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Necessary Spatial Resolution for Realistic Tactile Feeling Display

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Abstract

In this paper, we show a hypothesis on the sensing mechanism in the human tactile organ and its resolution. The hypothesis is that human skin cannot resolve any finer pattern than the resolution suggested by the two-point-discrimination test, but that variety created by four kinds of signals from four kinds of mechano-receptors makes it possible to detect fine feature of texture. This means if we control stimulus to four kinds of mechanoreceptors individually, the realistic contact-feeling display will not need higher spatial resolution than suggested by the two-point discrimination threshold. We examine this hypothesis through psychophysical experiments.

Keywords; virtual reality, haptic interface, tactile feeling display, spatial resolution, two-point discrimination, teletaction

1. Introduction

The recent development of the Internet is motivating a cutaneous display that makes people feel realistic tactile feeling, for on-line shopping or amusements [1,2]. For such a display not aiming some manipulation tasks [3,4,5,6,7,8,9], the display area should not necessarily be focused on the finger tip having the highest receptor density. Instead, high-fidelity of tactile feeling becomes crucial.

In this paper, we discuss the minimum requirement for the special resolution of such a tactile feeling display. Our target area in this study is the palm because it seems sufficiently sensitive for tactile feeling transmission and also dull enough for technological realization.

The two-pint discrimination threshold (TPDT) is one classical and popular measure of the skin resolution. This TPDT is the minimum distance with which we can identify 2 points given in a simultaneous two-point-contact. The TPDTs on a fingertip and a palm are 2~3 mm and about 10 mm respectively [10]. However, the evaluation of the tactile resolution includes some complex problems. Humans can identify a very fine feature of objects less than the TPDT. For example, our palms easily distinguish between the top and the bottom of a pen though the both sizes are smaller than the TPDT. Our skin is so sensitive that it hardly feel the motion of pins arrayed on a device create a realistic feeling of a cotton towel or a leather bag.

In order to understand this paradoxical problem and realize the realistic tactile display, we have to consider both spatial resolution and skin receptor's selective sensitivity in parallel. In this paper, we propose a hypothesis on the cutaneous sensing mechanism. The scientific proof of the hypothesis will need other researches including neurophysiological approaches beyond the research in this paper. However, the hypothesis suggests a base to understand the human skin perception. In the following, we describe the psychophysical experiments to examine the hypothesis, and show that we can control various tactile feeling to the palm by a low-resolution display device.

Fig. 1: Spatial resolution for displaying realistic tactile feeling on the palm.

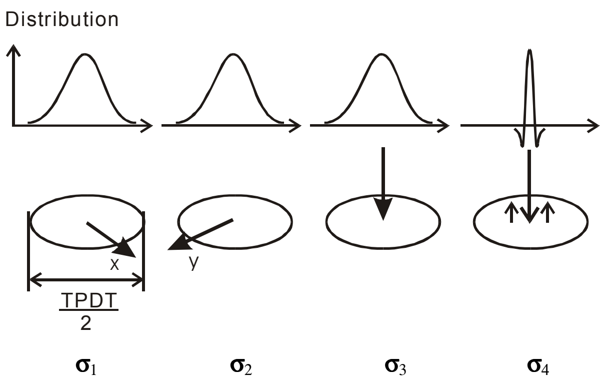

Fig. 2: Candidates for the four static stress bases in hypothesis 2. The arrows represent the direction of the applied force. The stress by $\boldsymbol{\sigma}_4$ does not reach the deep part of the skin.

2. A Hypothesis on human tactile perception

It is widely accepted that human glabrous skin has four kinds of mechanical receptors. Though thermal stimuli is also important for touch feeling [11], we omit that argument here. It is relatively easy to add thermal controller to a mechanical stimulator because high resolution and quick response are unnecessary.

The hypothesis we should examine here is:

> **Hypothesis**
>
> A half of TPDT is the sufficient resolution (interval of stimulation) for displaying any fine tactile feeling if we individually control stimulus to the four kinds of hand mechanoreceptors.

The hypothesis is based on an analogy of the human visual system. It says we do not need much finer resolution than the TPDT even if we should display very fine texture, as long as we stimulate the four kinds of the mechanoreceptors selectively. It is well known that human skin can distinguish very fine features of the texture [12,13]. The hypothesis insists that the human skin should perceive these fine features from the 4-D vector detected by the four kinds of receptors with sampling intervals 1/2×TPDT. If the four kinds have different spatial responses, they can detect such features, just as our three kinds of RGB visual receptors identify colors.

On the palm, it is said that the density of innervation of each types of receptors is 10~30 units/cm^2 [14]. Among the four types, the two kinds of the superficial receptors (Meissner corpuscle and Merkel cell) are located more densely than the others, and their densities are especially high on the fingertip [15]. The other two receptors (Rufini ending and Pacinian corpuscle) are located in the deep part of the skin. The temporal and spatial responses are various among the four types [16], but there is a certain temporal frequency range in which all the types respond well.

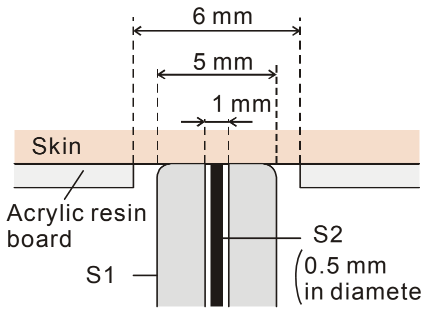

Fig. 3: Selective stimulator to a human palm. The S1 applies uniform normal stress ($\boldsymbol{\sigma}_3$) while the S2 applies concentrated normal stress ($\boldsymbol{\sigma}_4$ approximately).

3. Examination of the hypothesis

Let (x,y) be the spatial coordinate system on a hand. Suppose stress distribution given on the hand is written as $\boldsymbol{\sigma}(x,y,t) = (\sigma_x(x,y,t),\sigma_y(x,y,t),\sigma_z(x,y,t))$. Next we describe the subjective feeling to a stress distribution $\boldsymbol{\sigma}$ as $p(\boldsymbol{\sigma})$. A equation $p(\boldsymbol{\sigma}_1) = p(\boldsymbol{\sigma}_2)$ means that the tactile feeling to $\boldsymbol{\sigma}_1$ is identical to (indistinguishable from) that to $\boldsymbol{\sigma}_2$.

For a point Q(a,b) on the hand, we define $\Phi(\mathrm{Q})$ as a subspace of stress distribution in which the stress is zero outside the circle round the center Q with a radius of TPDT/2. That is

$$\Phi(\mathrm{Q}\ (a,b)) = \{\boldsymbol{\sigma};\ \boldsymbol{\sigma}(x,y,t) = 0 \text{ where } |(x-a,\ y-b)| > \mathrm{TPDT}/2\}.$$

Here we rewrite the hypothesis in a different manner.

> **Hypothesis 2**
>
> We can find four static stress bases $\boldsymbol{\sigma}_1,\boldsymbol{\sigma}_2,\boldsymbol{\sigma}_3$, and $\boldsymbol{\sigma}_4$ in $\Phi(\mathrm{Q})$ that realize $P' = P$ where
>
> $P = \{p(\boldsymbol{\sigma});\ \boldsymbol{\sigma} \in \Phi(\mathrm{Q})\}$
> $P' = \{p(\boldsymbol{\sigma});\ \boldsymbol{\sigma} = \alpha_1(t)\boldsymbol{\sigma}_1 + \alpha_2(t)\boldsymbol{\sigma}_2 + \alpha_3(t)\boldsymbol{\sigma}_3 + \alpha_4(t)\boldsymbol{\sigma}_4\}$.

This hypothesis means we can find four basic components of stress pattern whose summation can display any tactile feeling caused by any stress distribution given around Q. If it is true, an array of the stimulators giving the four bases with intervals of TPDT/2 will be able to produce any tactile feeling.

The equivalence of the hypothesis 2 to the original hypothesis is not very obvious. But from now we examine the hypothesis 2 instead of the original one that was a hint to come up with the second one.

The candidates we imagine now for the four bases are 1) smooth distribution (around Q) of *x*-directional stress, 2) *y*-directional stress, 3) *z*-directional stress (vertical to the skin), and 4) concentrated vertical stress that does not reach the deep part of the skin [17]. See **Fig. 2**. These candidates were obtained by the following logic. First, since the skin can discriminate among $\boldsymbol{\sigma}_1$,$\boldsymbol{\sigma}_2$, and $\boldsymbol{\sigma}_3$, the bases should include them. And because the human skin has an excellent ability to detect sharp edge, we added one more basis $\boldsymbol{\sigma}_4$ to them. We guess the $\boldsymbol{\sigma}_4$ is detected by the combination of Meissner corpuscle and Merkel cell [18].

In this paper we report results of examining hypothesis 2 for a subspace $\Phi_n(Q)$ included in $\Phi(Q)$ where $\Phi_n(Q)$ consists of stress distributions having no lateral components (no shearing stress). Then the two bases $\boldsymbol{\sigma}_3$ and $\boldsymbol{\sigma}_4$ in **Fig. 2** should display any tactile feeling for any $\boldsymbol{\sigma}$ in $\Phi_n(Q)$. In order to examine this, we prepared an apparatus as shown in **Fig. 3** that stimulates the skin with S1 and S2.

S1) Smooth normal stress distribution ($\boldsymbol{\sigma}_3$) by a moving cylinder with a diameter of 1/2×TPDT.

S2) Concentrated normal stress distribution ($\boldsymbol{\sigma}_4$ approximately) by a needle through the S1 cylinder.

The stimulator S1 represents an object with very small curvature, while the S2 very large curvature. We examine whether the combination of the S1 and S2 can create tactile feeling of an intermediate curvature of an object, and whether the curvature can be controlled continuously from a sharp tip to a smooth surface.

If this is true, the hypothesis 2 for the subspace $\Phi_n(Q)$ sounds very reasonable because the contact in general can be assumed as a combination of multiple contacts with various curvature surfaces.

Fig. 4 shows the apparatus for experiments. The diameter of S1 is 5 mm, a half of TPDT 10 mm on palm, while the inside diameter of S1 is 1 mm. The S2 is a pin with diameter of 0.5mm. Each stimulator moves independently in vertical direction. Subjects put the hand on a flat panel, and we apply the S1 and S2 through a hole in the panel. The examined part is the thenar for the easiness of the experiment.
The S1 and S2 are actuated by ultrasonic motors with displacement-resolution 0.002 mm/pulse.

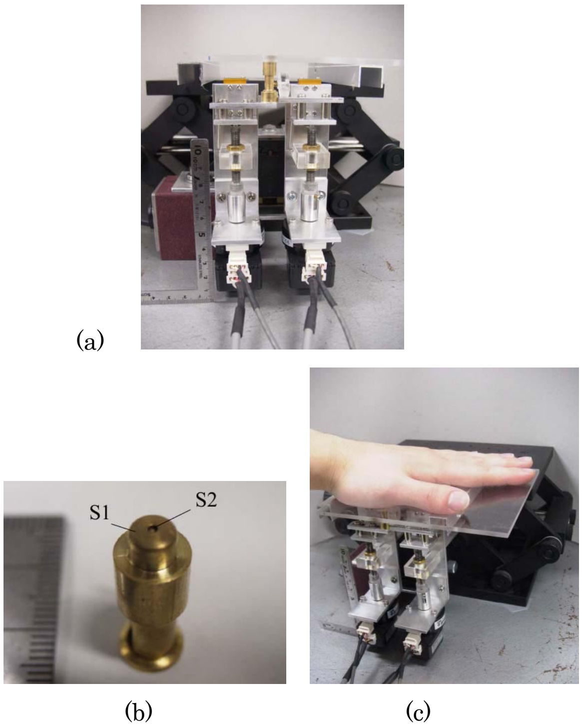

Fig. 4: Photographs of the apparatus. (a): The structure. (b): The stimulators S1 and S2. (c): A view of the experiment stimulating a thenar.

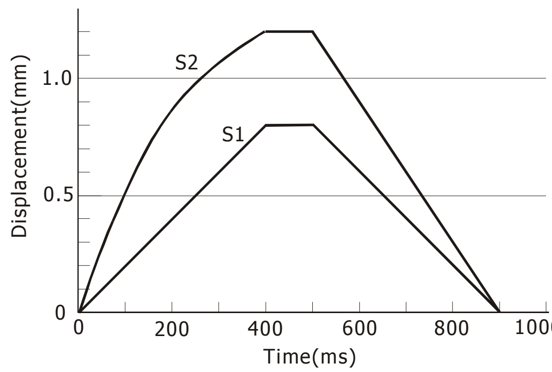

Fig. 5: Experiment I. Displacement patterns of the stimulator S1 and S2.

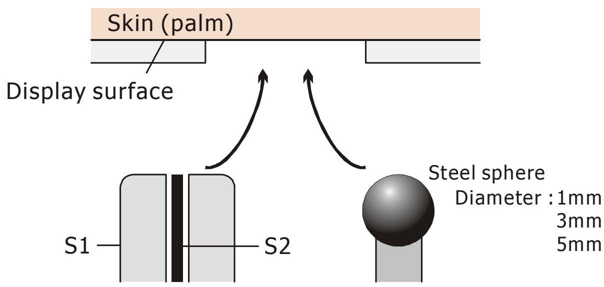

Fig. 6: Tactile feeling comparison between synthesized stimuli and real sphere surfaces.

4. Experiment I

When the S1 and S2 were driven by a signal pattern as shown in **Fig. 5** (they are at the same level at the beginning), the subjects did not feel a projection on a flat surface but an intermediate curvature surface. Then we examined if we could produce tactile feeling identical to a round object with an intermediate curvature by using S1 and S2. The hand is fixed and passive to stimuli.

Stimuli

We prepare the best driving pattern to create the feeling of the sphere 3 mm in diameter. In that best signal, the maximum displacements of S1 and S2 are 0.8 mm and 1.2 mm, respectively. We name this stimulus "Virtual." Another stimulus is a contact with a real 3 mm-diameter sphere moving in the S2 pattern in **Fig. 5**. We name this "Real." In addition to these, we prepare one more similar stimulus "V2" for a reference, in which S1 does not move (displacement zero) while S2 follows the S2 pattern in **Fig. 5**. Using these signals, we test if the subject can discriminate between the synthesized feeling by S1 and S2 and the real spherical object.

Procedure

We give the subject two stimuli sequentially at a 4 second interval. The one stimulus is the "Real" arising twice at a 1 second interval. The other is one of three kinds of stimuli "Virtual," "Real," and "V2" that also arise twice at a 1 second interval. Then the subject replies either "yes" or "no" to the question "Is the second stimulation (after the 4 second interval) identical with the first one?" See **Fig. 6**. The choice of the stimulus combination and the order are random, and each subject answers fifteen times to a series of trials. The subjects were six males in their twenties with eye-masks and headphones.

Results

Fig. 7 shows the percentage that the subjects answered "identical" in response to the sequentially given 2 stimuli. "Real-Real" means the case the tester touched the identical sphere twice, and "Real-Virtual" means stimulus "Real" and "Virtual" were given sequentially.

Even for "Real-Real," the subjects sometimes felt they were not identical. The result shows the stimulus "Virtual" felt so similar to the "Real" that they missed the difference once in twice even if they concentrated on that.

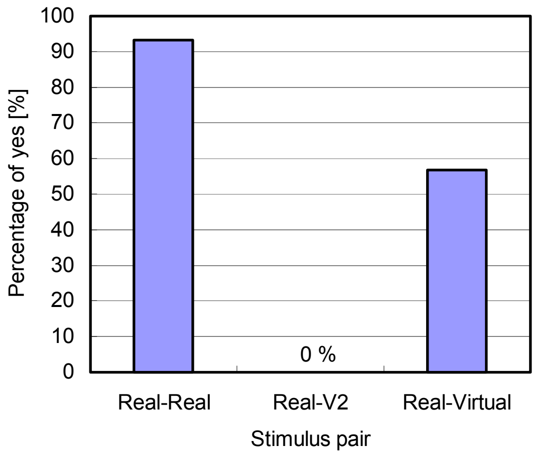

Fig. 7: Results of discrimination test. Percentage that the six subjects answered that the two stimuli given sequentially felt identical. The "Real-Virtual" means the case the stimulus "Real" and "Virtual" were given sequentially.

5. Experiment II

In this experiment we examine how the perceived curvature changes when we change the maximum displacement of S1 in **Fig. 5**.

Stimuli

Also in this experiment, the S2 is driven in the S2 pattern in **Fig. 5**. And the Subjects are given seven types of stimuli in which the S1 reaches the maximum displacement in seven manners. The times to reach the top and to start going down are common while the top displacements are (A) 1.2mm, (B) 1.1 mm, (C) 1.0 mm, (D) 0.9 mm, (E) 0.8 mm, (F) 0.7 mm, and (G) 0.6 mm, respectively. In stimulus (A) the subjects felt a smooth surface because the top displacements of S1 was equal to that of S2. In stimulus (G) they felt a sharp object because the projection of S2 was large.

The subjects answer the perceived curvature comparing with reference objects of metal sphere with diameters of 1, 3, and 5 mm, moving in the S2 pattern in **Fig. 5**.

Procedure

A subject receives one pattern of seven kinds of stimuli A, B, - - F, and G from the S1-S2 stimulator, and memorize the feeling especially paying attention to the curvature. Next, the subjects touch the three reference objects coming sequentially at constant intervals of 1 second, and they answer the comparison of the curvature between the S1-S2 stimulus and the reference objects. The answers are classified into the seven categories and give those categories points from 0 to 6 as shown in **Table 1**. For instance, if it felt as the same as the sphere with diameter of 3 mm, we give it 3 points. (Though feeling of the S1-S2 stimulator was not always identical with that of reference objects, comparison was possible.)

The experiment was done 3 times for each signal. During the experiment, the subjects wore headphones and eye-masks not to obtain any cues from the sound and sight. The subjects were five males in their twenties with eye-masks and headphones.

Table 1: Assigning points to the perceived curvature categories by S1-S2 stimulus.

Perceived diameter of sphere x [mm]	I $x < 1$	1	II $1 < x < 3$	3	III $3 < x < 5$	5	IV $x > 5$
Point	0	1	2	3	4	5	6

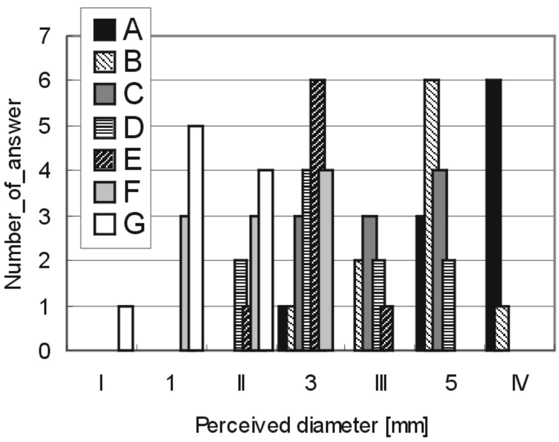

Fig. 8: Histogram of perceived curvature for various intensities of S1-S2. The maximum displacements of S1 were (A) 1.2, (B) 1.1, (C) 1.0, (D) 0.9, (E) 0.8, (F) 0.7 and (G) 0.6 mm, while S2 always moved in the S2 pattern in Fig. 5.

Results

Table 2 and **Fig. 8** show the perceived curvature versus stimulus A, B, - - F, and G. **Fig. 8** is a histogram of the perceived diameter classified following Table 1. The perceived curvature changed by the maximum displacement of S1. When maximum displacement of S1 decreased, subjects felt higher curvature. The average points for the stimulus A, B, - - F, and G are summarized in Table 2. And its graphical plots are shown in **Fig. 9**. For stimuli B - G, subjects felt finer object than the cylinder of S1 though the surface of S1 always touched the skin. The results showing continuous change of perceived curvature along the S2 projection change, is consistent with our hypothesis.

Table 2: Subjective curvature versus the maximum displacements of S1. The averaged points defined in Table 1 are shown.

Stimulus	A	B	C	D	E	F	G
Average point	5.4	4.7	4.1	3.4	3.0	2.1	1.3

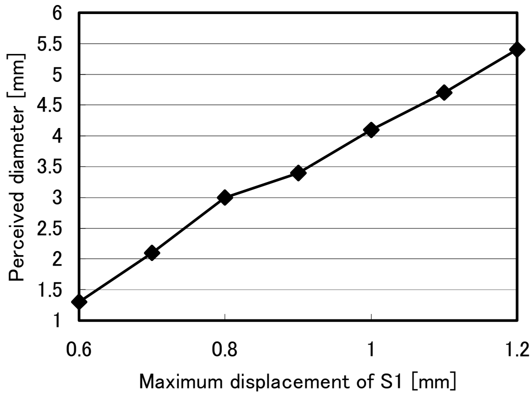

Fig. 9: Plots of Table 2. The perceived diameter is the average point in Table 2.

6. Summary and discussions

We proposed a hypothesis on realistic tactile display and its spatial resolution. It suggests that 4-D stimulators arrayed at intervals of TPDT/2 can produce any tactile feeling. The 4-D stimulator means a stimulator to the skin applying four bases of local stress distribution and their summation. And we showed the explicit forms of the four bases.

In experiments, we examined the hypothesis for a subspace Φ_n of tactile stimulation in which the stress has no lateral components. In this case the hypothesis tells us that the number of the bases to span all tactile feelings becomes two from four. Then one of the two bases is a local but smooth normal-stress distribution S1, and the other is a concentrated distribution S2.

In Experiment I, we examined whether the combination of the S1 and S2 can create tactile feeling of an intermediate curvature of an object. And we obtained a driving pattern of S1 and S2 in which the subjects felt once in twice that the stimulus was identical to that of an intermediate curvature of an object.

In Experiment II we confirmed the perceived curvature could be controlled continuously from a sharp tip to a smooth surface.

These results for the subspace Φ_n supported the hypothesis because the contact in general can be assumed as a combination of multiple contacts with various curvature surfaces.

However, we have to add a remark that it is not straightforward to display wide range of tactile feeling with a simple array of the cylinders and pins as is shown in **Fig. 3** because we easily feel the shapes of the cylinder and the pin by an active movement of the hand. In the experiments of this paper, the thenar was fixed and stimulated through a hole to obtain perfect passiveness.

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