A Cutaneous Perception Model and Its Examination by Ultrasound Tactile Display

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Abstract

We propose a tentative tactile perception model called Simple Bundle Model and examine it by a tactile display based on ultrasonic radiation pressure. The ultrasonic tactile display reproduces high-resolution stress patterns with wide bandwidth on the skin. It is a multi-purpose device for synthesizing high-fidelity tactile feeling, and useful to clarify the human tactile perception. The prototype could produce a 1 mm diameter focal point and 2 gf total force. We carried out experiments on tactile apparent movement using the display and found that tactile apparent movement is evoked quite stably even if the successive stimuli are not vibration but simple indentation. The result supports Simple Bundle Model, which suggests the possibility that a device with a simple structure can display a high-fidelity tactile feeling on a large area of the skin.

1 Introduction

In this paper we focus on the basic issue for sophisticating the cutaneous display, i. e. how to display realistic tactile feeling on the skin. In order to realize such a high-fidelity tactile display, there are at least two strategies. The first strategy is fabricating a device that can reproduce stress distribution on the skin with high resolution and wide bandwidth under sufficient controllability. The second strategy is constructing a device that gives the skin some alternative stimulation including non-mechanical stimulation [1, 2, 3] which produces equivalent tactile sensation to the actual touch sensation. In the future study, we will need a device based on the first strategy at the primary stage of the development in order to understand the cutaneous perception, and at the next stage we should be able to design a simple structure of tactile display based on the latter strategy, like we display all colors to our eyes using a knowledge that our visual organs sense the light spectrum by the three filtered amplitudes of RGB. In this paper, we show a tentative model of cutaneous perception to start with. Next we show a device reproducing skin stress with sufficient controllability that is based on the above mentioned first strategy. We present basic experiments to examine the perception model that will lead to the device design of the second strategy.

2 Simple Bundle Model: A Basic Model of Cutaneous Perception

The recent researches have come to uncover what physical parameters the mechanoreceptors detect. Maeno et al. discussed the roll of the skin structure using 2D FEM analysis [4]. Dandekar et al. calculated deformation of a 3D FEM model faithful to the monkey and the human fingers, and compared the strain at the receptor location with physiological data of nervous pulses under the same finger deformation. In that paper they suggested that Merkel cells (SA-I) detect the strain energy at the receptor locations [5].

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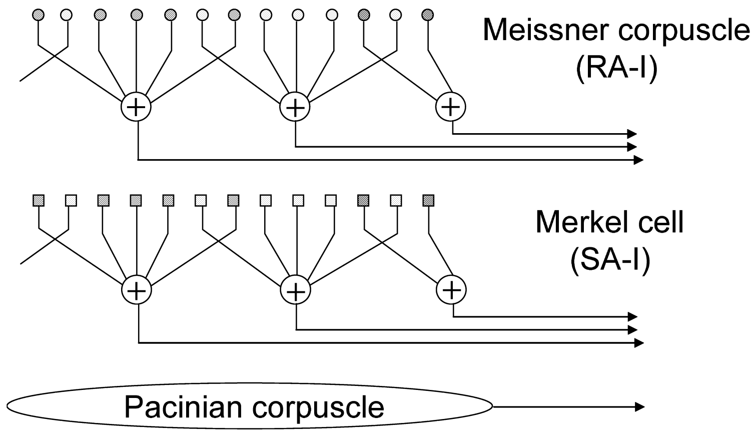


Figure 1: A tentative tactile perception model (SB model) to start the discussion. Each non-operational nerve bundle (Simple Bundle) in the population of superficial mechano-receptors (Meissner corpuscle and Merkel cell) samples 1 degree-of-freedom signal at a rate comparable to the visual frame rate.

Nara et al. showed that the helical structure of Meissner corpuscle (RA-I) gives the selective sensitivity to the shear stress (in a coordinate system parallel to the skin surface) [6]. Their logics are compelling though we have to wait more scientific experiments to fully convince us. At least it would be safe to say that the two kinds of superficial mechanoreceptors have different properties in both spatial and temporal selectivity attributed to their physical structures. The next sensing structure we have to clarify is how the nerves connect and what kind of processing is carried out among them to extract information from the skin surface. Regarding this problem, each researcher seems to have his/her own individual idea, and we have no common perception model. Here we start with a tentative model named "Simple Bundle Model (SB Model)" illustrated in Fig. 1. In this model, we assume the following not-obvious matters.

Hypothesis 1 Two kinds of superficial mechano-receptors, Meissner corpuscle (RA-I) and Merkel cell (SA-I) have indivisual sensitivities to the deformation. The two kinds of mechano-receptors are bundled independently into fibers connected to the brain.

Hypothesis 2 The brain detects 1 degree-of-freedom intensity signal (coded into the pulse frequency) for each bundle at a sampling rate comparable to the visual frame rate.

Hypothesis 3 The spread of receptors bundled into a single fiber is comparable to the two point discrimination threshold.

While Hypothesis 1 seems to be already accepted by many researchers, Hypothesis 2 might confuse the readers. Of course the mechano-receptors are sensitive to high frequency vibration as many literatures reported [7], and the human can distinguish the frequency from the ratio of the intensities perceived by multiple kinds of mechano-receptors, even under the hypothesis.

Hypothesis 2 means there is only one way of calculation for outputing 1-DOF intensity inside one bundle, and that the pulse frequency counted within the sampling interval is all of the information. We assume tactile hyper-acuity [8] is also realized by sensing intensity ratios among neighboring bundles whose receptive fields overlap with each other.

The third hypothesis is the most controversial one. 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-point contact as two when the two stimulations are given simultaneously. On a palm TPDT is as

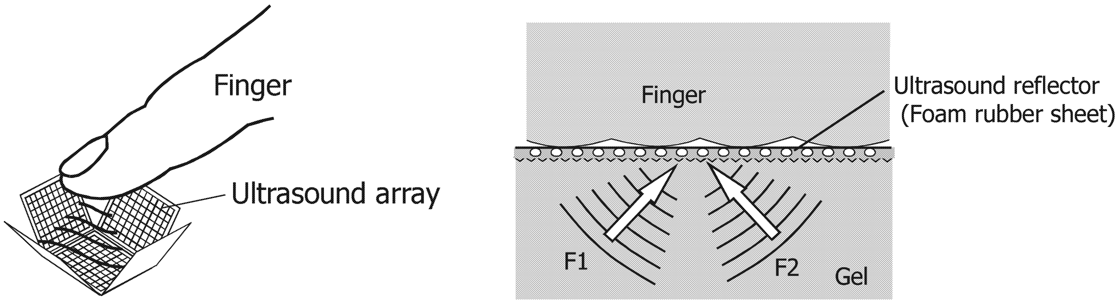


Figure 2: Tactile display using acoustic radiation pressure.

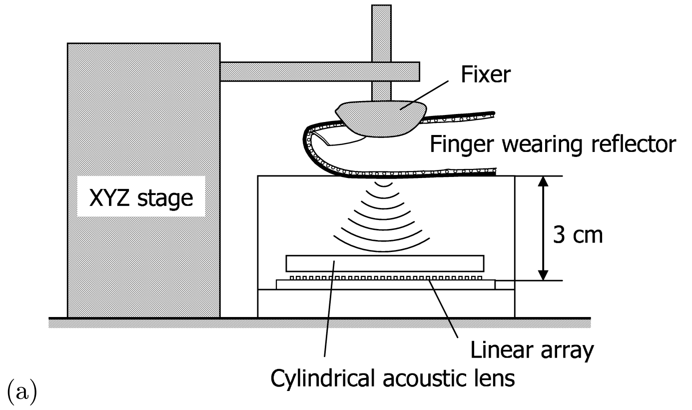
large as about 10 mm [17]. If we consider the largeness of TPDT, the hypothesis 3 might seem unnatural because we can easily distinguish the sharpness of object with a very high sensitivity. For example, a tip of a pencil and the bottom-end of it can never be misidentified. One possible explanation consistent with the Hypothesis 3 is that the human detects the sharpness of the object by the two-degree-of-freedom values from the SA-I and the RA-I receptors. A recent research clarified the perceived sharpness strongly depends on the temporal change rate of the stimulation more than actual sharpness, in the intensity range inducing no algetic perception [18]. Since the temporal change rate affects the ratio of RA-I response to SA-I response, this supports that explanation.

This "simple bundle model" might be quit natural for some readers that have not been unfamiliar with tactile issue, while it might also be too simple for other researchers. We propose we start with this simplest model. We believe this model holds good until a phenomenon inconsistent with this model is found. Whether SB model is true or false is significant for tactile display design because we will be opened to many alternative structures for a tactile display if the SB model is true. A tactile display based on "Multi-primitive tactile stimulation (MPTS)" [18] we proposed is an example of it.[1]

3 Stress reproduction by ultrasound radiation pressure

One straightforward method to understand cutaneus perception including judging the above mentioned SB model is to clarify what tactile feeling arises for controlled stress distributions on the skin. For such a scientific purpose, the available technologies based on mechanical stimulators [9] have limited controllability. The greatest difficulty is controlling a contact condition between the mechanical stimulator and the skin that might move unexpectedly. Controlling numerous pins in a wide bandwidth remains as a challenge. Our proposal is to use ultrasonic radiation pressure. One obvious merit using ultrasound is that both spatial resolution and temporal bandwidth are easily obtained. It was first shown by Dalecki

[1]MPTS is an effective method for a wide area tactile display when SB model is true. In order to straighten up MPTS, we tentatively define "TPDT area" at first. This is an area whose side is equal to the TPDT. Secondly, we also introduce an idea, degree-of-freedom (DOF) of stimulation, which includes the idea of resolution. Then we raise a question "How many DOF is required within a TPDT area to display all variation of cutaneous feeling?" Intuitively, we might imagine that high resolution is necessary in order to display a fine texture. If we divide the TPDT area into n-square elements for independent stimulation, the DOF used for stimulation per a TPDT area is n^2, or $3n^2$ if we also control the force directions. On the other hand, if we seek appropriate bases in all possible stress patterns, the actually required DOF for producing all tactile sensations might be smaller than n^2. We call these fundamental stress patterns "primitives," while we call displaying tactile feeling by such primitives multi-primitive stimulation (MPTS) method. If SB model is correct, the minimum number of the primitives m should be as small as two, the number of kinds of the superficial mechanoreceptors. The number is dramatically smaller than the number required in single-primitive stimulation, n^2 or $3n^2$. This hypothesis is proved when we find appropriate primitives. We are now searching the primitives that can selectively stimulate the two kinds of mechanoreceptors [19].



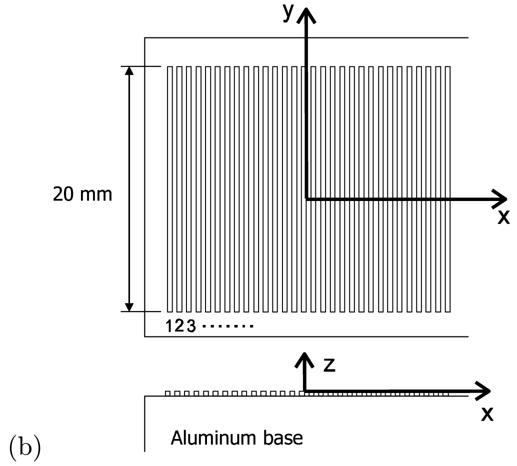


Figure 3: Experimental setup of ultrasonic tactile display (a), and the structure of the linear acoustic array used in the experiment.

et al. [10] that radiation pressure can provide enough force to produce tactile feeling. In this paper we show an arrayed ultra sound device especially designed to clarify the human tactile perception [11, 12]. Fig. 2 shows the basic principle of the display. Users put their fingers on an elastic gel covered with a thin ultrasound reflector. The reflector is easily realized by a thin foam rubber sheet using the large impedance mismatching between the solid and the air. When we focus the ultrasound near the surface, radiation pressure proportional to the acoustic energy density is induced. The radiation pressure P by a vertical beam to the surface is given as

$$P = \alpha E = \alpha \frac{p^2}{\rho c^2} \tag{1}$$

where E, p, ρ, and c respectively denote energy density of the sound beam near the surface, acoustic pressure, density of the sound medium, and the sound velocity. The α is a constant related to the reflection property of the surface. If all the acoustic energy is absorbed on the surface, α is equal to 1, while for the surface that reflects all the sound energy of the vertical beam, the α is 2. Since the sound power carried by the beam is given as

$$W = E/c \tag{2}$$

the smaller the sound velocity is, the larger the radiation pressure becomes for a constant power loss. The sound velocity of air, for example, is about 340 [m/s] while that of water is about 1,500 m/s. However, because of the easiness in impedance matching between a PZT sound emitter and a sound medium, we chose ultrasound-conductive gel or water as a sound medium. The first advantage of using ultrasound for tactile display is the large margin of frequency between the ultrasound and human tactile perception. If we use 3 MHz ultrasound, the frequency is 3,000 times larger than the bandwidth of tactile perception 1 kHz. Then, it is easy to scan the focused beam over an effective area. If the focused spot diameter is 1 mm, a 1 cm by 1cm area can be scanned within 1 ms even if the beam stays for 10 μsec (30 times larger than the period of the sound) for one stimulating point. The second advantage is the spatial resolution. If we use 3 MHz ultrasound, the wavelength is 0.5 mm in water or ultrasound-conductive gel. This means such high frequency sound can generate fine radiation-pressure pattern without any fragile mechanical parts. The third advantage is that it is free from contact problems because the device surface is elastic. When we stimulate the skin mechanically with hard pins, it is difficult to control the contact condition and contact pressure precisely. Unexpected forces arise by the movements of the user's skin. The fourth

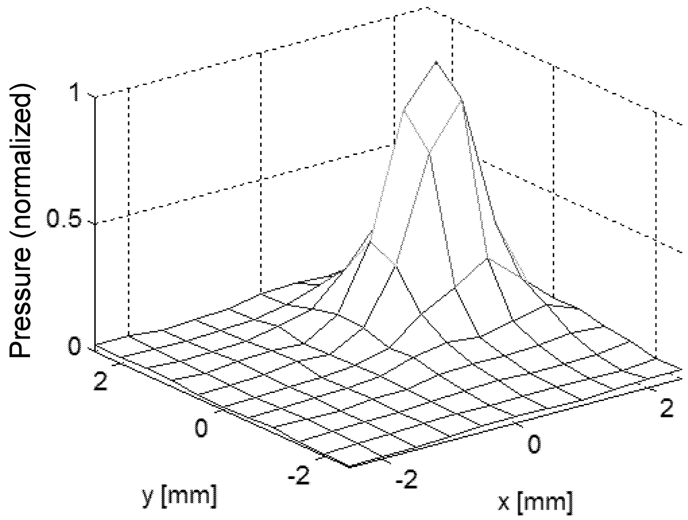


Figure 4: Spatial distribution of radiation pressure for a 3 MHz - 60 ch linear transducer.

advantage is that force direction is also controllable. Since the direction of the applied force depends on the beam direction, the 3D force vector on the skin can be controlled theoretically.

3.1 Prototype system

The prototype of the ultrasonic tactile display is shown in Fig. 3. The ultrasound medium used in the experiments of the next section is water. The 60 ch ultrasonic array was fabricated by Nihon Dempa Kogyo Co., Ltd. Japan, with special consideration to the heat diffusive structure. The focused beam profile measured at 3 cm from the ultrasound array and the frequency characteristics are shown in Fig. 4 and 5, respectively. In the frequency characteristics, fluctuation of the gain is within 5 dB from 20 Hz to 1 kHz. The reason why the frequency characteristic curve is not ideally flat is that the dynamics of the ultrasound medium affected it. We attained stable 2 gf of the total force by radiation pressure.

Using this device, we can plan effective psychophysical examinations of SB model. For example, we know that the human can detect the slide of the pin-like object on the skin sensitively. We can imagine existence of some special detectors to sense a slide of such a pressure pattern. If some local slide detectors are found, we have to discard the SB model.

We know that apparent motion [13, 14, 15] occurs when vibrators attached on the skin are switched sequentially, but we have not actually confirmed whether sequential vertical motions without vibration induce the same feeling as a real sliding motion. If we use a pin array with 5 mm interval on the finger, for example, and push the pins sequentially with every 30 ms interval, we usually differentiate it in perception from a real sliding motion. The imperfectness of the apparent motion without vibration was reported by Hulin [16]. This differentiation can be explained by the following possibilities 1 or 2.

- Our tactile organs have local sliding detectors. The SB model is incorrect.
- We simply distinguish them by the difference of the surface-force temporal profile attributed to the imperfectness of the stimulator.

Dismissing the possibility 2 is not straightforward by the traditional stimulator, though this is critical

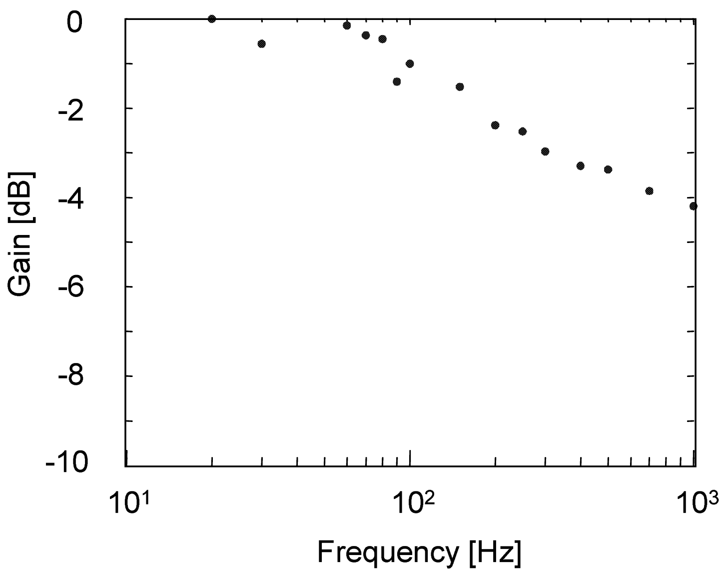


Figure 5: Frequency characterisitics of radiation pressure for a 3 MHz - 60 ch linear transducer.

to examine the perception model. If the total-force profile is different, it would be easily detected by the output of Pacinian corpuscle. The proposed ultrasound device is ideal to solve such kind of problems. It can display sequential vertical force (at fixed points, like "wave") keeping the total force constant (shifting the center of the total force). We can compare this stimulation with a continuous sweep of a force spot by the identical device.

4 Experiments

Two types of stimulation were employed and compared. One type of stimulation was called STR (Stroking). In STR, after applying a gradually increasing force for 250 ms at the starting point A, as shown in Fig. 6, we moved the focal point continuously along the subjects' finger from the starting point A to the endpoint B while the force at the focal point was kept at a constant value (i.e. no vibrations were applied), then we decreased the applied force gradually to zero for 250 ms at the end point B. The applied force during sweeping was fixed to 1.2 gf.

Another type of stimulation was called 3PT (3 points). In 3PT, after applying a gradually increasing force for 250 ms at the starting point A, we applied the force only to the three points on the finger; the starting point A, the middle point M and the end point B. The point M was located just at the center between A and B. The pressure at each point was changed so that the center of the applied force moved at a constant velocity and that the total amount of applied force was kept at 2 gf. The reason why the applied force was different from that of STR is that when the applied force of STR was equal to that of 3PT, subjects felt different stimulus-intensities between them. After moving the focal point to B, we gradually decreased the applied force to zero for 250 ms at B. Fig. 7 explains how the applied force at each point was changed.

The parameter d indicates the distance between the starting point A and the end point B. In the experiments, the cases of $d = 10$ and 20 mm were examined. Another parameter T_m (Time of Motion) indicates the time required for the focal point to move from A to B. In the experiments, T_m is selected

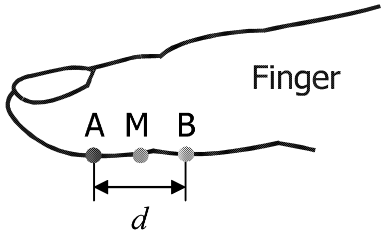


Figure 6: The position of each point on the finger pad. The starting point A is located at the center of the finger pad. The position of the end point B is determined by the parameter d. M is the midpoint of the line segment AB.

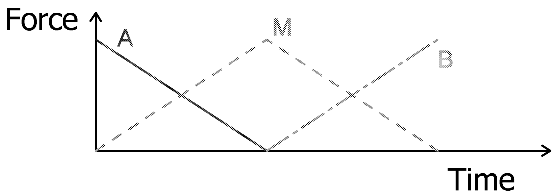


Figure 7: Schematic drawing of the force change at each stimulation point in 3PT type stimulation. The solid, dashed and dash-dot lines represent forces applied to A, M and B, respectively. Note that the total amount of the force is always kept at a constant value and that the center of the force is moved at a constant velocity.

among 20, 40 and 80 ms. We examined if we can distinguish STR for 3PT for above mentioned d and T_m, along the procedures explained in the next section.

4.1 Procedures

Subjects sat and placed their left index fingers on the top of the tactile display. The position of the finger was adjusted by XYZ stage so that the center of the finger pad coincides with the starting point A. First, the subjects were exposed to one type of stimulation S1 and then, after 1 sec interval, another type of stimulation S2 was applied. The subjects were asked whether S1 and S2 were the same type of stimulation or not. The answer was chosen from yes or no. A combination of S1 and S2, (S1, S2) was chosen from all possible sets: (STR, STR), (STR, 3PT), (3PT, STR), (3PT, 3PT). In each experimental session, the order of the four sets of stimulation was randomized but the number of times each set of stimulation was presented was equal. The d of STR and 3PT is equal, and d and T_m are constant through one experimental session. In this experimental procedure, the percentage of correct answers reaches 50 % if the subjects can not distinguish the two types of stimulation from each other at all. Nine experimental sessions were carried out for each subject in order to examine all possible combinations of d and T_m. For each session and each subject, the percentage of correct answers was recorded.

4.2 Results

Fig. 9 shows the percentages of correct answers for T_ms. Fig. 9 (a) and (b) are for d = 20 and 10 mm, respectively. Except for Subject C (dashed line), the graphs have a similar tendency. In both cases

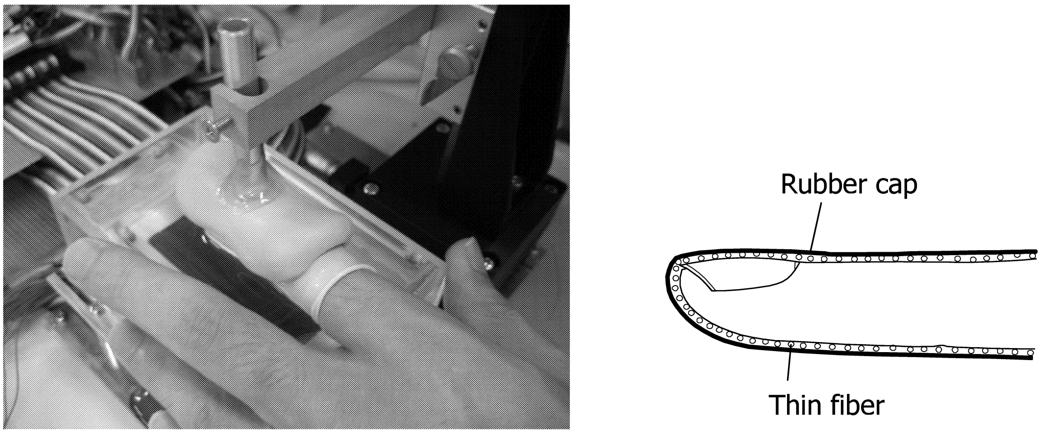
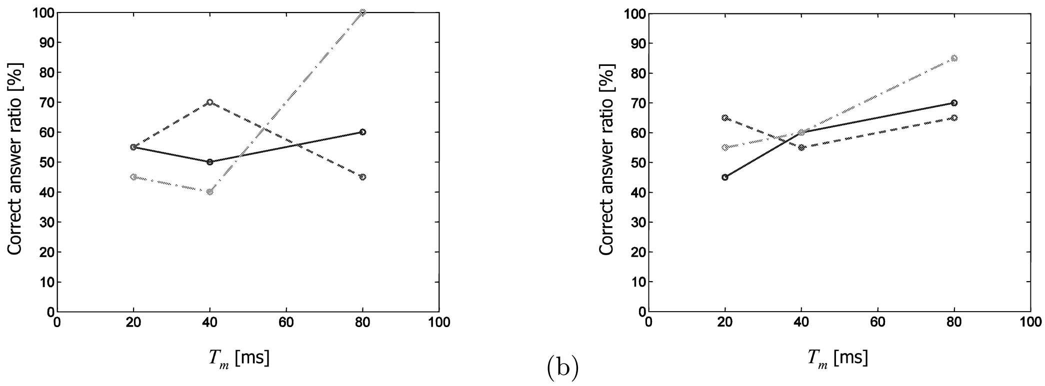


Figure 8: Photograph of the experiments



(a) (b)

Figure 9: The results of the experiments for d = 20 mm (a), and 10 mm (b). The solid line represents the results of Subject A. The dash-dot line and the dashed line are of Subject B and C, respectively.

of d = 20 mm and 10 mm, the correct answer ratio decreased to about 50 % when T_m was as small as 40 ms. This means the condition to induce an apparent motion indistinguishable form a real stroking is given by T_m regardless of the sliding velocity. The important result of this experiment is that the tactile feeling of 3PT was perfectly the same as that of STR under the condition.

5 Summary and discussions

In this study we proposed a tentative tactile perception model called Simple Bundle Model and examined it by a tactile display based on ultrasonic radiation pressure. The ultrasonic tactile display reproduces high-resolution stress patterns with wide bandwidth on the skin. It is a multi-purpose device for synthesizing high-fidelity tactile feeling, and useful to clarify the human tactile perception. The prototype could produce a 1 mm diameter focal point and 2 gf total force. We carried out experiments on tactile apparent movement using the display, and found that tactile apparent movement indistinguishable from a real sliding motion is evoked quite stably even if the successive stimuli are not vibration but simple indentation.

Conventionally, the tactile apparent motion was supposed to be induced only by vibratory stimulation.

The ultrasound device that can exactly control the pressure on the skin clarified that the successive indentation induces sliding motion that is perfectly indistinguishable from the real sliding. This means that the human skin has no local detectors of sliding motion and a continuous sliding motion can be evoked when sequential stimulations are given on the fixed points, for shorter switching intervals than a certain threshold. The reason why the subjects failed to feel apparent motions in the conventional experiments seems that the apparatus was imperfect so that it induced a harmful vibratory cue to distinguish it from real stroking motions. (For vibratory stimulations, the subjects could not notice the vibratory cues because they continuously felt vibration.)

The result supports Simple Bundle Model, which suggests the possibility that a device with a simple structure can display a high-fidelity tactile feeling on a large area of the skin.

References

[1] N. Asamura, N. Yokoyama and H. Shinoda,"Selectively Stimulating Skin Receptors for Tactile Display," IEEE Computer Graphics and Applications, Vol. 18, No. 6, pp.32-37, November.-December, 1998.

[2] Kajimoto, Kawakami, Maeda, Tachi, "Tactile Feeling Display using Functional Electrical Stimulation," Proc. of The Ninth International Conference on Artificial reality and Telexistence (ICAT'99), 1999.

[3] M. Konyo, K. Akazawa, S. Tadokoro, T. Takamori, "Wearable Haptic Interface Using ICPF Actuators for Tactile Feel Display in Response to Hand Movements," J. of Robotics and Mechatronics, Vol. 15, No. 2, pp. 219-226, 2003.

[4] T. Maeno, K. Kobayashi, and N. Yamazaki, "Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors," Bulletion of JSME International Journal, Vol. 41, No. 1, C, pp. 94-100, 1998.

[5] 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," Transactions of the ASME, Vol. 125, pp. 682-691, 2003.

[6] Takaaki Nara and Shigeru Ando, "The Mechanical Property of the Coiled Axon of Meissner Corpuscles for Human Tactile Sensing and its Application to a Biomimetic Tactile Sensor with a Helical Structure," Proceedings of the 11th International Conference on Solid State Sensors and Actuators 2001, pp.1666-1669, 2001.

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

[8] J. M. Loomis, "An investigation of tactile hyperacuity," Sensory Processes, Vol. 3, pp. 289-302, 1979.

[9] J. Pasquero and V. Hayward, "STReSS: A Practical Tactile Display System with One Millimeter," Proc. of Eurohaptics 2003, 2003.

[10] D.Dalecki, S.Z.Child, C.H.Raeman and E.Carlstensen, "Tactile perception of ultrasound," Journal of acoustical society of America, pp3165-3170,1995

[11] T. Iwamoto, T. Maeda, H. Shinoda, "Focused Ultrasound for Tactile Feeling Display," Proc. 2001 International Conf. on Artificial Reality and Telexistace, pp. 121-126, 2001.

[12] Takayuki Iwamoto, Daisuke Akaho, and Hiroyuki Shinoda, "High Resolution Tactile Display Using Acoustic Radiation Pressure," Proc. SICE 2004, pp.1239-1244, 2004.

[13] J. H. Kirman, "Tactile Apparent Movement: The Effects of Interstimulus Onset Interval and Stimulus Duration," Perception & Psychophysics, Vol. 15, pp.1-6, 1974.

[14] J. H. Kirman, "Tactile Apparent Movement: The Effects of Number of Stimulators," Journal of Experimental Psychology, Vol. 103, pp.1175-1180, 1974.

[15] C. E. Sherrick, R. Rogers, "Apparent Haptic Movement," Perception & Psychophysics, Vol. 1, pp.175-180, 1966.

[16] H. Hulin, "An Experimental Study of Apperent Tactual Movement," Journal of Experimental Psychology, vol. 10, pp. 293-320, 1927.

[17] S. R. Geiger ed. "Handbook of Physiology, Section 1: The Nervous Sytem," American Physiological Society, 1984.

[18] Yasutoshi Makino and Hiroyuki Shinoda, "Selective Stimulation to Skin Receptors by Suction Pressure Control," Proc. SICE 2004, pp.2103-2108, 2004.

[19] 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.