SICE Annual Conference in Sapporo, August 4-6, 2004
Hokkaido Institute of Tecnology, Japan

Selective Stimulation to Skin Receptors by Suction Pressure Control

Yasutoshi MAKINO[1] and Hiroyuki SHINODA [1]

1 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, shino}@alab.t.u-tokyo.ac.jp

Abstract: In previous works, we have proposed two methods for whole palm-covering tactile display. One is “Suction Pressure Stimulation” and the other is “Multi-Primitive Tactile Stimulation”. In those studies, we used two pressure patterns as “primitives” which were considered to be significant patterns to create real tactile sensation. In this paper, we clarify the relationship between the primitives and response of mechanoreceptors using 3-D FEM analysis. The results indicate that two primitives activate two superficial mechanoreceptors RA and SA I selectively.

Keywords: tactile display, haptic interface, virtual reality

1. Introduction

The objective of this study is to realize whole palm covering tactile display which can produce realistic tactile feeling to the palm. Previous works proposed a lot of stimulating methods such as mechanical actuators [1] [2] [3], including pneumatic actuators [4], electrical stimulation for firing nerve fibers [5], and radiation pressure of ultrasound [6]. However the methods can not be applied to a large area covering tactile display because of following reasons.

- A large deformation caused by a strong force makes it difficult to control pressure distributions on the skin surface precisely because of unstable contact of stimulators to the skin.
- To cover the large area like a whole palm, it is considered that we have to prepare a huge number of stimulators to produce realistic cutaneous feelings.

In order to solve these problems, we have proposed two methods “Suction Pressure Stimulation” and “Multi Primitive Tactile Stimulation”.

“Suction Pressure Stimulation (SPS)” is a new tool of tactile display which is based on our discovery of tactual illusion. The illusion is that we feel compressed sensation as if something like a stick pushes up the skin when we pull the skin through a hole by air suction. This discovery indicates that our mechanoreceptors detect strain energy but not stress or strain tensor directly. One of the advantages of the SPS is that we can give touch sensations with little interference with surrounding stimulators since the skin deformation only occurs within a suction hole. This advantage is the solution to the first problem.

“Multi-Primitive Tactile Stimulation (MPTS)” was proposed in a previous study [7] though it was not named so in it. The method is that if we array appropriate “primitives” with their intervals comparable to two-point discrimination threshold, we can produce various feelings to the skin. The “primitives” are determined as fundamental stress patterns to create touch sensation. If the necessary number of primitives is small, we can cover large area like a whole palm with small number of stimulators. This method can be the solution of the second problem.

In previous studies [12][13][14], we have chosen two primitives by taking the feeling curvature into account. One was a smooth pressure pattern (S1) to display plane surface and the other was a concentrated pressure pattern (S2) to simulate pin like sensation. By combining these two primitives, we confirmed that the display could produce medium curvature sensation. Moreover we also confirmed that the display could produce large smooth surface by activating many S1 holes simultaneously. However, we did not discuss the sufficiency of two primitives though we have shown the possibility of the methods in the papers.

In this paper, we try to clarify the relationship between the given primitives to the skin and related response of mechanoreceptors using 3-D FEM analysis. We show the results that two primitives used in the previous studies were appropriate stimulations for activating two superficial mechanoreceptors RA and SA I respectively.

2. Preceding Studies

Suction pressure stimulation

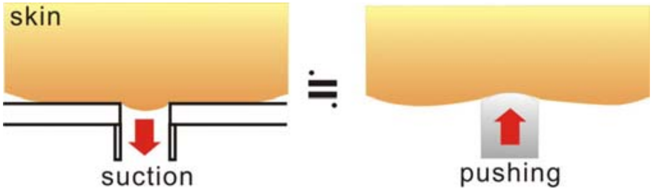

Figure 1. Schematic illustration of suction pressure stimulation. Pulling the skin by air suction makes compressed sensation as if something is pushing up.

Figure 1 is a cross-sectional illustration of the SPS applied to a skin. When we put our palm on a rigid plate with a hole and pulling the skin through the hole by lowering air pressure, we feel compressed sensation as if something like a stick is pushing up the skin. This illusion suggests that our mechanoreceptors detect only strain energy but not stress or strain tensor directly. This possibility of detecting the strain energy under the skin surface was already suggested by Srinivasan et al. [8].

In order to clarify this idea, we examined strain energy distributions under the skin surface by Finite Element Methods (FEM) using FEMLEEG (HOCT SYSTEMS Co.,Ltd, Japan). Physical parameters such as Young's modulus, Poisson's ratio and depths of the mechanoreceptors were based on a previous study by Maeno [9].

Figure 2 shows the strain energy distributions under the skin surface. Figure 2 (a) simulates a suction pressure stimulation with the hole diameter of 1.5 mm and Figure 2 (b) imitates a push by a real stick with the diameter of 1.5 mm that gives a similar feeling as the suction stimulation produces. It is obvious that the 3-D distributions under the skin surface seem different between the two cases. In suction pressure, strain energy is localized near the surface.

On the other hand, when we focus on the mechanoreceptor level (approximately 0.7mm below a skin surface), the distributions are similar as shown in Figure 3. This is the reason why we can not discriminate the suction stimulation from compression and it suggests that sign of stress is undetectable for human.

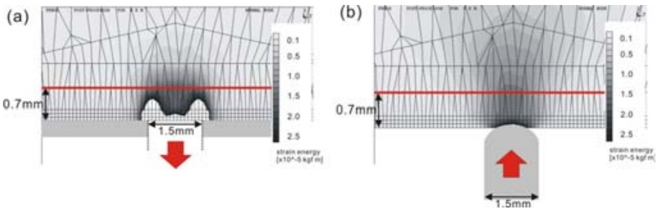

Figure 2. Distribution of strain energy by suction pressure (a) and positive pressure caused by a sticklike object (b). The distributions at the skin surface are different from each other.

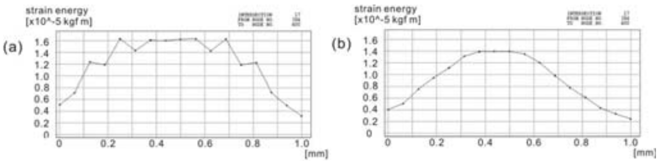

Figure 3. Distribution of strain energy near the receptors. Suction pressure (a) and positive pressure caused by a stick-like object (b). The distributions are similar to each other.

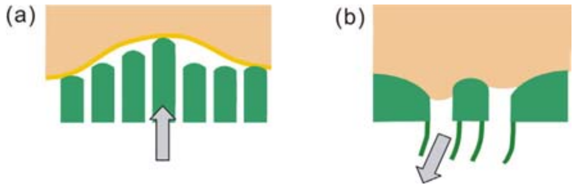

Figure 4 (a) Large displacement of a pin in a tactile display array interferes with the neighboring pin contact to the skins. (b) Suction pressure stimulation causes no interference with neighboring stimulators.

One of the advantages of the SPS is that we can give stable stimulation to the skin surface. When we push the skin with a large displacement of one pin as is shown in Figure 4 (a), other pins surrounding that pin lose their contact to the skin. Therefore we can not control stress distributions precisely. In contrast, when we stimulate the palm by SPS shown in Figure 4 (b), the deformation of the skin surface occurs locally within the hole because the skin remains constrained on the tactile display plate. Hence the interference between plural holes is avoidable.

Multi primitive tactile stimulation

Two-point-discrimination threshold (TPDT) is well known as a parameter of tactile resolution. The TPDT is defined as the minimum distance to discriminate two points contact as two when the two stimulations are given simultaneously. On a palm TPDT is as large as about 10 mm, however, we can easily distinguish the sharpness of object with a very high sensitivity although the size of them is smaller than the threshold. For example, a tip of a pencil and the bottom-end of it can never be misidentified. It indicates that it is insufficient to array stimulators with their intervals of the two- point discrimination threshold.

To straighten up this problem we define “TPDT area” at first. This is an area whose side is equal to the TPDT. Secondly, we also introduce a concept “Degree-of-Freedom (DOF)” which includes the concept of “resolution”. Then the problem can be described as follows. “How many DOF is required within a TPDT area?”

Traditionally, it is considered that high resolution is necessary in order to display a fine texture. If we divide the TPDT area into n-square elements (Figure 5 (a)), it means that the required DOF of stimulation per TPDT area is n-square, or 3 times n-square if we also control the force directions.

On the other hand, if we seek an appropriate basis in all possible stress patterns, the actually required DOF for producing all tactile sensations might be smaller than dividing the area into small regions (Figure 5 (b)). We call these fundamental stress patterns “primitives.” If the necessary number of the primitives m is dramatically smaller than the number required in single-primitive stimulation (n^2 or $3n^2$), we can realize a large area tactile display with sparse array of stimulators. We named this concept “Multi-Primitive Tactile Stimulation (MPTS)”.

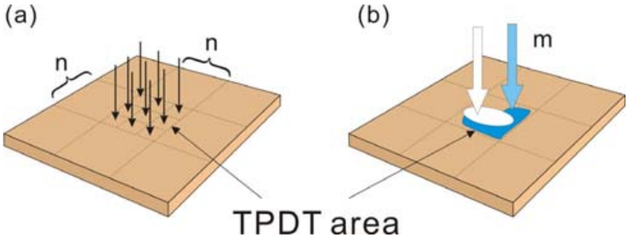

Figure 5 Two approaches to create various sensations. (a): Using primitives of δ-functions with a high density. (b) Using appropriate primitives with small degree-of-freedom per TPDT area.

A big issue of the MPTS is finding the minimum set of primitives to cover whole tactile sensations. In the previous studies, we focused on the curvature of stimulators because we easily distinguish contact sharpness. We prepared two kinds of holes as the primitives. One produced a smooth surface (S1) and the other displayed a pin tip (S2). By changing the size of holes and stiffness of holes' edge, we realized the difference of two primitives. As a result, we confirmed that we feel medium curvature (medium sensation between S1 and S2) when we activate two primitives simultaneously.

3. FEM Analysis

In our previous experiments, we considered that the two primitives of concentrated and smooth stress distributions can be realized by two kinds of suction holes with different diameters and stiffness of their edge. We found, however, the perceived curvature was strongly influenced by the transient profiles of suction pressure. When we pull the skin quickly, we feel sharper sensation than slowly pulled stimulus. We also found another several tactual characteristics. For example, when we pull the skin through plural S2 holes (pin-like primitive) simultaneously with their decreasing pressure speed slow, we feel large smooth surface. If the diameter of the suction hole is larger than about 6mm, pushed sensation tends to become suction or pinched feeling.

To understand these psychophysical phenomena, we chose two steps. As the first step we made a palm model to calculate the strain energy distributions under the skin surface by FEM analysis. In this step, we obtain the relationship between spatial stress patterns given to the skin surface and physical parameters of deformation under the skin. We made simple three dimensional palm model with three layers (shown in Figure 6). Each layer imitates the epidermis, dermis and subcutaneous tissue with no epidermal ridges between the epidermis and dermis. In this study we calculate "strain energy densities" and "shear strain energy densities" at the border of the dermis and epidermis. The "shear strain energy density" is an energy density calculated only from the shearing components of stress/strain tensor in a coordinate system along the skin surface. Finally we obtain couples of parameters of a strain-energy sum and a shear-strain -energy sum. The strain-energy sum is a sum of the strain energy densities within the TPDT area, the shear-strain -energy sum is a sum of the shear strain energy densities. We call the two dimensional plot of the couple of parameters a "SS plot."

In the second step we analyze the response of the mechanoreceptors based on the SS plots. As shown in Figure 2, since the strain energy induced by SPS is localized near the surface, we only consider the responses of superficial mechanoreceptors Meissner's Corpuscles (RA) and Merkel's Cell (SA I). Although the temporal dependence of each mechanoreceptor is well investigated (ex. [11]), there is no common understanding on the spatial parameters of deformation detected by each mechanoreceptor. In this study, we assume the following hypotheses based on previous works[8][9].

1) SA I detects the strain energy at the border between the dermis and epidermis.
2) RA detects the shear strain energy (defined before) at the border between the dermis and epidermis.
3) The SA I receptors within the TPDT area are bundled into one nerve fiber, and the sum of the receptors' responses reaches the brain. The RA receptors are also connected to the brain in the same manner.

Based on these assumptions, we analyze the nerve responses from the SS plots and temporal characteristics of SA I and RA receptors described in [11].

In the calculation of the first step, a FEM analysis software ANSYS (Cybernet Systems Co., Ltd) was used. The diameter of the area for strain energy calculation (at the border between epidermis and dermis) is 8 mm which is comparable to the TPDT on a palm. In the next section we show the results of the SS plots for pushing and SPS, changing the pushing objects and diameters of holes.

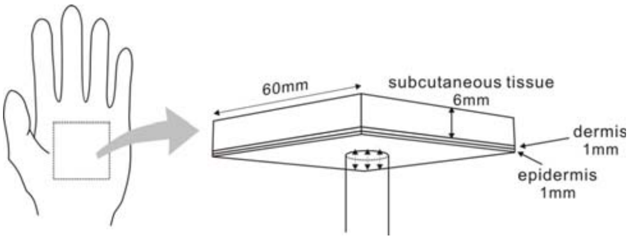

Figure 6 Three-dimensional palm model consists of three layers.

4. SS Plots for SPS and Stick-Pushing

Figure 7 shows the SS plots when stick-like objects with various diameters are pushed on the skin vertically. The horizontal axis indicates the strain-energy sum and the vertical axis indicates shear-strain-energy sum within the TPDT area. In the FEM analysis, linear elastic body was assumed, consequently, the difference of the total pushing forces of the stick results in the shift parallel to the 45 degree line in the log-log plot. The colored area in Figure 7 illustrates the possible area of the SS plots for vertically pushing objects. The red curve in the figure shows the SS plots for a constant pushing force 0.3 N with various diameters of pushing objects. It is seen that a small diameter of object makes a higher shear strain energy than a large diameter of object.

On the other hand, Figure 8 shows the results for suction pressure stimulation. The figure shows that the suction pressure control can give the SS plots of the blue area. The blue curve is the plots for a constant pressure of -30 kPa with various diameters of suction holes. The remarkable feature is that the effect of the hole-size is opposite to case of pushing. That is, pulling the skin through a large hole induces large shear-strain energy.

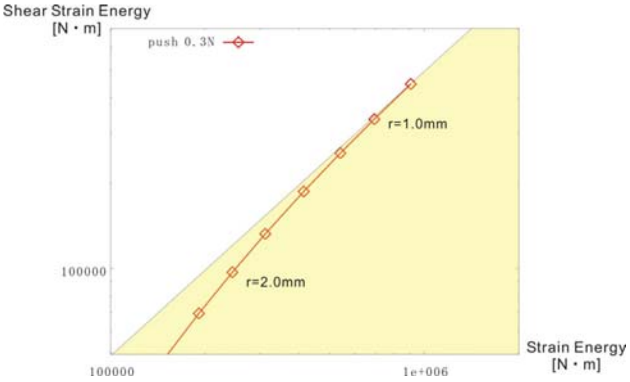

Figure 7 SS plots (2D plots of shear-strain-energy sum and strain-energy sum at the receptor level) for vertical pushing of stick-like objects. The red curve shows the SS plots for a constant pushing force 0.3 N with various diameters of objects.

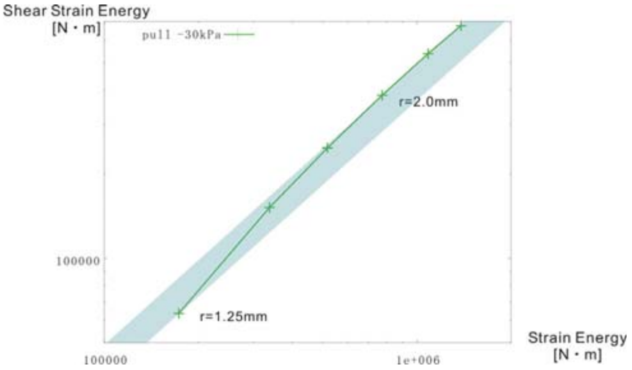

Figure 8 SS plots (2D plots of shear-strain-energy sum and strain-energy sum at the receptor level) for suction pressure stimulation. The green curve shows the SS plots for a constant pressure -30 kPa with various diameters of suction holes.

5. Analysis of Receptor Response

Relationship between SS plots and Perceived Sharpness

In this section, we consider combining the SS plots and actual perceived sensations. We focus on the “SS ratio” defined as the ratio of vertical component (shear–strain -energy sum) to horizontal component (strain-energy sum) in Figure 7. Then we can say that a large SS ratio produces sharp sensation. In other words, a higher response of RA can be perceived as a sharper object. This is because the SS ratio increases in monotone with the decrease of size of the pushing objects.

Secondly, we consider the temporal characteristics of each kind of mechanoreceptors. Based on the hypotheses in section 3, the horizontal axis (strain-energy sum) corresponds to the response of SA I and the vertical axis (shear -strain-energy sum) corresponds to the response of RA. The preceding studies by many researchers have revealed that the sensitivity of RA is strongly influenced by the temporal profiles because a RA receptor detects the velocity (temporal differential) of the deformation. In contrast, SA I response is proportional to the strain energy with no temporal filtering. Therefore, we can expect the temporal profile affects the RA sensitivity mainly. In the SS plots, the increase of the RA sensitivity is virtually equivalent to the increase of shear-strain-energy sum as shown in Figure 9. As a result, colored area including the deep blue area can be created by the SPS.

This virtual shift of SS plot explains the change of feeling in sharpness by temporal suction profile as we mentioned before. When we pull the skin quickly, the SS ratio virtually moves upward. Then we feel a sharper object.

In the previous studies, we also varied the stiffness of the edge of the suction holes as well as the hole-size and the temporal profiles. When we pulled the skin through the hole with a soft material on the edge, we felt a large smooth surface. This phenomenon is also explainable by the SS ratio. If the edge is soft enough, the shear-strain energy decreases. As a result, the SS ratio moves downward and we feel a blunt object.

Other tactile feeling by SPS

When we pull the skin slowly by S2 holes, the perceived SS ratio decreases, which produces a feeling of a large object. Therefore we feel large smooth surface with plural S2 holes with slowly decreasing rate.

If the size of the hole becomes large, the SS ratio will be beyond the possible ratio, i.e. there might not be created by any real pushing objects. Hence we feel unnatural sensation like suction or pinch sensation.

In the next section, we examine this model of tactile sensation by quantitatively comparing the SS ratio of the SPS with that of the evaluated objects.

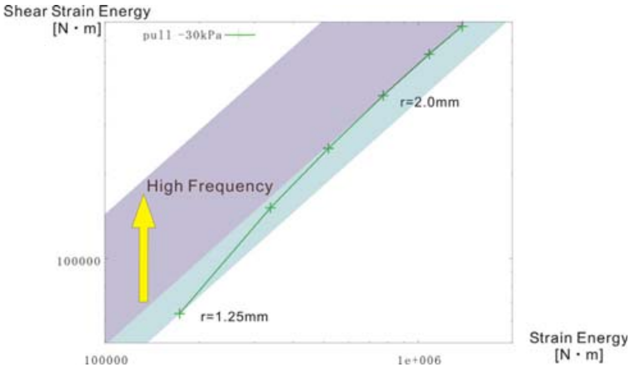

Figure 9 Influence of temporal dependence can be described as virtual increase of shear strain energy

Quantitative examination of the hypotheses

Figure 10 that merges Figure 7 and Figure 9, gives the correspondence between the hole-size of SPS and the diameter of the real pushed object. The green area is the overlapped area between pushing and suction stimulation. Our tactile sensation model says any touch sensations with their SS plots in the green area can be produced by the SPS.

In the previous psychophysical study [14], the perceived curvatures were evaluated for the SPSs. The subjects answered the curvatures of the virtual objects comparing with reference objects with various curvatures. In that experiment, one of the SPSs, S1, was air suction through a hole with the radius r = 2.0 mm. The other one, S2, was air suction through a hole with the radius r = 1.25 mm. The S1 and

S2 was used for displaying a flat plane and a pin-like object, respectively. Figure 11 shows the results. The subjects answered the S2 stimulus felt sharper than S1 stimulus.

Those experimental results seem inconsistent with our tactile sensation model described above. As Figure 10 shows the SS plots for S1 and S2 are equivalent to the pushing pins with the radiuses of 0.8 mm and 2 mm, respectively. The corresponding radius for S1 is smaller than the one for S2, which is inconsistent with the experimental results in Figure 11.

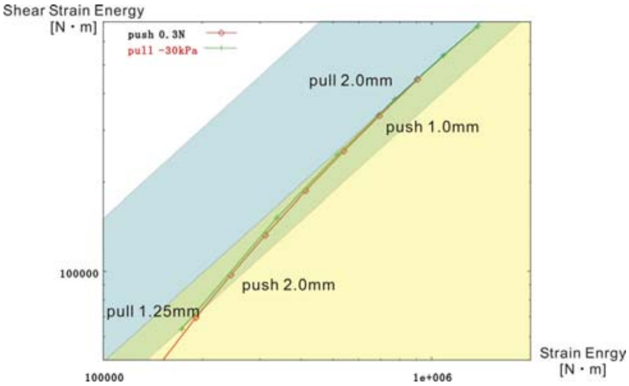

Figure 10 Merged graphics of pushing pin stimulation and suction pressure stimulation.

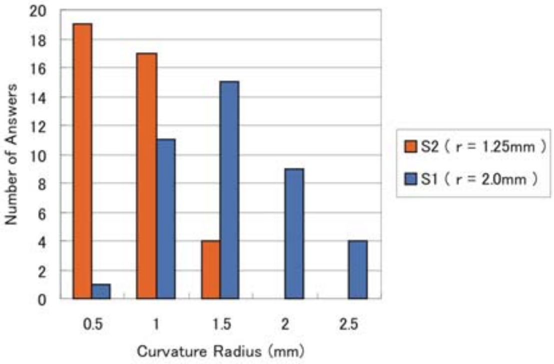

Figure 11 Evaluated curvatures of SPS ([14])

The apparent inconsistency can be explained by the temporal profile of air suction and the stiffness of the hole-edge. Figure 12 shows the corresponding plots of S1 stimulation and its evaluated curvature radius of pushing. The SS ratio for the SPS is not coincident with the one for an object having the evaluated radius in that experiment. However in that experiment, S1 stimulation was realized by slowly decreasing pressure with the soft hole-edge composed of sponge. We think this moved the perceived SS ratio downward as Figure 12 shows and the perceived diameter of the object became large.

In the case of S2 stimulation, it is also explainable as same way. The S2 was realized by pulling the skin quickly through the hole with the rigid edge composed of metallic pipes. Therefore the perceived SS ratio moved upward as shown in Figure 13 and the perceived diameter of the object became small.

These results indicate that the SS ratio is considered to be useful to determine the spatiotemporal profiles of tactile displays. Considering the SS ratio, we can stimulate superficial mechanoreceptors selectively.

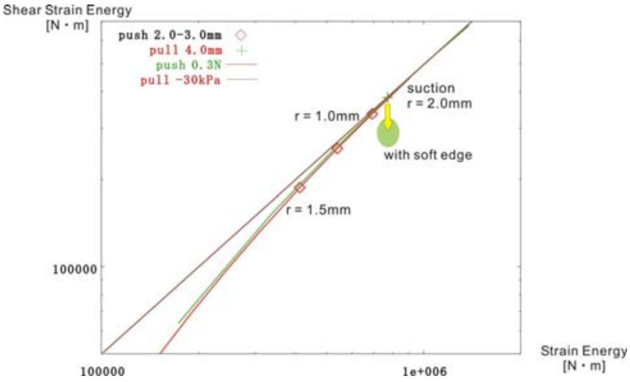

Figure 12 Comparison of suction by S1 hole with evaluated size of pushing objects.

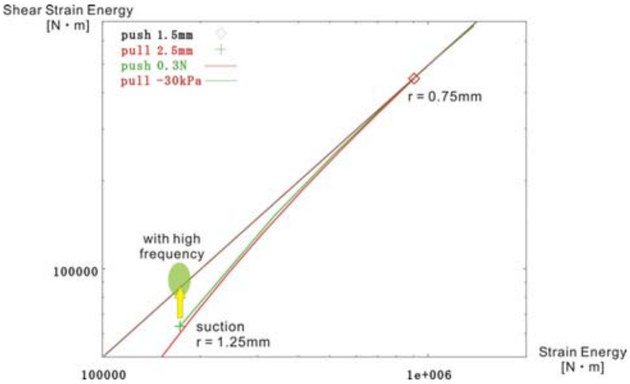

Figure 13 Comparison of suction by S2 hole with evaluated size of pushing objects.

6. Conclusion

In previous papers, we have proposed two methods "Suction Pressure Stimulation" and "Multi-Primitive Tactile Stimulation" for whole palm-covering tactile display. In those papers, we confirmed that medium sharpness can be displayed by combination of two different curvature stimulations. We called these fundamental stimulation "primitives". However, the primitives were selected intuitively and the sufficiency of the primitives was not argued. In this paper, we clarified the relationship between the SPS and related response of cutaneous mechanoreceptors. When we focus on the ratio of strain-energy to shear-strain-energy, the feeling acuity can be explained. Three dimensional FEM analysis revealed that the primitives were the stimulation which activated superficial mechanoreceptors RA and SA I selectively.

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] K. Dandekar, B.I. Raju and M.A. Srinivasan: “3-D Finite-Element Models of Human and Monkey Fingertips to Investigate the Mechanics of Tactile Sense,” *Journal of Biomechanical Engineering*, Vol. 125, pp. 682-691, 2003.

[10] 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.

[11] S.J. Bolanowski, Jr., G.A. Gescheider, R.T. Verrillo and C.M. Checkosky: “Four ChannelsMediate the Mechanical Aspects of Touch,” *J. Acoust. Soc. Am.*, Vol. 84, No. 5, pp.1680-1694, 1988.

[12] Y. Makino, N. Asamura and H. Shinoda: “A Cutaneous Feeling Display Using Suction Pressure,” *Proc. SICE 2003*, pp. 2096-2099, 2003.

[13] Y. Makino, N. Asamura and H. Shinoda: “Multi Primitive Tactile Display Based on Suction Pressure Control,” *Proc. IEEE 12th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, (Haptic Symposium 2004)*, pp. 90-96, 2004.

[14] Y. Makino, N. Asamura and H. Shinoda: “A Whole Palm Tactile Display Using Suction Pressure,” *IEEE Int. Conf. on Robotics & Automation*, pp.1524-1529, 2004.