Proposal for tactile sense presentation that combines electrical and mechanical stimulus

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Abstract

This study proposes a combination of electrical and mechanical stimulation as a foundational method to realize a tactile display with a high temporal and spatial resolution. We further confirm the interaction between the electrical and mechanical stimulations. The interaction (1) lowers tactile threshold and (2) reduces the so-called "electrical" sensation. The results of this study may resolve certain practical difficulties with regard to electro-tactile displays.

1. Introduction

Several studies have reported on tactile displays that use mechanical stimulation. These studies proposed the replication of (1) the surface property of the object or (2) skin deformation. More specifically, there are two strategies with respect to the abovementioned proposals—using vibration or exerting pressure. Many of the former-approach-based tactile displays employ the vertical vibration of a pin array to change the physical amplitude and oscillating frequency on the surface of the skin [1, 2].

Spatial and temporal frequencies are very important parameters with regard to tactile displays. Certain mechanical devices realize a high spatial resolution by employing special types of actuators such as the shape-memory-alloy (SMA) actuator; however, their response times are typically relatively low. Others used a piezoelectric device as the actuator to solve the response time problem. As the actuator must be small enough, many of these devices generate a large amplitude through using mechanical resonance, which leads to a band-limited temporal frequency.

On the other hand, certain studies proposed the use of electrical current as stimulus in order to directly stimulate the sensory nerves [3, 4, 7]. One apparent advantage of the electro-tactile displays is that they can achieve a high resolution both temporally and spatially; however, this is not true. Since the electrical stimulation cannot easily stimulate the receptors that reside deep beneath the skin, it cannot stimulate the Pacinian corpuscles (PC) that lie in deeper regions. As a result, the high temporal frequency, which is normally handled by the PC, cannot be easily replicated by electrical stimulation [10]. In addition, the regulation of current amplitude is also difficult. Therefore, the so-called "electric" sensation during stimulation hinders its practical usage.

We think that tactile displays should give rich information with a simple structure. Based on this motivation, despite the apparent disadvantage, we believe that by employing an electric stimulus we can realize a practical tactile display. In this paper, we propose an electrovibration display that uses electrical and mechanical stimulations simultaneously. This concept of using two complementary techniques helps maintain the advantage of using an electric stimulus efficiently.

2. Reasonable combination

By combining electrical and mechanical stimulations, we anticipate two advantages as follows:

Optimal role allocation

One possible advantage is that the two types of stimulations can stimulate different types of receptors; this may lead to the realization of an optimal tactile display design.

There exist different types of mechanical receptors in the human skin—Merkel cells (SA1), Meissner corpuscles (RA), and PC. Each of these provides a different spatiotemporal responses; the human tactile sensation is a combination of the activities of these receptors (Fig. 1) [8, 9]. From Fig. 1, we can see that the human skin is incapable of sensing both the temporally and spatially high frequency regions.

As discussed previously, creating tactile displays that support all spatiotemporal spaces using a single type of actuator is quite difficult. However, humans can perceive only a limited range of spatiotemporal

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spaces; we can therefore optimize the tactile display design by combining electrical and mechanical stimulations.

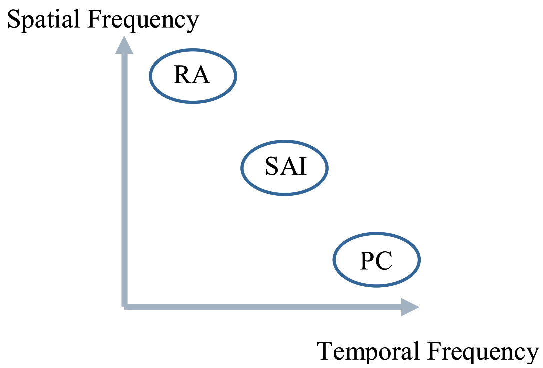

Fig. 1: Schematic illustration of the spatiotemporal roles of the mechanoreceptors (RA: Meissner corpuscle, SAI: Merkel cell, and PC: Pacinian corpuscle).

The electro-tactile display should be able to control the "temporally low but spatially high frequency" regions, while the mechanical display can control the "temporally high but spatially low frequency" regions.

Decrease in the threshold value

Another possible advantage of simultaneous electrical and mechanical stimulation is the local interaction between these two types of stimuli. A previous study on vibrotactile threshold introduced the concept of FSR (functional stochastic resonance) that uses a combination of electrical and mechanical stimulations [6]. It was discussed that the vibrotactile threshold can be decreased by adding an electrical "noise" stimulus of a suitable intensity. Therefore, conversely, the electrical current threshold of electrical stimulation should reduce due to mechanical stimulation

Considering these two possible advantages, an "optimal" electrical and mechanical tactile display should comprise (1) dense electrodes and (2) sparse actuators. A dense display can be easily realized by employing electrical stimulation. The sparse actuator works both as a high-frequency stimulator and threshold reducer for the electrical stimulation.

Scope of this paper

As mentioned above, there are two possible merits of the combination of electrical and mechanical stimulation. This paper mainly focuses on the latter of these two merits. The known signal was used in order to obtain a more efficient result instead of a noise. We conducted comprehensive measurements of the electro-tactile threshold under the application of both types of stimuli.

From the viewpoint of these two stimulation methods, we need to consider three parameters—amplitude, frequency, and waveform. The influence of amplitude must differ greatly in each subject. About frequency and waveform of electric stimulus, optimization has already been performed by previous work. Since we used a combination of the two stimuli, a new parameter—"phase"—that arises between the electrical and mechanical stimuli was introduced. Therefore, we verified the influences of the following three parameters: phase, waveform of mechanical stimulus, and frequency of mechanical stimulus.

3. Experiments

3.1. Experiment with synchronized stimuli

In this subsection, it is necessary to generate a mechanical stimulus waveform whose phase differs from that of the electrical stimulus waveform.

There are numerous mechanoreceptors scattered in our fingers. The receptors in a particular region activate when the skin deformation in that region reaches a certain value. When a sinusoidal mechanical stimulation is applied to the skin surface, the mechanoreceptors activate with spatially different timings because each point reaches the threshold differently (Fig. 2).

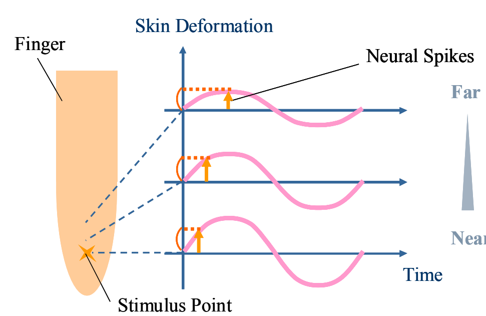

Fig. 2: The delay of nerve activity caused by the distance from the point of impression of the sinusoidal mechanical stimulus.

On the other hand, when an electrical stimulus is applied, all the receptors that receive a sufficient current fire together. Therefore, we used an impulse wave for the mechanical stimulation so that the nerves are activated at the same moment, even the numerous tactile receptors spread spatially. This mechanical stimulation was a kind of imitation of the electrical stimulation. Using this technique, we can observe the interaction of two types of stimulation.

We generated two sequences with phase differences of 0 and 180 degree (Fig. 3).

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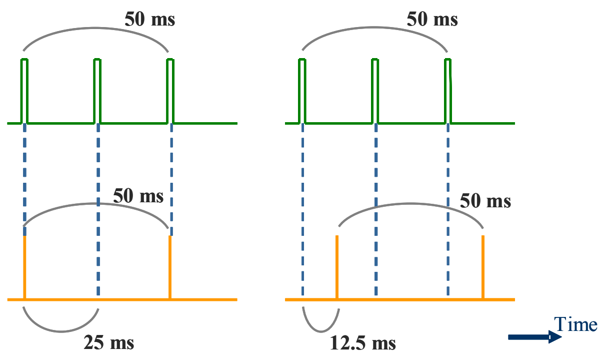

Fig. 3: Mechanical and electrical stimulation (left) with no phase difference, and (right) with 180degree phase difference.

3.1.1. Apparatus. We constructed an experimental system, as shown in Fig. 4. A stainless steel pin of diameter 1mm was placed in the center of an aluminum board with a hole of diameter 6 mm. The pin was vertically driven by a linear actuator through the hole in the board. The actuator can output 800N. During electrical stimulation we used anodic stimulation where the pin and the aluminum board served as anode and ground, respectively. The subjects placed their right-hand index fingers on the pin.

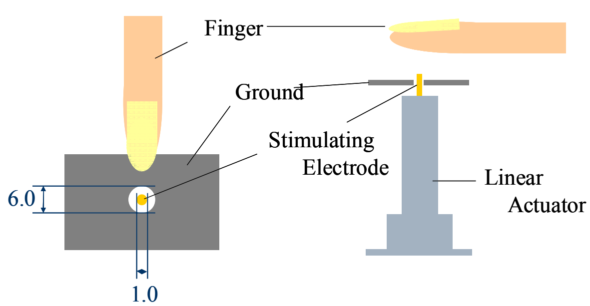

Fig. 4: System configuration: top (left) and side (right) views.

3.1.2. Experiment procedure. The mechanical stimulus was the pulse wave of 40 pps (pulses per sec), while the electrical stimulation was set to 20 pps. In one set of the experiment, the mechanical pulse height was set to certain value. We ask the subjects to adjust the amplitude of electrical pulse so that they can sense 20Hz vibration (method of adjustment).

As the subjects can easily distinguish between 40Hz and 20Hz, cognizing 20Hz means that the elicited sensation was not solely derived from mechanical stimulation, but also from electrical stimulation. The pulse frequencies were chosen because these frequencies are the frequency range of the RA, which resides in the shallow part of the skin and perceives vibration. This is because RA are expected to fire preferentially by anodic stimulation.

The mechanical pulse height was 0 through 10 µm. For each pulse height, five sets of experiments were conducted. The subject group comprised four people between the age group of 23–31 years.

3.1.3. Results. Fig. 5 shows the rate of decrease in the electrical threshold of one subject. The horizontal axis and vertical axes represent the amplitude of the mechanical stimulus and the rate of an electric current threshold value on the basis of the time of not adding mechanical stimulus that the subject perceived 20Hz vibration.

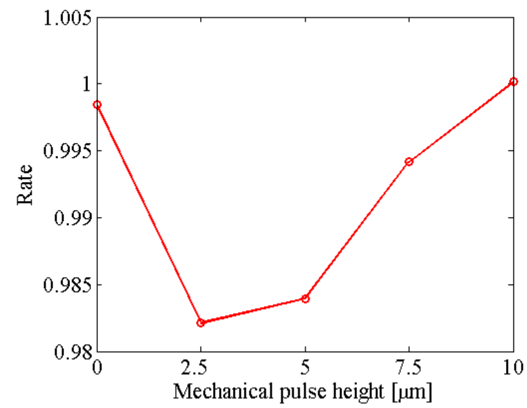

Fig. 5: Threshold of the electrical stimulation

The graph shows typical V-shape. Here, two points warrant discussion: First, the threshold decreased with the addition of a mechanical stimulus with an adequate amplitude. Second, the threshold increased on adding a stronger mechanical stimulus. The reslt shows that at least a certain interaction exists between electrical and mechanical stimuli.

3.2. Experiment with de-synchronized stimuli

To see if the time delay between mechanical and electrical stimulation affects the threshold, we conducted the following experiment. In this experiment, we used a sequence with a time delay between electrical and mechanical stimulations. The delay was fixed to 12.5ms (i.e. 180 degree phase difference for 40Hz stimulation)

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3.2.1. Results. Fig. 6 shows results of one subject, comparing with the previous experiment. The data obtained from the second experiment exhibited the same trends as those obtained from the previous one. No significant difference was observed between the delayed (green line) and no-delayed (red line) sequence results.

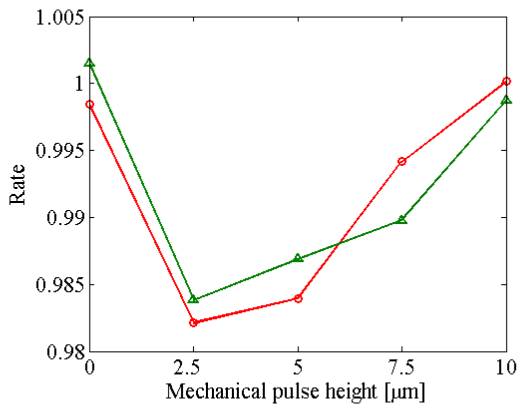

Fig. 6: Threshold values of the electrical stimulation: delayed (green line) and no-delay (red line) sequences.

3.3. Experiment with sinusoidal wave

Previous experiments with a pin electrode indicated that the timing of the nerve firing does not induce significant problem. Based on this result, we decided to use a sine wave as the mechanical stimulus. Our future goal is to combine "a simple vibrator which stimulates large area" and "a high density matrix electrode" (Fig. 7). This is considered to be a solution toward realizing an optimal system. Furthermore, this improvement facilitates the easy development of the device.

3.3.1. Apparatus. The electrodes were arranged at intervals of 2.5 mm each in a 3 × 5 matrix. This electrode plate was mounted on and driven by a linear actuator. In the following experiment, one electrode of the array was used, and the actuator used was the same as that used in the pre-experiment. The mechanical pulse height was changed to 0 through 70 μm because recognition of sine wave vibration is difficult compared with impulse wave.

Since the threshold value was dramatically changed if the subject's finger moved, we fixed the subject's finger to the electrode plate.

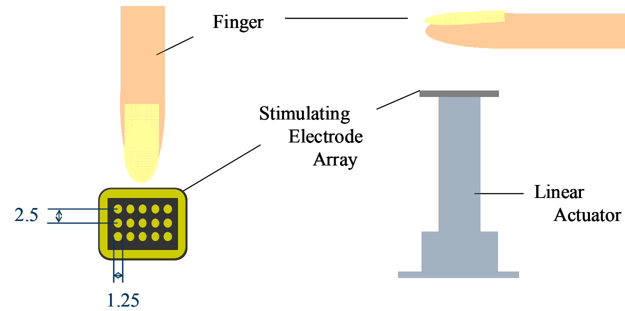

Fig. 7: System configuration: top (left) and side (right) views.

3.3.2. Experiment procedure. A 40Hz sine wave was applied as the mechanical stimulus and the electrical stimulation was set to 20pps. The remaining conditions were the same as that in the previous experiments.

3.3.3. Results. Just like the previous experiments, the results of the 3rd experiment showed V-shape graph, indicating that the interaction between mechanical and electrical stimulation occurred as we expected.

3.4. Experiment with high frequency

In all the previous experiments, mechanical stimulation was 40 times per second, while electrical stimulation was 20 times per second. To see if the matching of the frequency between the mechanical and electrical stimulation is the necessary condition for the interaction, we changed the mechanical vibration frequency to 240Hz.

In the first three experiments, frequency of mechanical vibration was the resonance frequency of RA. As the electrical pulse also stimulates receptors which reside in the shallow part of the skin including RA, we can say that both in the mechanical and electrical stimulation, RA were stimulated. On the other hand, frequency of vibration used in this experiment is resonance frequency of PC. PC is not considered to be stimulated by the electrical stimulation (because it is in a deeper region of the skin). Therefore, in this experiment, mechanical and electrical stimulation stimulates different types of receptors. An advantage of this technique is that, theoretically, there is no cross talk between the electrical and the mechanical stimuli since it is the threshold value that we are observing.

The mechanical pulse height was 0 through 30 μm, because recognition of high frequency wave is easier than low frequency wave. The remaining conditions are the same as that in the previous experiments.

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3.4.1. Results. Just like the previous experiments, the results of the 4th experiment showed V-shape graph, indicating that the interaction between mechanical and electrical stimulation occurred even if the frequency of mechanical stimulation is much higher than the electrical stimulation.

4. Discussion

We have measured interaction between mechanical and electrical stimulation in four different conditions as follows.

1. Mechanical stimulus was 40pps impulse and electrical stimulus was 20pps, electrical pulse was synchronized with mechanical impulse.
2. Electrical pulse was delayed 12.5ms with mechanical impulse.
3. Mechanical sine wave was used. Contactor was changed from pin to plate.
4. Mechanical stimulus was 240Hz sine wave.

In all the experiments, we saw that there were certain interactions between mechanical and electrical stimulation. To quantitatively compare these four experiments, minimum current normalized with current without mechanical stimulation for each experiment is calculated (Fig. 8). The horizontal and vertical axes represent the experiment numbers as described above and the rates of a threshold value, respectively. The circles, triangles, squares and stars represent the average of each of 5 trials by four subjects.

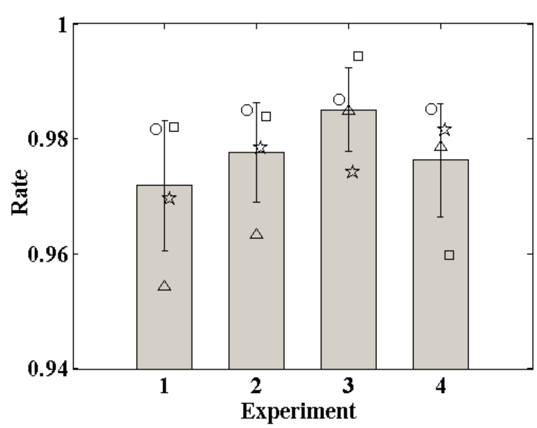

Fig. 8: Results of the four experiments (Experiment number is described in the text)

Explore the interaction levels

Let us consider how the interaction between the electrical and mechanical stimuli works. The human tactile signal-processing system is roughly divided into two layers. One is a receptor level and the other is a nerve center level.

Our first hypothesis is that the interaction occurs in the receptor level. We hypothesized that the nerve that does not activate under the application of a subthreshold electrical stimulus can be activated by subthreshold mechanical stimulation. We call it, "a peripheral level interaction hypothesis". This hypothesis assumes that the interaction occurs in the same mechanoreceptor, or in the same nerve fiber (Fig. 9). As addition of membrane potentials caused by mechanical and electrical stimulation is the key point, temporal synchronization is essentially important in this hypothesis.

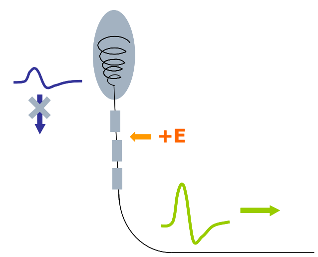

Fig. 9: Peripheral level interaction hypothesis

However, in the second experiment, it turned out that time delay of electrical stimulation does not significantly change the result. The "peripheral level interaction hypothesis" was therefore rejected, which insisted that nerve firing will arise as a result of the mechanical and electrical stimuli added to the same mechanoreceptor.

It is an interesting fact that the threshold of electrical stimulation decreases by applying mechanical stimulation even when the phase difference = 180 degree (i.e. time delay was 12.5ms). It implies that the mechanical stimulus applied before a fixed interval (assumed to be sufficiently long) from the electrical stimulation lowered the threshold. From this result the existence of the integration process with the temporal resolution larger than 12.5ms is suggested. Thus far, no study has reported on the role of group stimulus in human perception; however, their contribution may be considered in this case.

Our second hypothesis is the "center level interaction hypothesis". Several different receptors activities can be considered as a group stimulus. When the number of active receptors reaches threshold, we perceive sensation. In this hypothesis, both mechanical and electrical stimulation activated some receptors, but the number did not reach the threshold. When both are applied, sum of the active receptors reached threshold. As the second hypothesis assumes integration process in our brain, our next interest is what level of the central nerve process is related to this interaction phenomenon. It is well known that at the entrance of our somatic sensory system (i.e. Brodmann's area 3a), each region of the cortex receives inputs from single type of mechanoreceptors. In the higher level (i.e. Brodmann's area 1 and 2), information from different types of receptors are integrated.

In the 4th experiment, theoretically, mechanical and electrical stimulation stimulates different types of receptors. The result of that experiment showed a possibility that the interaction worked even in this case. For the first time, it was shown that the "decrease in the threshold value" occurs universally, irrespective of the type of receptor.

Reduction in the so-called electrical sensation

During the experiment, another interesting side-effect was observed. It is a reduction of so-called "electric feeling". In other words, by adding mechanical stimulation, the sensation by electrical stimulation became somewhat more "natural". As this "electric feeling" is one of the major drawbacks of electrical stimulation, we should dig the phenomenon deeper in our next study.

7. Conclusion

The objective of this study is to present an easy approach to realize a spatially and temporally high-grade tactile perception device. In this paper, we demonstrated the effectiveness and impact of the combination of electro-tactile stimulation and mechanical stimulation. As a result, some of the shortcomings posed by the usage of only electrical stimulus can be overcome.

"A peripheral level interaction hypothesis" was rejected in this paper; however, there exists physiological evidence suggesting that both electrical and mechanical stimulations actually activate the RA respectively. Furthermore, we need to reconsider the reason as to why interaction didn't occur clearly at the peripheral level.

We fabricated an electrode array mounted on a linear actuator; it exhibited the same tendency as that of a pin electrode. Furthermore, the possibility of the interaction between different-species receptors was shown. These two results can help realize an optimal system that employs a combination of "high temporal resolution mechanical stimulation" and "high spatial resolution electrical stimulation".

Following the addition of mechanical stimulation, further studies investigating the efficiency limit of electrical stimulation are required. The investigation of the types of tactile stimuli that can be sensed by employing a method to control the different spatiotemporal spaces will yield interesting results.

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