Proceedings of the 2004 IEEE
International Conference on Robotics & Automation
New Orleans, LA • April 2004

# A Whole Palm Tactile Display Using Suction Pressure

Yasutoshi Makino, Naoya Asamura and Hiroyuki Shinoda

*Department of Information Physics and Computing,*
*Graduate School of Information Science and Technology,*
*The University of Tokyo*
*7-3-1, Hongo, Bunkyo-ku, Tokyo,113-8656, Japan*
{yasutoc, asamura, shino}@alab.t.u-tokyo.ac.jp

*Abstract* - **In this paper, we propose a large-area tactile display by controlling suction pressure. This research is based on our discovery of tactile illusion that pulling a skin through a hole with air suction causes a sensation as if something like a stick is pushing the skin. This illusion implies that our mechanoreceptors are insensitive to the sign of stress (negative or positive), i.e. we detect not stress directly but strain energy. There are two key concepts to realize our tactile display. One is the tactile illusion mentioned above and the other is "multi primitive tactile stimulation." We explain our approach to produce various tactile sensations from a sharp edge to a plane surface with a simple structure of display device based on air pressure control, and report the experimental results.**

***Index Terms - tactile display, haptic interface, cutaneous stimulation, tele-robotics, virtual reality.***

## I. INTRODUCTION

Displaying realistic tactile feeling is a challenge for many researchers in tele-robotics and virtual reality. The previous works using mechanical actuators [1], [2][3] including pneumatic actuators [4], electrical stimulation to firing nerve fibers [5], and radiation pressure of ultrasound [6], were intended to be applied on a fingertip that is the most sensitive part in a human body surface. Our goal of the study is realizing a tactile display that can produce realistic touch sensation in a large area like a whole palm. A problem in realizing a large-area-covering tactile display is that we have to attach a large number of stimulators for producing tactile sensations from fine textures to smooth plane surfaces.

In order to solve this problem, a concept of "Multi Primitive Tactile Stimulation (MPTS)" was proposed in a previous study [7] although it was not named so in it. In that research they tried to produce cutaneous sensation using 2 DOF tactile primitives (basis of stress pattern) given on a skin surface with their intervals comparable to two-point-discrimination threshold (TPDT). And it showed the 2 DOF stimulus produced sensations ranging from a sharp edge to a smooth surface on a palm. Since the TPDT on a palm is about 10 mm, MPTS can dramatically reduce the density of the stimulator. However one problem they faced was a precise control of the primitives. In mechanical actuation, when a large displacement is given to one of the pins, surrounding pins will lose their contact with skin as shown in Figure 1.

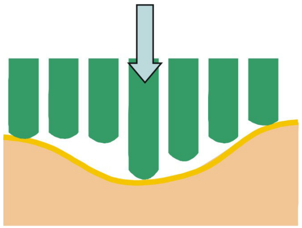


Figure 1. Large displacement of a pin in a tactile display array interferes with the neighboring pin contact to the skins.

In this paper we introduce "Suction Pressure Stimulation (SPS)" as a new tool of tactile display. We discovered an illusion that pulling a skin by air suction through a hole produces a feeling as if something like a stick is pushing on the skin as shown in Figure 2. This phenomenon implies that our mechanoreceptors detect strain energy around them while they can not discriminate a sign of stress (positive or negative). An obvious advantage of this method is interference between neighboring stimulators can be avoidable because deformation arises only within a hole while the skin surface remains constrained on the tactile display.

Combining SPS with MPTS, we show a novel structure of large-area-covering tactile display. In experiments we confirmed that we can produce tactile feelings ranging from a sharp edge to a plane surface.

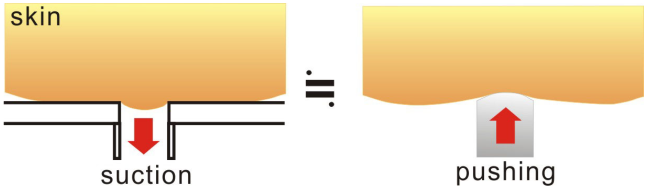


Figure 2. Schematic illustration of suction pressure stimulation. Drawing air causes a sensation as if something is pushing up.

## II. BASIC PRINCIPLES

### A. Suction pressure stimulation

Figure 2 is a cross-sectional illustration of Suction Pressure Stimulation (SPS) applied to a skin. When we put our palm on a rigid plate and pulling the skin through a suction hole by lowering air pressure, we feel as if something like a stick is pushing up the skin. When we asked 10 subjects "what do you feel this stimulation is like ?" applying suction pressure through a 6 mm-diameter hole, 9 of 10 subjects replied that they felt as if the skins were pushed by a stick like a pencil's bottom-end as shown in Figure 2.

This illusion that we can not discriminate suction pressure stimulation from the pushing-up suggests that our mechanoreceptors detect only strain energy while they cannot distinguish between positive stress and negative stress as Srinivasan et al. indicated this possibility [8].

To confirm this idea, we examined strain energy distribution in the skin by Finite Element Methods (FEM) using FEMLEEG (HOCT SYSTEMS CO.,LTD, Japan) and physical parameters of Young's modulus, Poisson's ratio and depths of the mechanoreceptors based on a previous study by Maeno [9]. Figure 3 shows the strain energy distributions under the skin surface induced by suction pressure with the hole diameter of 1.5 mm (a) and a push by a real stick with the diameter of 1.5 mm (b) that gives a similar feeling. As shown in these figures, the 3-D distributions under the skin surface seem different between the two cases. However, if we pay attention to the mechanoreceptor level (approximately 0.7mm below a skin surface), we find those distributions are similar as Figure 4 shows.

When we stimulate the palm by SPS, the deformation of the skin surface arises locally around the hole because the skin remains constrained on the tactile display plate. Therefore the interference between plural holes dose not occur. Another advantage is that it is easy to integrate stimulators with remote valves of air pressure. These advantages are effective to realize MPTS described in the next section.

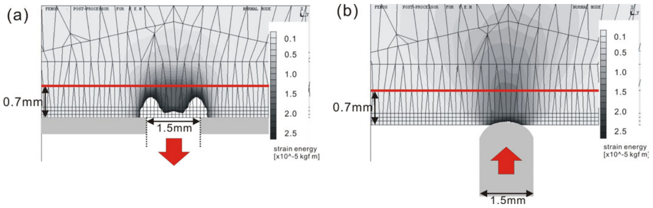


Figure 3. Distribution of strain energy by suction pressure (a) and positive pressure caused by a sticklike object (b). The distributions at the skin surface are different from each other.

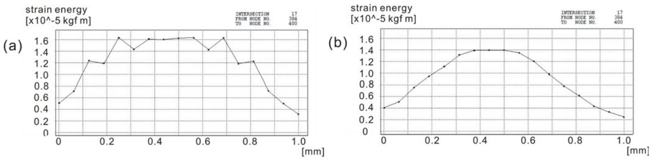


Figure 4. Distribution of strain energy near the receptors. Suction pressure (a) and positive pressure caused by a stick-like object (b). The distributions are similar to each other.

### *B. Multi primitive tactile stimulation*

Two-point-discrimination threshold (TPDT) is a well known parameter of tactile resolution. TPDT denotes the minimum distance that we can correctly distinguish two-point contact as two. On a palm TPDT is as large as about 10 mm. A pin array with the interval of TPDT, however, is not sufficient to cover all possible tactile sensations, since we easily discriminate plural patterns of stress within a TPDT circle. For example, a tip of a pencil and the bottom-end of it can never be misidentified although the diameters of these are smaller than the TPDT of a palm.

Here we introduce a concept of multi-primitive tactile display. That rooted in a question how many degree-of-freedom (DOF) of stress-pattern-basis we need to produce all possible tactile sensations. If we display both a sharp tip of a 1 mm wire and a plane surface in a TPDT area of $50\ \text{mm}^2$ by using a simple pin arrays, for example, we need 2500 = 50 by 50 DOF stimuli (7500 = 3 by 2500 if we also display the direction of the force), which requires high density of stimulators. However, if we seek an appropriate basis in all possible stress patterns, the necessary and sufficient DOF for producing all tactile sensations is possibly smaller than the one a simple pin array requires. We call these fundamental stress patterns "primitives." It leads us to display various touch sensations with dramatically lower density of stimulators than the one required in single-primitive stimulation, which enables us to realize a large area tactile display.

A previous study [7] suggested that necessary number of primitives for covering normal-stress-oriented tactile sensations is two at the minimum. The two primitives examined there are shown in Figure 5. A smooth surface (S1) and a pin tip (S2) are two extreme stimulations which are easily distinguished. The study [7] reported that a combination of two primitives given simultaneously created medium curvature. But it also reported poor reproducibility of the results, because the interference between two kinds of stimulation made the control of intensity ratio unstable. We expect that we can easily realize stable MPTS by using SPS which prevents interference with the neighboring stimulators.

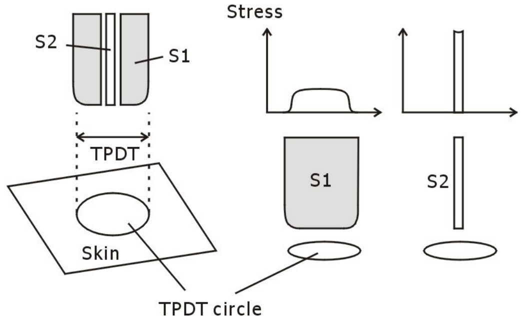


Figure 5. Two primitives that a previous work [7] chose. The S1 gives a smooth pressure distribution and the S2 gives a concentrated pressure distribution.

## III. TACTILE DISPLAY DESIGN

The structure of our tactile display is shown in Figure 6 and 7. Two primitives are arrayed alternately as a chess-board. The larger holes are for producing a smooth sensation. We call these holes "S1 holes." The smaller holes are for producing a sharp sensation. We call these holes "S2 holes." These are located with their intervals of 8 mm. We explain the functions and their parameter decisions in the following descriptions.

### A. S1 hole

The role of the S1 holes is inducing smooth sensation on the skin. It is desirable that our palm feels a contact with a smooth plane surface when we apply uniform suction pressure to all S1 holes. In order to realize such S1 holes, we have to minimize the stress concentration caused by S1 holes at the receptor level.

The optimum size of the S1 hole is determined as follows. Let the horizontal and vertical interval of the S1 hole-center be *D,* and let the length of the square-hole side be *L*. Now we apply uniform suction pressure through all S1 holes. Then the applied normal pressure distribution on the skin $p(x,y)$ is given roughly as follows when the edge of the hole is elastic to release stress concentration.

$$p(x,y) = -Af(x)f(y) + B(1-f(x))(1-f(y)) \quad (1)$$

where

$$f(x) = \begin{cases} 1 & (nD - L/2 < x < nD + L/2) \\ 0 & \text{otherwise} \end{cases}$$

The $f(x)$ is illustrated in. The term $-Af(x)f(y)$ means the negative pressure at the exposed area to suction pressure. The term $B(1-f(x))(1-f(y))$ means the positive pressure given by the display plate. Here we consider an optimization problem that we determine optimal *L* and *D* so that we make the spectrum of $p(x)$ localized in a low spatial-frequency domain, while we can neglect very high spatial frequency components that does not reach the mechanoreceptor level.

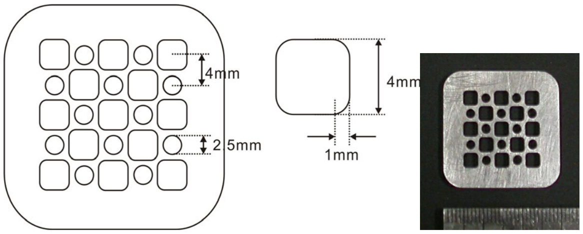


Figure 6. The overall structure of the tactile display. Two primitives are arrayed alternately as chess-board pattern.

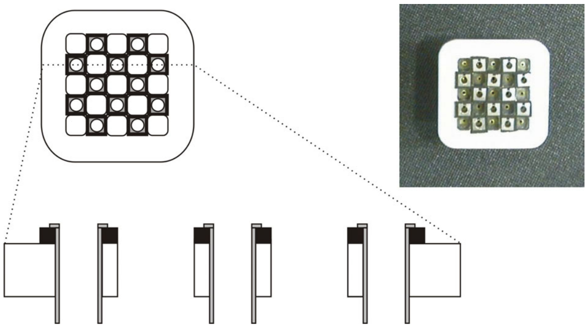


Figure 7. The cross-section of the surface. The plate in Figure 6 has a sponge layer on it to avoid stress concentration at S1-hole edge. The S2 hole is a pipe with 0.8 mm thickness supported by the sponge with a rim.

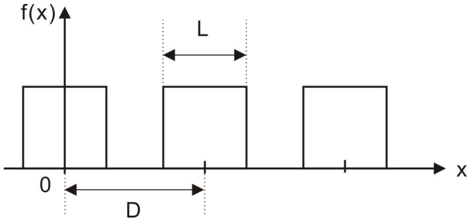


Figure 8. Illustration of $f(x)$. The interval between S1 hole-center is denoted as *D* whose maximum value is comparable to TPDT.

The first strategy is making *D* as large as possible. The maximum of *D* is comparable to TPDT. We consider here the maximum is 8 mm on the palm. The next strategy depends on the ratio between *A* and *B* that is determined by the elastic property of the skin. If $B = 0$ (the pressure from the surface plate of the display is negligible) the most effective strategy is making *L* as large as possible. For the actual human skin, however, in which a relatively hard surface-skin-layer is supported by a more elastic dermis layer, the spatial average of $p(x,y)$ is expected to be close to zero. Then the dominant frequency component in $p(x,y)$ is the fundamental frequency of the chess-board pattern. On this assumption, the best strategy to minimize the second harmonic of spatial frequency is to satisfy

$$L \approx D/2 . \quad (2)$$

Then we fabricated a display device following this strategy. The third harmonic or higher harmonic hardly expected to reach the mechanoreceptors.

### B. S2 hole

In the design of S1 holes, the shape was determined so as to reduce high spatial-frequency. In S2 holes design, it is required to localize the stress distribution for producing concentrated pressure. This stimulation is easily created by the sharp edge of the holes. It is also required that the existence of S2 should not influence S1 stimulations.

Figure 7 shows our approach which satisfies the above requirements. The S2 hole is a pipe with 2 mm inner diameter and with 0.8 mm thickness supported by the sponge with a rim. Then the S2-hole-edge hardly induce harmful stress when the S1 hole is activated, because the support of S2 by the sponge layer is elastic, while the suction pressure through S2 is effective regardless of the elasticity of the sponge. The schematic illustration of two DOF stimulations is shown in Figure 9.

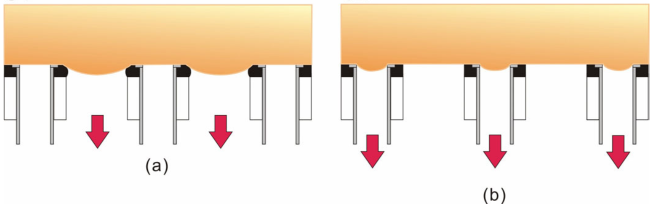


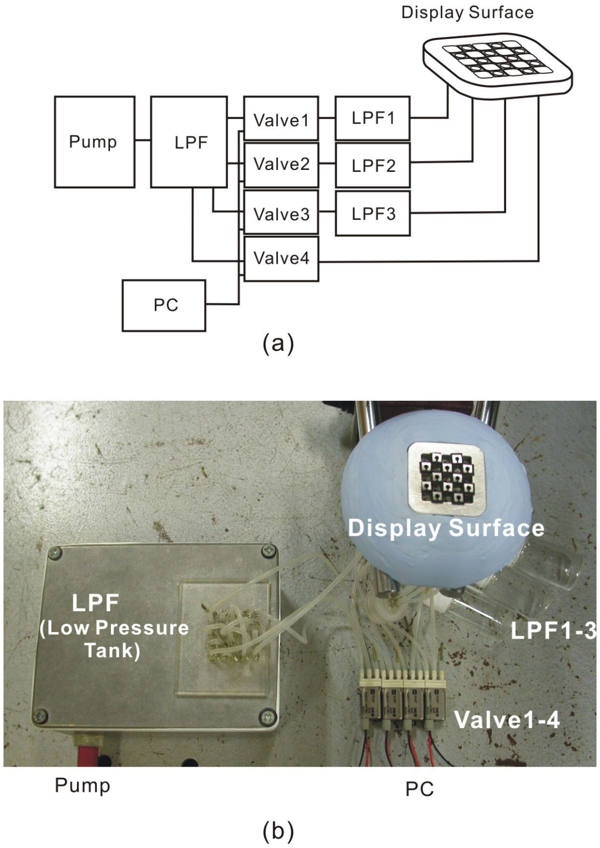
Figure 9. Schematic illustrations of two DOF stimulations. When we pull a skin through the S1 holes (a), the sponge layer reduces stress concentration at the square-hole-edge. When S2 holes are activated, edge of the pipe induces concentrated stress effectively (b).

## IV. EXPERIMENTS

### *Experimental settings*

Figure 10 shows the block diagram and a photograph of the following experiments. We control the suction pressure on the palm with small valves. The LPF is a cavity connected to fine tubes for eliminating noise caused by vibration of pump.

Eight subjects (7 male and 1 female) compared the stimulations with real reference objects and they chose the most similar reference.



(a)

(b)

Figure 10. Block diagram of the experimental system (a). We control suction pressure by four valves. The valve1, 2 and 3 are for S1 holes and valve4 controls S2 hole pressure. The lower picture (b) shows the photograph of the system. We fabricated a palm rest with hard rubber in order to secure a stable contact between hand and stimulators.

### *A. Experiment I: Comparison of sharpness*

First, we had subjects evaluate the feeling sharpness caused by S1 hole only (flat stress distribution primitive), S2 hole only (concentrated stress), and S1 and S2 simultaneously by comparing them with real reference object. This experiment was designed for determining the maximal sharpness displayed by the device, and for confirming the MPTS hypothesis that when we apply two primitives S1 and S2 with appropriate intensity, we perceive them as a single object with a medium curvature (sharpness) between the two primitives.

Figure 11 shows the stimulation patterns. Each duration times and the minimum pressures were determined empirically by pilot experiment to equalize the intensity of three stimulations and to produce a natural sensation.

### *B. Experiment II: Comparison of smoothness*

When we pull the skin through many S1 holes simultaneously for producing large flat surface, the readers may imagine that we feel unevenness. In this experiment II, we examined this possibility. The subjects were asked to choose the most similar reference object to the imagined object by the simultaneous S1 hole stimulation (S1x9) as shown in Figure 11, where the references include uneven surfaces with the same periodicity of the S1 array.

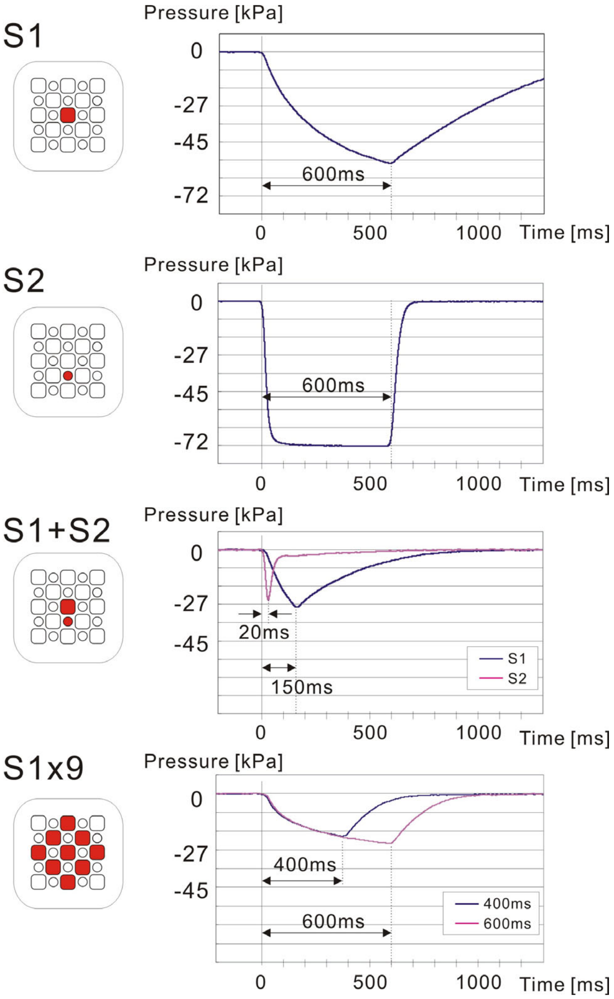


Figure 11. Active holes are shown on the left hand and suction pressure patterns for each stimulation are right hand. In stimulation S1, only central hole becomes active during 600 ms. In the case of S2, a single S2 hole is also activated for 600 ms. In S1+S2, the suction pressure and duration time are determined so that we feel the equal intensity to the S1 and the S2 stimulation. In order to produce a sensation of contact with large flat surface, we activate nine S1 holes. We prepare two suction patterns to adjust the intensity so that every subject can feel natural sensations.

We empirically determined these temporal suction patterns in Figure 11 for producing intended contact sensations for a smooth surface by the S1 and a sharp tip by the S2. In this procedure we found the perceived acuity changed according to the rate of temporal pressure change. The S2 pressure pattern has rapider pressure change than the S1 pressure pattern, which means the faster pressure change induces the sharper sensation.

### *C. Experimental procedure*

Experiment I and II were done at the same time. The subjects were asked to choose the most similar reference object from ten reference objects. The eight in the ten reference objects have smooth round surfaces. The curvature radiuses are 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 5.0, and 22.0 mm, respectively. The other two references had uneven surfaces. One was a needle array and the other one was 1 mm radius-hemisphere-head pin array. The intervals of the needles and pins were both equal to the interval of S1 holes.

Comparison tests were done as follows.

1) Subjects sat in front of the apparatus and put their left hand on the stimulator with their elbow on an arm rest with no visual and auditory information.
2) Four stimulations (3 stimuli for experiment I and 1 stimulus for experiment II) were given to the palm in random order.
3) Subjects were allowed to move their hand off stimulation surface and they tried to compare the imagined object with the reference objects. They could both see and touch the reference objects freely.
4) Until they decided which reference was the most similar to the stimulus, subjects could feel the same stimulation repeatedly.
5) When they decided, they answered the number of the reference.

Four stimuli were randomly given 5 times for each trial. Therefore one subject perceived stimulations 20 times. We obtained 40 data sets for each 4 stimulations.

## V. RESULTS

Figure 12 shows the results of experiment I and II. Horizontal axis indicates the curvature radius of reference objects and vertical axis indicates the number of answering.

When we applied the S2 stimulus, the subjects answered it was similar to the objects with the curvature radius 0.5 mm or 1.0 mm in most of the cases.

It is obviously shown that S2 hole stimulation was perceived as the smallest object, S1 was the largest object, and S1+S2 was a medium curvature object. These results support the hypothesis of MPTS that the combination of S1 and S2 primitives causes medium sensation.

In the experiment II, no subjects replied unevenness of the stimulation after we adjusted the intensity of the suction pressure. Two subjects reported that intense pressure makes unnatural feeling because of the tension of skin surface. The perceived intensity depends on subjects, probably by the compliance of skin surface.

Therefore we adjusted the intensity of S1 holes beforehand personally, and the graph shows the adjusted result. It shows that pulling a skin through the nine S1 holes produce a realistic smooth surface with the curvature radius 5 mm or more.

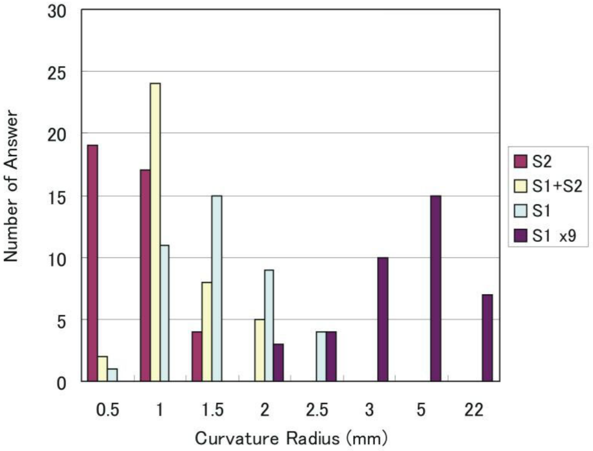


Figure 12. The results of the evaluation radius

## VI. SUMMARY AND DISCUSSIONS

In this paper, we proposed a new whole palm tactile display using suction pressure. By the Suction Pressure Stimulation (SPS), Multi Primitive Tactile Stimulation (MPTS) method was easily realized because SPS caused negligible interference among the stimulators.

We fabricated a palm tactile display system based on SPS and MPTS that creates two kinds of basic patterns of stimulations (primitives) for producing various tactile sensations. One primitive called S1 is a large hole with sponge-covering edge to display smooth surface and the other one called S2 creates concentrated pressure like a tip of a sharp pin with sharp edge of the hole floating on the sponge.

In experiments using this system, we confirmed that it could produce a tactile sensation ranging from the contact sensation of a sharp edge to that of a smooth surface. In the first experiment, it was demonstrated that a single S2 stimulus produces a sharper edge less than 1 mm curvature radius, and that combination of S1 and S2 stimulations creates medium property. In the second experiment, subjects felt as if a smooth surface touched on the palm when we activated plural S1 stimulators with adequate suction pressure.

In this paper we chose two primitives based on an intuitive consideration that two extreme pressure patterns that have the lowest and the highest degree of concentration would span the space of tactile feeling. As we described in section IV, however, we found the perceived sharpness depended on the rate of temporal pressure change. Since the two kinds of epidermal mechanoreceptors (FAI and SAI) have different frequency characteristics, it suggests that firing ratio between them is a main factor that determines the perceived sharpness. Then the next hypothesis we have is that the tactile feeling is determined by the 2 DOF parameters of the local sums of FAI and SAI firing per each TPDT unit. In order to decide if this proposition is true or false, we have to clarify the relationship between surface stress distribution and stress pattern at the mechanoreceptor level. If this proposition is true, we might have to find the primitives so that they can stimulate FAI and SAI with the maximum independence.

## REFERENCES

[1] Y. Ikei, K. Wakamatsu and S. Fukuda: “Image Data Transformation for Tactile Texture Display,” *Proc.VRAIS '98*, pp.51-58, 1998.

[2] M. Konyo, S. Tadokoro, T. Takamori, K. Oguro: "Artificial Tactile Feeling Display Using Soft Gel Actuators", *Proc. 2000 IEEE Int. Conf. on Robotics and Automation*, pp.3416-3421, April, 2000.

[3] J. Pasquero and V. Hayward: “STReSS: A Practical Tactile Display System with One Millimeter Spatial Resolution and 700 Hz Refresh Rate,” *Proc. of Eurohaptics 2003*, 2003.

[4] G. Moy, C. Wagner, R.S. Fearing: “A Compliant Tactile Display for Teletaction,” *Proc. IEEE Int Conf. Robotics and Automation*, pp. 3409-3415, 2000.

[5] H. Kajimoto, N. Kawakami, T. Maeda and S. Tachi: “Tactile Feeling Display using Functional Electrical Stimulation,” *Proc. 1999 ICAT*, 1999.

[6] T. Iwamoto, T. Maeda and H. Shinoda: “Focused Ultrasound for Tactile Feeling Display,” *Proc. 2001 ICAT*, pp. 121-126, 2001.

[7] N. Asamura, T. Shinohara, Y. Tojo, N. Koshida and H. Shinoda: “Necessary Spatial Resolution for Realistic Tactile Feeling Display,” *Proc. 2001 IEEE Int. Conf. on Robotics and Automation*, pp. 1851-1856, 2001.

[8] M. A. Srinivasan and K. Dandekar: “An Investigation of the Mechanics of Tactile Sense Using Two-Dimensional Models of the Primate Fingertip,” *Trans. ASME, J. Biomech. Eng., Vol.118, pp.48-55*,1996.

[9] T. Maeno, K. Kobayashi and N. Yamazaki: “Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors,” *Bulletin of JSME International Journal*, Vol. 41, No. 1, C, pp. 94-100, 1998.