Selective Stimulation to Superficial Mechanoreceptors by Temporal Control of Suction Pressure

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Abstract

In this paper we propose a new set of primitives to realize a large-area covering realistic tactile display. They stimulate the skin surface with suction pressure (SPS method) as our former paper proposed. The difference from the former device is that a single suction hole provides a pair of primitives. Since the identical hole provides the multiple primitives, we can expect Multi-Primitive Tactile Stimulation is realized more stably, and the physical structure is simpler than the former method. The method uses the frequency characteristics of the mechanoreceptor sensitivity and a feature of SPS that suction pressure through a hole does not reach the deep receptors, Pacinian corpuscles. We show the basic theory and results of fundamental experiments. In the experiments, we show the spatial feature of the virtual object (edged or round) can be controlled by the temporal profile of the primitives. We explain the reason of the phenomena based on a tactile perception model called Simple Bundle Model.

Keywords: Tactile Display, Haptic Interface, Virtual reality

1. Introduction

The objective of this study is to realize a whole-palm covering tactile display which can produce realistic touch sensations on the palm. The general difficulty for achieving such a tactile display is that a large number of stimulators are required to cover such a large area.

In order to avoid the expansion of the number of the stimulators, we proposed "Multi Primitive Tactile Stimulation (MPTS)" method in the previous study [1]. The idea of "primitive" was brought by an analogy of the visual display of RGB colors. Visual displays control the appearance of each pixel by combining only three fundamental colors varying the intensities. Similarly we inferred that a high-fidelity cutaneous display only needs a sparse array of stimulation units each of which produces several fundamental skin-deformation patterns like the primary colors. The interval of the units can be as large as the two-point discrimination threshold (TPDT) on the skin.

At the first step in determining optimal primitives, we focused on a perceived curvature since the human can easily discriminate the sharpness of an object even when the size of the contact area is smaller than TPDT. We succeeded in changing perceived curvatures within a TPDT area by combining two different pressure patterns produced by suction pressure stimulations [11][12]. Though the previous experiments partly supported the theory, the results was still lacked the reproducibility to fully convince the theory. The most serious problem of the former device was the alignment of the stimulators. In the former one, the multiple primitives were applied on the different points on the skin in a stimulation unit. Therefore the contact conditions between the skin and each stimulator sometimes lost evenness, which resulted in a lack of reproducibility. The intensity ratio among the stimulators in a unit should be precisely controlled in MPTS method. The intensity errors sensitively affected the perceived tactile feeling. The spatial unevenness of the receptor density of the human skin was also an undesired property for the former method.

In this paper, we propose a new set of primitives. They stimulate the skin surface with suction pressure as the former paper proposed. The difference from the former device is that a single suction hole provides a pair of primitives. Since the identical hole provides the multiple primitives, we can expect MPTS is realized more stably, and the physical structure is simpler than the former method.

In the new method, the suction pressure of each hole is driven by two independent mechanisms. One is an air pressure regulator working at a time constant of T. Tentatively we assume T is as long as 50 ms. The other one is an electromagnetic valve that induces high-frequency (~40 Hz) pressure alternation. The intensity of the latter one is also controlled at a time constant T. Each mechanism is intended to selectively stimulate SA-I receptors and RA-I receptors, respectively [2].

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We fabricated a basic apparatus to examine the new method. The details and implementation of the apparatus are described in section 2. Psychophysical experiments and their results are shown in section 3. The experimental results showed the feasibility of the new method as a whole-palm covering realistic tactile display.

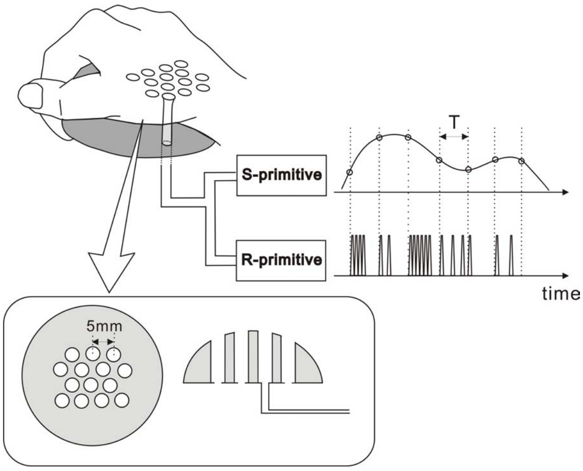

Figure 1 Schematic diagram of the new SPS method.

2. Preceding Studies

The study is based on our recent studies of "Suction Pressure Stimulation (SPS)." SPS uses an illusion that the human can not distinguish a compression by a pin-like object from a suction pressure stimulation through a hole. A possible explanation for this phenomenon is that the mechanoreceptors are sensitive to the strain energy while insensitive to the sign (positive/negative) of the stress.

Figure 2 shows the strain energy distribution under the skin surface [11]. Figure 2 (a) is the result for a suction pressure stimulation and Figure 2 (b) for a push by a real stick that gives a similar feeling as the suction stimulation produces. The 3-D distributions under the skin surface seem different between the two cases, however, when we focus on the mechanoreceptor level (shown by the red lines), the distributions are similar each other.

One advantage of using SPS instead of usual positive-pressure stimulation is that it causes small interferences between neighboring stimulation points since the skin surface is constrained on the device. Another advantage is that the skin deformation by SPS hardly reaches the deep part of the skin as shown in Figure 2. Therefore we can stimulate the superficial mechanoreceptors without stimulating deep receptors, Pacinian corpuscles.

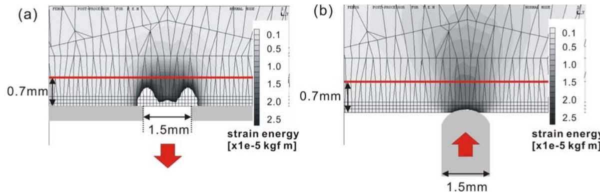

Figure 2. Distributions of strain energy by suction pressure (a) and positive pressure by a stick (b). The distributions at the skin surface are different from each other.

In the previous study of "Multi-Primitive Tactile Stimulation (MPTS)," we sought a pair of primitives as follows. One is a primitive that induces a sensation of a sharp edge and the other one is a primitive that induces a sensation of a smooth surface. As the first primitive, we used a small suction hole with a sharp edge, and we used a large round-edged hole as the second primitive. We could confirm that we feel a medium-curvature object by combining the two primitives. We also noticed, however, the perceived sharpness of the virtual object strongly depends on the temporal profile of the suction pressure. This hinted the new primitives proposed in this paper.

3. Whole Palm Tactile Display Using New Primitives

Figure 1 shows our new tactile display system. Multiple suction holes are located at 5 mm intervals. We display tactile feeling by controlling the air suction pressure of each suction hole.

The air pressure of each hole is controlled independently by two mechanisms. One is an air pressure regulator working at a time constant of T~50 ms. The other one is an electromagnetic valve that induces high-frequency (~40 Hz) pressure alternation. The amplitude of the vibration is also controlled at a time constant T.

The first mechanism is intended to selectively stimulate SA-I receptors, we call this "S-primitive." The second primitive is intended to selectively stimulate RA-I receptors using a property that a RA-I receptor has a high sensitivity to approximately 40 Hz vibrations. We call this "R-primitive."

R-primitive hardly stimulates the deep receptors from the deformation transmission characteristics by SPS. Therefore we hardly felt macroscopic vibration by R-primitive in our experiments.

Determining the required time-constant T is the topic of the future work. The T determines the information quantity that the hand can obtain. We imagine that the T is as large as 50~100 ms for covering most of the tactile feeling.

In this paper we conducted a basic experiment to examine the tactile-feeling space spanned by the two primitives.

4. Basic Experiments

4.1. Purpose

To evaluate the tactile-feeling space, we planed the following experiment. The purpose of the experiment is to confirm what feeling we get from the S-primitive, R-primitive and combination of them. We examine this using a single hole.

4.2. Experimental Settings

Figure 3 shows the block diagram of experimental settings. The valve can switch the connection of the suction hole. "On" state is that the hole is connected to the bottle. "Off" means the suction hole is opened to the atmosphere and the connection to the hole is closed. Using these apparatus, we prepared three stimuli.

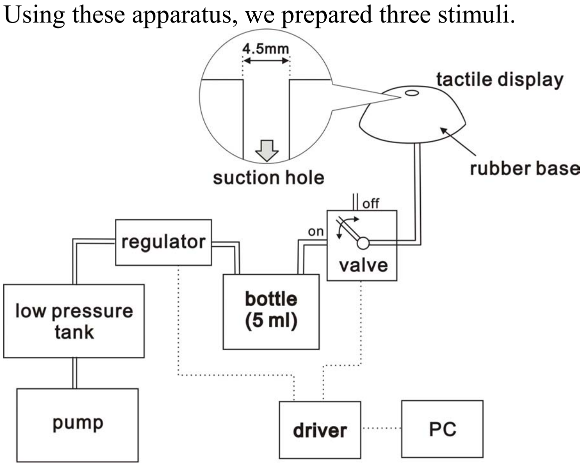

Figure 3 Block diagram of the experimental settings.

Stimulus (1) --- S-primitive

Only the regulator is driven. The valve is always "on". The air pressure changed with a large time constant. The bottle is used to eliminate vibratory components of the regulator for attenuating the activation of RA-I receptors.

Stimulus (2) --- S-Primitive + R-Primitive

The regulator lowers the air pressure. At the same time, the valve is switched twice at 40 Hz. Then the valve is constantly "on" and the hole pressure is lowered with a large time constant.

Stimulus (3) --- R-primitive

In the beginning, the valve is "off", and then the regulator is activated for lowering the pressure of the bottle. After that the valve is switched twice at 40 Hz and returned to "off."

Figure 4 shows the observed pressure patterns at the skin surface. The maximum pressure of the stimuli was determined beforehand so that subjects felt no painful sensations. The threshold of the pain was investigated in a pilot experiment. The threshold of the pain was about 2 times larger than the final pressure of S-primitive. The suction hole had its edge as shown in Figure 3 and its diameter was about 4.5 mm which was smaller than TPDT.

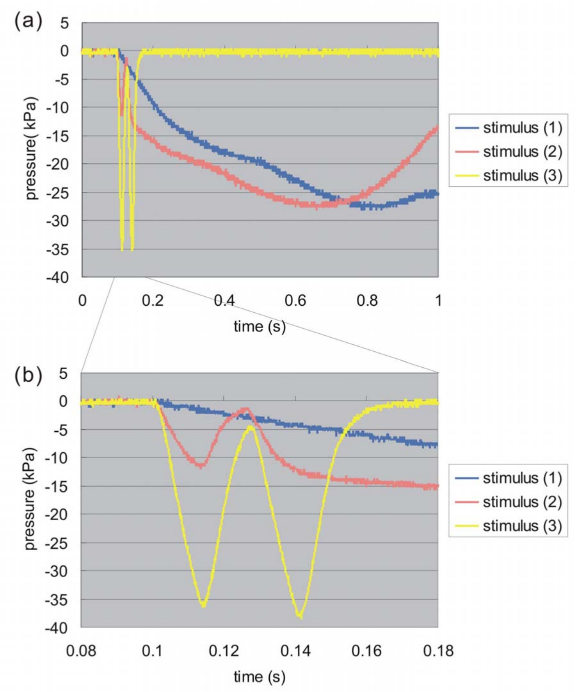

Figure 4 Three pressure patterns used in the experiment. (a) shows the overall profiles of the stimuli. (b) is zoomed graphics at the rising edge for 0.1s. The stimulus (1) is S-primitive and the stimulus (3) is R-primitive. The combinations of two primitives are shown as the stimulus (2).

4.3. Procedures

The experiments were conducted as follows.

1) The subjects sat on a chair in a comfortable posture. They were compelled to listen to white noise to eliminate auditory cues.
2) Each subject was required to put the left palm on the tactile display with elbow rest.
3) One of the stimuli was given to the left palm in random order.
4) Subjects were allowed to feel the stimulus as many times as they wanted.
5) The subjects were asked to compare the virtual stimulus with references of real objects using right hand and to choose the most similar one among them.
6) Thee stimuli were given five times each to one subject in total.

We prepared seven reference objects (described in Figure 5). The reference No. l, 2, and 3 were hemispherical objects. Their curvature radii were 2.5mm, 2.0 mm and 1.5mm, respectively. Reference No. 6 and 7 were cylindrical objects. We prepared truncated cone-like reference as No. 4 and 5 because the subjects in the pilot experiment reported that they perceived the shape of such objects for stimulus (2). These references were chosen intentionally so that the subjects could find a similar reference to the virtual stimuli. These references were made by cutting the top of the hemisphere. The radii of the hemisphere were 1.5 mm and 2.0mm. And the radii of the cross-sectional surface were about 1.0mm and 1.5 mm. The difference of the reference No. 5 from No. 2, No. 6 or No.7 was clearly discriminable from the evidence of the edge though it might seem very similar. The subjects were 6 males and l female who knew nothing about the purpose of the experiment.

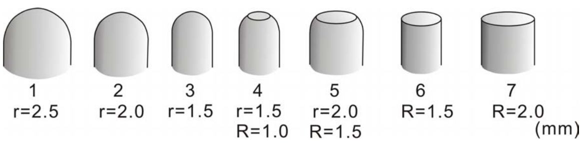

Figure 5 Seven references used in the experiment. Reference No. 1,2,3: hemispherical objects. No. 4, 5: truncated cone-like reference. No. 6, 7: cylindrical objects. In the picture, "r" indicates the curvature radius and "R" represents the radius of the top circle.

5. Results

Figure 6 shows the results of the virtual stimuli by SPS compared to the actual reference objects. The horizontal axis indicates the reference number given in the Figure 5. The vertical axis indicates the number of the answers. The blue bars show the histogram of the answers when we gave the S-Primitive only (stimulus (1)). It is obvious that the stimulus (1) was evaluated as a hemispherical object. On the other hand, the stimulus (3) (R-Primitive only) was evaluated as cylindrical objects which is shown with yellow bars. Evaluated sizes were comparable to the size of the hole (4.5mm) in both cases. When we activated two primitives simultaneously, the stimulus (2) was mostly perceived as a truncated cone-like object (No. 5). The answers from the subjects indicated that reference No. 5 was felt like flat surface with edge-like sensation though the edge was felt duller than the actual cylindrical references.

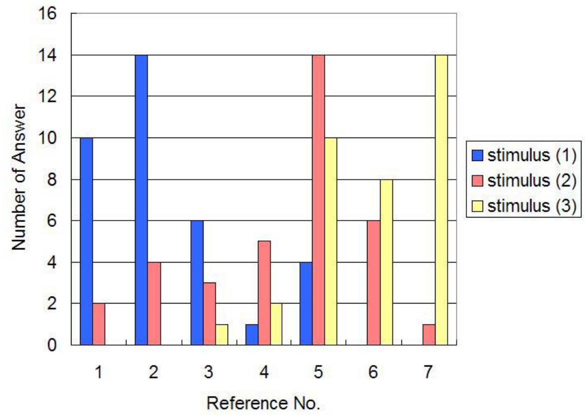

Figure 6 Results of the comparison between SPS and actual reference objects.

6. Discussions

In the pervious section, we confirmed that combination of S-primitive and R-primitive with different temporal profiles of suction pressure could produce a tactile feeling of both a surface with edge and a round smooth surface.

In this section, we try to answer the question why the perceived objects were changed in such a manner as shown in Figure 5. And we discuss if the two primitives are sufficient to cover the tactile-feeling space.

First we introduce a tentative model named "simple bundle model (SB model) [13]." In section 6.2, we discuss the generally accepted properties of the mechanoreceptors. Based on the discussion in 6.1 and 6.2, we try to give a reasonable explanation for our experimental results.

6.1. Simple Bundle Model

To straighten up the discussions, we introduce a tentative model named "simple bundle model (SB model)." The model represents how the nerves are connected and what kind of processing is carried out among the cutaneous receptors to extract information from the skin surface. In the model, we assume the following not-obvious matters. (Schematic illustration is shown in Figure 7.)

I. The two kinds of superficial mechanoreceptors are bundled independently into fibers connected to the brain.
II. 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.
III. The spread of receptors bundled into a single fiber is comparable to the two point discrimination threshold.

While Hypothesis I seems to have been already accepted by many researchers, Hypothesis II might confuse the readers. Of course the mechanoreceptors 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 mechanoreceptors, even under the hypothesis. Hypothesis II means there is only one way of calculation for outputting 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. On a palm TPDT is as large as about 10 mm though we can easily distinguish the sharpness of an 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 for the ability consistent with the Hypothesis III 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 proposition that the S-primitive and R-primitive can display from an edged surface to a round smooth surface seems equivalent to the proposition that SB model is true. If SB model is true, the experimental results are naturally understood.

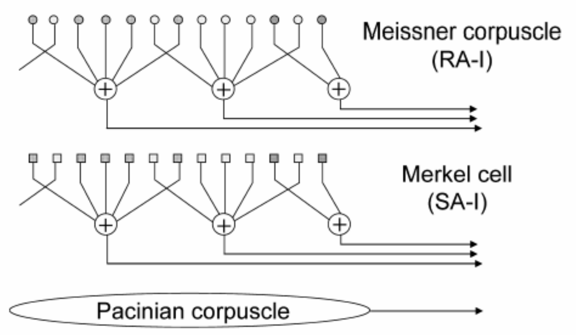

Figure 7. A tentative tactile perception model (SB model) to start the discussion. Each non-operational nerve bundle (Simple Bundle) in the population of superficial mechanoreceptors (Meissner corpuscle and Merkel cell) samples 1 degree-of-freedom signal at a rate comparable to the visual frame rate. (Here we supposed the sampling interval is "*T*.")

6.2. Discrimination between spatial feature and temporal feature

The next natural question is why the subjects perceived the spatial difference (edged or round) by the difference of the temporal profiles.

The recent researches have come to uncover what physical parameters the mechanoreceptors detect. Maeno et al. discussed the role of the skin structure using 2D FEM analysis [6]. 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 [4]. 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) [5]. Their logics are compelling though we have to wait more scientific experiments to be fully convinced.

Figure 8 shows FEM results related to this matter. We calculated the sum of the strain energy and the shear strain energy at the superficial receptor level. "Shear strain energy" means the strain energy calculated only by the shearing components. We plotted the calculated values for various contact objects in a 2D space spanned by the two parameters, strain energy and shear strain energy. Seven radiuses of uniform circular pressure distribution from 0.75 mm to 2.25 mm were chosen. The both axes are logarithmic.

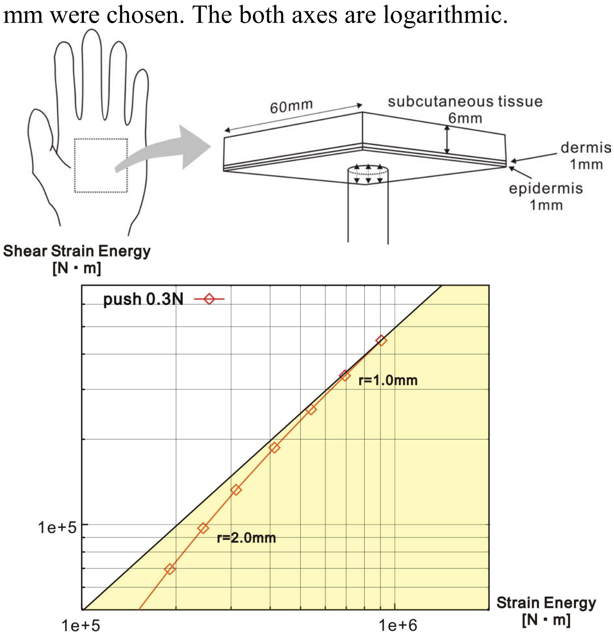

Figure 8. FEM results of strain energy at the superficial receptor level. We calculated the sum of the strain energy and the shear strain energy (strain energy calculated only by the shearing components) for various diameters of uniform circular pressure distributions. The results are plotted in a logarithmic 2D space spanned by the two parameters.

The results show that the ratio of shear strain energy sum to strain energy sum reflects the diameter of the object. If RA-I receptors are selectively sensitive to the shearing deformation as the previous studies suggested, RA-I fires selectively for a sharp object. This means that it is possible to estimate the sharpness of the object from the firing ratio between RA-I and SA-I. Therefore it is natural that the perceived sharpness should depend on the ratio of R-primitive and S-primitive in the experiments.

The final question is how the human skin discriminates between a "slowly touching sharp object" and a "quickly touching round object." At present we imagine that the discrimination is carried out by the signals from the Pacinian corpuscles. When RA-I actively fires with Pacinian not being activated, theoretically the brain can sense that the object was "slowly touching sharp object."

In our experiments, R-primitive using SPS hardly activate the Pacinian. Then it is natural that we feel an object with edge at a proper intensity of R-primitive compared with S-primitive.

If the R-primitive is too strong compared to S-primitive, the plot is put on the white area in Figure 8. In that case, we feel a textured surface and perceived contact area becomes larger.

7. Summary

In this paper we proposed a new set of primitives to realize a large-area realistic tactile display. They stimulate the skin surface with suction pressure (SPS method) as the former paper proposed. The difference from the former device is that a single suction hole provides a pair of primitives. Since the identical hole provides the multiple primitives, we can expect Multi-Primitive Tactile Stimulation is realized more stably, and the physical structure is simpler than the former method. The method uses the frequency characteristics of the mechanoreceptor sensitivity and a feature of SPS that suction pressure through a hole does not reach the deep receptors, Pacinian corpuscles. We showed the basic theory and results of fundamental experiments. In the experiments, we showed the spatial feature of the virtual object (edged or round) could be controlled by the temporal profile of the primitives. We explained the reason of the phenomena based on a tactile perception model, called Simple Bundle Model.

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