface. In order to prevent stress concentration on the edges, we rounded them and they are covered with the silicone rubber.

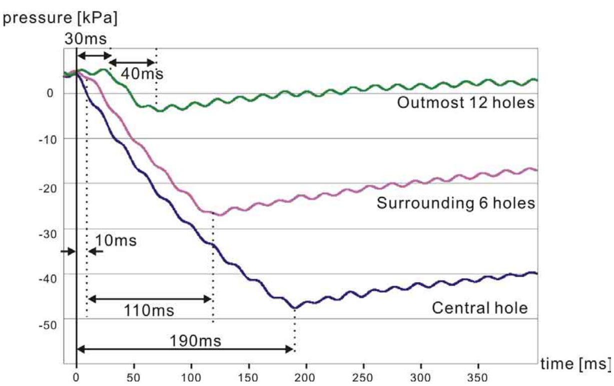


Figure 14: Transition patterns of suction pressure for displaying smooth surface

We evaluated smoothness of the virtual smooth surface. Two reference objects are compared with the stimulation. One reference is a smooth surface with the curvature radius 10 mm shown in Fig. 15 D. The other one is an uneven surface with 19 steel balls (whose radius is 2.5mm) at intervals of 5 mm (Fig. 15 E) equal to the interval of the suction holes. Our palms feel slight roughness for the reference object E although we hardly notice the roughness of the surface when we simply put our hands on the display device in Fig. 13. That is because the contact area of the object E with the skin is smaller than that of the display device with the skin.

Eight subjects (7 males and 1 female) compared virtual smooth surfaces with these two reference objects D and E. We provided suction pressure to the left hand of a subject and the subject touch the reference objects with the right hand. Then we asked subjects which stimulation was smoother. The subject was allowed to answer that the smoothness was in the same degree. The smooth surface and uneven surface were provided 5 times respectively without visual and auditory information.

Figure 15: Two reference objects. A smooth surface with the curvature radius of 10 mm (D), and an uneven surface with 19 steel balls with the radius of 2.5 mm (E).

Figure 16 shows the result of evaluation on perceived smoothness of displayed surfaces. Horizontal axis shows evaluated smoothness. The “number of response” of class 1 means the number of the answer that virtual stimulation felt as smooth as the actual smooth object D. The class 3 was evaluated as the same roughness as the uneven object E. This result shows the perceived smoothness of virtual surface is a little rougher than that of the actual smooth surface D and little smoother than that of object E.

When we examine this result, however, we have to consider one fact that 4 subjects of 8 did not distinguish two actual objects D and E. They answered these two stimulations were identically smooth. Therefore we have eliminated the results of 4 subjects, who could not discriminate two references, from the data in Fig. 16.

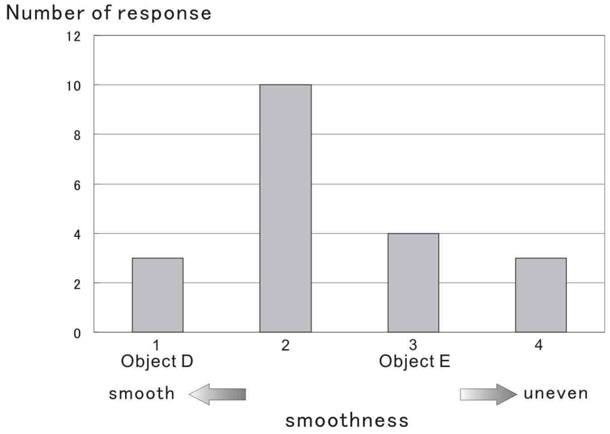


Figure 16: The results of surface smoothness comparison. The virtual surface is evaluated as medium smoothness between an actual smooth object D and an uneven one E.

5. Summary and Discussion

In this paper, we proposed a new method of displaying tactile sensation using suction pressure. Since it enables us to easily control stimulation elements independently and precisely, the method makes Multi Primitive Tactile Stimulation feasible.

We fabricated a tactile display system based on MPTS with suction holes to examine the principle. The system had an array of two kinds of suction holes S1 and S2 as tactile primitives. The S1 primitive is a hole with a rounded edge that gives a smooth pressure distribution. The S2 primitive is a hole with a sharp rigid edge that gives a concentrated stress distribution. In the first experiment, we confirmed that applying S1 and S2 simultaneously makes subjects feel a medium property (surface curvature) of a virtual object. In the second experiment, we confirmed S1 array produced a sensation of a contact with a smooth large surface.

In experiment I, the perceived curvature was not perfectly independent of the location of the stimulator. We also sometimes felt two independent stimulations by S1 and S2 instead of feeling a synthesized single round surface. This is because the sensitivity of our skin is not uniform on the palm. One practical solution is increasing the number of the primitives. If we prepare an intermediate primitive between S1 and S2, the stability of the stimulation will be dramatically improved.

In experiment II, a perfectly smooth surface was not displayed with a S1 array. We chose the intensity of the stimulators in order to tune so that perceived intensity becomes comparable to that of the actual reference contact. The stimulation to the superficial mechano-receptors, however, might be much larger than the stimulation by the actual reference contact.

We have to mention another unnatural feeling by this method. We felt some shearing forces on the skin with pain sensation for more intense stimulation than the pain threshold. This is because the suction stimulation induces more intense shearing stress in a skin than usual contacts do.

Finally we point out that the perceived sharpness strongly depends on the temporal waveform of the signal. Even when we stimulate the skin only with the S1 hole, the quicker the pressure drop is, the sharper the virtual object felt. We suppose that the evaluation of sharpness is strongly affected by the ratio between FA I and SA I firings. The research on it is under way.

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