Psychophysical evaluation of receptor selectivity in electro-tactile display

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Abstract

We have been developing an electro-tactile display to present realistic tactile sensation for Virtual Reality and robot teleoperation. This paper shows quantitative evidence that Meissner corpuscles are selectively activated in our specific setup of electrical stimulation, dubbed "Meissner mode." We also show the fundamental limitation of electro-tactile displays, which is caused by the physical incapacity to selectively stimulate Pacinian corpuscles, which reside in the deeper tissue, because shallower parts are inevitably co-activated.

Keywords: *Virtual Reality, tactile display, electrical stimulation, Meissner corpuscle, Pacinian corpuscle*

1 Introduction

1.1 Electro-tactile display and selective stimulation

The electro-tactile display is a type of tactile display that uses an electric current as a stimulus. We have been working on the electro-tactile display to present realistic skin sensation for Virtual Reality and robot teleoperation[1][2].

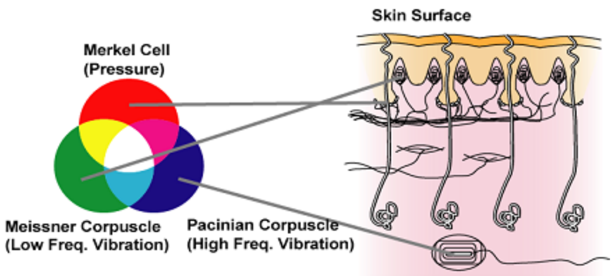

Figure 1 Primary color approach. If each type of receptor is selectively stimulated separately, the stimuli could be treated as "primary colors," and combining these stimuli could produce any tactile sensation.

Our approach is as follows. There are four types of mechanical receptors in human skin, which convert skin deformation into nerve activities: Meissner corpuscles, Merkel cells, Pacinian corpuscles and Ruffini endings. If we selectively stimulate each of these receptors separately, we could treat the stimuli as "primary colors," analogous to the three primary colors in vision, and produce any tactile sensation by combining them (Figure 1).

1.2 Meissner and Pacinian corpuscle

This paper deals with two types of receptors, Meissner and Pacinian corpuscles. As both of them respond to mechanical vibration, we believe that selective stimulation of these receptors is indispensable to present tactile texture.

Meissner corpuscles are located in the shallow part of the skin (less than 1[mm]), and reacts to low frequency vibration (20-70[Hz]), with a resonant frequency of about 30[Hz]. Pacinian corpuscles are located in the deeper part of the skin (about 2[mm]), and reacts to high frequency vibration (100-300[Hz]), with a resonant frequency of about 250[Hz] (Figure 2).

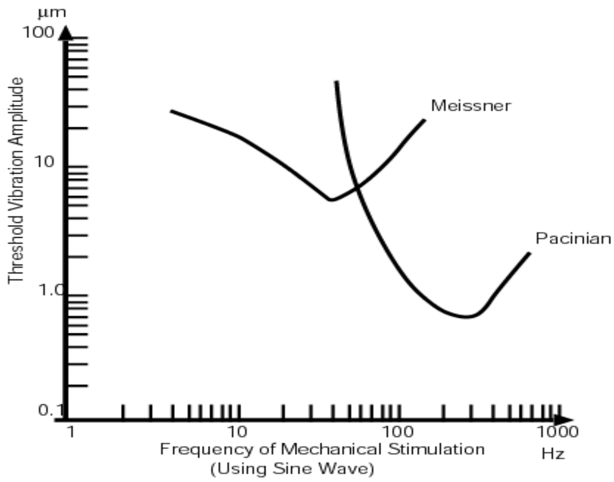

Figure 2 Activation threshold of the Meissner and Pacinian corpuscles when mechanical stimulation (sine wave) is applied on the skin surface[3].

We used electrical stimulation to generate tactile sensation. An electric current pulse from surface electrodes generates an electric field inside the skin, which induces nerve activity. Compared to conventional mechanical tactile displays, the electro-tactile display can be manufactured very thin, durable and free from mechanical resonance.

In our previous work, we showed theoretically and experimentally that selective stimulation of these two receptors is possible by changing the current polarity and electrode size [1].

We used normal concentric electrodes comprised of an inner stimulating electrode and an outer surrounding electrode. If the inner diameter of the outer electrode is sufficiently small, an electric current from the inner electrode to the outer electrode only passes through the shallow part of the skin, which activates shallow receptors.

In particular, Meissner corpuscles are more easily activated by anodic stimulation (inner electrode works as anode and outer electrode works as ground) than cathodic stimulation (Figure 3). We call this setup "Meissner mode".

On the contrary, if the inner diameter of the outer electrode is large, the electric current reaches deeper tissue, which also activates deeper receptors such as Pacinian corpuscles. We call this setup "Pacinian mode."

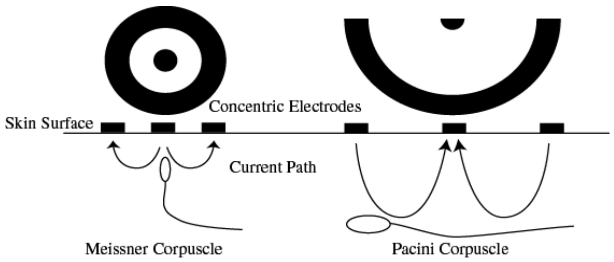

Figure 3 Selective stimulation with an electric current pulse. (Left) Meissner mode. Positive pulse is applied from the central part of small concentric electrodes. (Right) Pacinian mode. Negative pulse from central electrode reaches to deeper tissue.

The perceived sensation (vibratory sensation) for each mode has been qualitatively explained in previous works by the role of each type of receptors[1]. However, this paper is the first quantitative validation of the selective stimulation of the Meissner and Pacinian corpuscles in electro-tactile display, verified by psychophysical experiment.

2 Experiment

2.1 System configuration

We constructed a mechanical and electrical stimulator as shown in Figure 4. An electrode (stainless steel, 1.0[mm] in diameter) is mounted on a voice coil, which stimulates the finger skin both electrically and mechanically. Electrode motion is measured by a photo reflector.

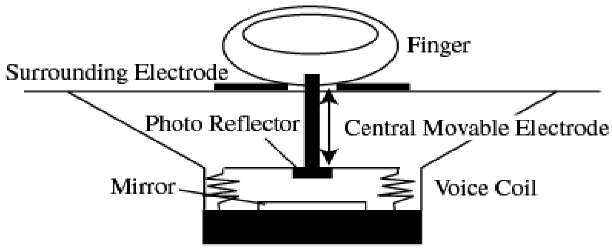

Figure 4 Mechanical and electrical stimulator. An inner electrode is mounted on a voice coil. Mechanical vibration is observed by the photo-reflector, which is attached on the coil.

2.2 Frequency discrimination with mechanical sine wave

First, we measured the frequency discrimination threshold of mechanical sine wave vibration with the method of limits. Four participants, three males and one female between 25 and 35 years old, were asked to place their finger on the electrode.

Standard and comparison stimuli with a vibration amplitude of 0.1[mm] were presented for 1.0[s], and the participants were asked which stimulus frequency was higher (Figure 5). The standard frequencies were 15, 30, 60 and 120[Hz]. The comparison frequency started from either 0.5× or 2.0× the standard frequency, and gradually approached to the standard frequency as long as the participant answered correctly.

The first comparison frequency in which the participant answered incorrectly was considered the frequency discrimination threshold.

A typical result is shown in Figure 6. The horizontal axis is the standard frequency, and the vertical axis is the ratio of discrimination threshold frequency to standard frequency. We see from the figure that for all frequencies, upper and lower discrimination thresholds are within 0.8 to 1.2, which means that the participant could discriminate a frequency difference of about 20%.

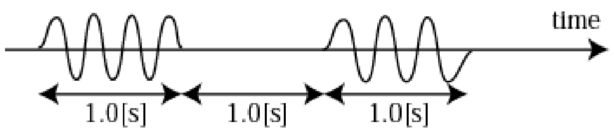

Figure 5 Standard and comparison mechanical sine wave with amplitude of 0.1[mm] was applied on a finger-pad for 1.0[s], and participants were asked which stimulus was higher in frequency.

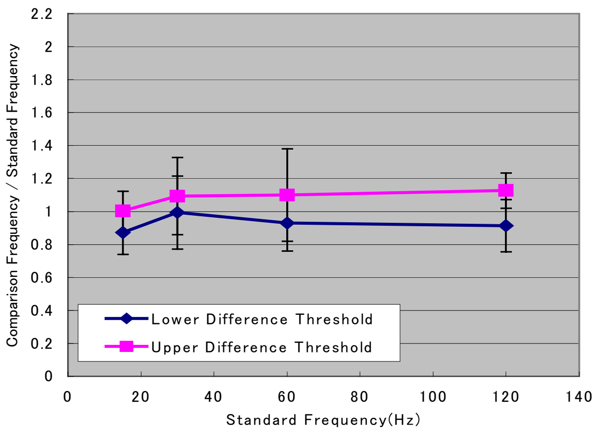

Figure 6 Upper and lower difference thresholds of mechanical vibratory stimulation (sine wave), obtained by the method of limits. The horizontal axis is the standard frequency, and the vertical axis is the ratio of discrimination threshold frequency to standard frequency.

2.3 Frequency discrimination in Meissner mode

The same test was conducted for electrical stimulation. We used the Meissner mode (Figure 7).

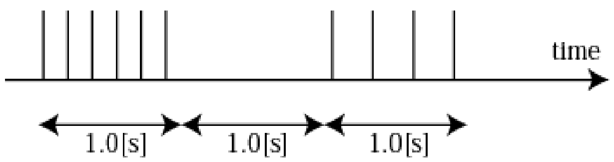

Figure 7 Standard and comparison electrical stimuli were presented for 1.0[s]. Pulse amplitude was 2.4[mA] and pulse width was 0.2[ms].

Previous work showed that in mechanical vibration, nerves that are connected to the receptors are electrically activated at the same frequency as the vibration[4]. Therefore, conversely, we supposed that if electrical pulses are applied, participants should perceive the pulse train as mechanical vibration with the same frequency, which should result in the same frequency discrimination threshold.

The experiment set-up was as follows: the central electrode was 1.0[mm] in diameter, the inner diameter of the outer electrode was 6.0[mm] and the stimulation was anodic pulses (Meissner mode) at frequencies of 15, 30, 45, 60 and 120[Hz]. The pulse amplitude was 2.4[mA] and pulse width was 0.2[ms]. The result is shown in Figure 8.

At 15[Hz] and 30[Hz], the results are quite the same as the mechanical vibration. However, at 45[Hz], the upper threshold suddenly reached to about 2, which means that the participants could not interpret 90[Hz] stimulation to be higher than 45[Hz].

This puzzling result is explained by assuming that Meissner corpuscles are selectively stimulated. In mechanical stimulation, 15[Hz] and 30[Hz] are the frequencies where only Meissner, not Pacinian corpuscles are activated (Figure 2). Therefore, there is no difference between mechanical and electrical stimulation from the receptor's viewpoint. However, from 70[Hz] or more, Pacinian corpuscles are also activated in mechanical stimulation. At that frequency, it is quite natural to conclude that we discern frequency by observing the activity ratio of both the Meissner and Pacinian corpuscles.

This reveals the contrast between electrical and mechanical stimulation. In electrical stimulation mode, as we mentioned before, only Meissner corpuscles are activated even at high frequency. This situation should never happen in mechanical stimulation. Hence, the participants could not discern the frequency of the stimulation.

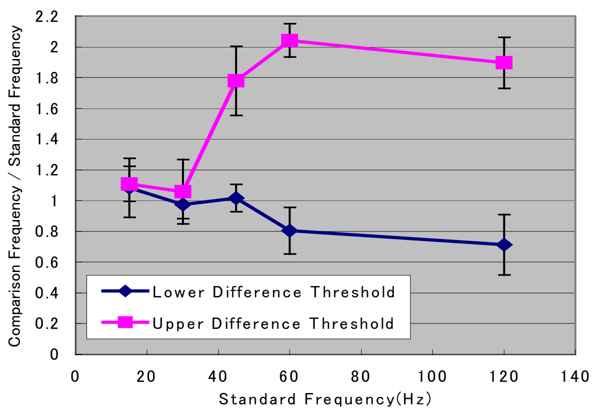

Figure 8 Upper and lower difference thresholds of electrical stimulation. Positive pulse with 2.4[mA] amplitude, 0.2[ms] width was applied on the finger-pad through the concentric electrode with 1.0[mm] and 6.0[mm] inner and outer diameter.

2.4 Verification of the hypothesis by deep tissue stimulation

If the above-mentioned rationale is true, the frequency discrimination threshold should decrease if we also stimulate Pacinian corpuscles. This is achieved in Pacinian mode, which was performed by using the inner electrode with 3.0[mm] in diameter and outer electrode with 10.0[mm] in inner diameter. We stimulated using cathodic current pulses. The result is shown in Figure 9. The discrimination threshold approached to 1 at a higher frequency, which supported our hypothesis.

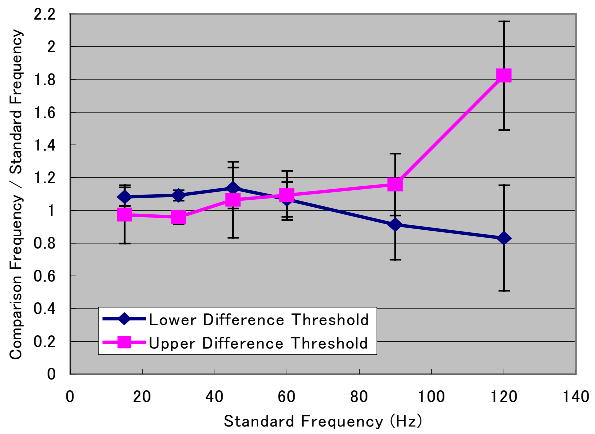

Figure 9 Upper and lower difference thresholds of deeper part electrical stimulation. Negative pulse with 2.4[mA] amplitude, 0.2[ms] width was applied on the finger-pad by the large concentric electrode with 3.0[mm] and 10.0[mm] inner and outer diameter.

However, at 120[Hz], the upper threshold reached about 2, which means the participant could not interpret 240[Hz] pulses to be higher than 120[Hz] pulses.

This result is also explained by comparing mechanical and electrical stimulation. In mechanical stimulation, only Pacinian corpuscles are activated at 200[Hz] or more (Figure 2). However, in electrical stimulation, Meissner corpuscles are also activated in Pacinian mode. Therefore, our brain mistakes the vibration frequency as being within the Pacinian-Meissner co-activation range, which is lower than 200[Hz] (Figure 2), resulting in a misinterpretation of the stimulation frequency.

3 Conclusions

In this paper, we showed quantitative evidence that Meissner corpuscles are selectively activated in our specific setup of electrical stimulation, dubbed "Meissner mode."

We also showed the fundamental limitation of electro-tactile displays, which is caused by the fact that we could not selectively stimulate Pacinian corpuscles, which reside in the deeper tissue, because the shallow part is inevitably co-activated. This limitation was observed as the limitation of frequency perception, in which pulses with more than 200[Hz] were not interpreted correctly. This limitation was already reported in the 1970's[5], although there has never been an explanation based on receptor activity.

To overcome this limitation, we are considering a hybrid method of applying mechanical and electrical stimulation simultaneously. Mechanical stimulation aims to selectively stimulate Pacinian corpuscles, while electrical stimulation targets Meissner corpuscles. Selective stimulation of Pacinian corpuscles with a mechanical vibrator is not so difficult, because Pacinian corpuscles has the highest resonant frequency (about 250[Hz]) of all receptors. At the same time, the density of Pacinian corpuscles in the skin is relatively low. Therefore, the only requirement for Pacinian selective stimulation is to fabricate a sparse mechanical vibrator matrix and vibrate at high frequency. On the contrary, the Meissner corpuscle is densely populated (1[mm^{-2}]), and the fabrication of an appropriately dense display with electrodes is far more practical than using mechanical stimulators.

4 Acknowledgments

This work was supported by the Japan Society for the Promotion of Science, Grant-in-Aid for Scientific Research (A) 15200007.

5 References

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