Combination of Cathodic Electrical Stimulation and Mechanical Damped Sinusoidal Vibration to Express Tactile Softness in the Tapping Process *

Vibol Yem, Member, IEEE, and Hiroyuki Kajimoto, Member, IEEE

Abstract—A damped sinusoidal vibration is generally used to reproduce the sensation of tapping. However, the type of actuator generally used in the field of tactile display cannot produce very low-frequency vibrations, and thus cannot activate Merkel cells to produce the sensation of cutaneous pressure. In this study we propose a method that combines cathodic electrical stimulation, which produces a pressure-like sensation, with a mechanical damped sinusoidal vibration. Our experiment demonstrated that the cutaneous pressure sensation produced by cathodic electrical stimulation mostly affects the perception of softness, allowing our method to reproduce sensations of softness/hardness over a wider range than when using mechanical vibration alone. Most participants felt that the combination of these two stimulations provided a more realistic tapping sensation.

Keywords—Softness, tapping, cathodic electrical stimulation, mechanical sinusoidal vibration

I. INTRODUCTION

When tapping an object with a finger, it is thought that we sense the pressure on the finger pad and the softness or hardness of the object through the activities of the Merkel cells, Meissner’s corpuscles and Pacinian corpuscles that are found in the skin of the finger pad. In studies of haptic displays, damped sinusoidal vibration is well known and commonly used to provide the sensation of hardness of the material while tapping a surface, or in the impact between the two surfaces [1][2]. It is also known that the frequency of vibration is the main parameter that influences the perception of hardness [3]. However, the vibration actuators generally used in the tactile research field are unable to generate vibrations below several Hz (e.g. for the Haptuator (TL002-14-A, Tactile Labs Inc.) the peak amplitude occurs at a frequency of 100 Hz, for the Force Reactor (Alps Electronic Co.) at 280 Hz, and for the DC motor (HS-V1S, STL JAPAN Co.) at 40 Hz [4]), which is the area of activity of the Merkel cell, and therefore their ability to reproduce softness is limited.

When representing softness by presenting a sensation to the skin, it is known that the softness of an object can be reproduced by changing the contact area with the skin [5][6][7][8]. This is because when a soft surface is pressed, the contact area is wider than for a hard surface. However, a tapping motion is faster than a pressing motion, involving a more abrupt change in the contact area. It is therefore believed that softness or hardness is sensed from the object’s reaction force and the activities of selected receptors rather than from the contact area.

Against this background, in this study we propose a method that combines cathodic electrical stimulation, which mainly elicits pressure sensation, with a mechanical damped sinusoidal vibration to express softness perception in the tapping process. Our experimental results showed that, with our proposed method most participants could perceive a softer and more realistic tapping sensation than when presented with a mechanical vibration alone.

II. RELATED WORK

There are four known types of mechanoreceptors for tactile sensation. These are Ruffini endings, Merkel cells, Meissner’s corpuscles and Pacinian corpuscles, corresponding to the sensations of skin shear deformation, pressure, low frequency vibration, and high frequency vibration respectively [9]. As Figure 1. shows, Ruffini endings and Merkel cells are slow adaptive receptors that generate neural activity for the "displacement" and "displacement and velocity" components of mechanical stimulation respectively. In contrast, Meissner’s corpuscles and Pacinian corpuscles are fast adaptive receptors that generate neural activity for the "velocity" and "acceleration" components of mechanical stimulation. Merkel cells and Ruffini endings respond to very low-frequency vibrations (under 0.1 Hz to several Hz), whereas Meissner’s corpuscles and Pacinian corpuscles respond to high-frequency vibrations (10 Hz to 100 Hz, and 60 Hz to 800 Hz respectively). The optimal sensitivities of Meissner’s corpuscles and Pacinian corpuscles are 30 Hz and 250 Hz respectively.

* This work was partly supported by JSPS KAKENHI Grant Number JP17FI7351, JP15H05923 (Grant-in-Aid for Scientific Research on Innovative Areas, “Innovative SHITSUKSAN Science and Technology”), and the JST-ACCEL Embodied Media Project.

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Figure 1. Adaptation characteristics and receptive field of the four types of mechanoreceptor

<table>
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<tr>
<th>Adaptation</th>
<th>Small receptive field</th>
<th>Large receptive field</th>
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<tbody>
<tr>
<td>Rapid adaptation</td>
<td>Meissner</td>
<td>Pacinian</td>
</tr>
<tr>
<td>Slow adaptation</td>
<td>Merkel</td>
<td>Ruffini</td>
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</tbody>
</table>

978-1-5386-4067-8/18/$31.00 © 2018 IEEE 84 Haptics Symposium 2018, San Francisco, USA
In the tapping process, there is almost no perception of skin shear deformation and therefore Ruffini endings are not the main receptors for this process. Okamura et al. [1] collected vibration data to model the material tapping sensation. They observed that harder materials produce a higher vibration frequency (e.g. 30 Hz for rubber, 100 Hz for wood, and 300 Hz for aluminum). Their experimental results lead us to conclude that hardness is perceived as harder when mainly Pacinian corpuscles are activated than when mainly Meissner corpuscles are activated. The sensation of pressure also occurs on the skin of the finger pad through the object’s reaction force. Since Merkel cells respond to pressure and are sensitive to low vibration frequencies, we can expect cutaneous pressure to affect our perception of making sensation softer. Equally, because a stronger reaction force represents a harder material, it is reasonable to assume that pressure affects our perception of making sensation harder. The aim of this work is to reveal how cutaneous pressure has effect on our perception of softness or hardness and whether it makes the sensation softer or not.

Several studies have developed wearable devices that present the fingertip with a sensation of cutaneous pressure [10][11][12]. However, these devices use a mechanical actuator to generate the physical force, and so they are large and slow in responsiveness. We used electrical stimulation to present a pressure-like sensation to the fingertip. Two types of electrical stimulation can be used: anodic stimulation and cathodic stimulation [13]. It is known that cathodic stimulation produces a pressure-like sensation that supposedly stimulates mainly Merkel cells whereas anodic stimulation produces a vibration-like sensation that supposedly stimulates mainly Meissner’s corpuscles [13][14]. Sato et al. [15] proposed a method that uses both anodic and cathodic stimulation to present a force vector to the fingertip. Several studies have proposed a method that combines both electrical and mechanical stimulation to reproduce a higher quality of tactile sensation [16][17]. However, none of these studies confirmed that electrical stimulation affects our perception of softness or hardness. In this study we used only cathodic electrical stimulation combined with a damped sinusoidal vibration produced by a mechanical actuator to investigate the perception of softness in the tapping process.

III. EXPERIMENT

The experiment investigated whether cathodic electrical stimulation combined with mechanical damped sinusoidal vibration can be used to control the intensity of the softness perceived in the tapping process. We also investigated whether our method was effective in presenting participants with a more realistic tapping sensation compared with the previous method that presented them with a mechanical vibration. The evaluation was based on a questionnaire using the Likert scale.

A. Apparatus

Figure 2. shows the device used to present both an electrical stimulation and a mechanical vibration to the participant’s fingertip. We used a vibration actuator developed by Alps Electric Co., Ltd. to generate the mechanical vibration [18]. The vibration waveform was generated by a microcontroller (mbed LPC1768, NXP Semiconductors) and amplified with an amplifier (OPA2544T, Texas Instruments, Inc.). A three-axis acceleration sensor with an analog signal output (MMA7361LC, Freescale Semiconductor, Inc.) was mounted on the vibration actuator to measure the amplitude of the vibration, which could be adjusted from the keyboard of a PC. The oscilloscope (TDS 2004B, Tektronix) was used to observe the waveform and amplitude of the vibration. The acceleration sensor measured the vibration on the x, y and z axes, and the total amplitude of vibration was calculated from the following equations. Figure 3. shows the observed vibration waveforms on the x and z axes and the total amplitude in real time.

\[ A_x = \sqrt{A_{x,x}^2 + A_{x,y}^2 + A_{x,z}^2} \]  (1)

\[ A_y = \frac{1}{2} \left( \max(A_{y,x} - A_{y,x}) - \min(A_{y,x} - A_{y,x}) \right) \]  (2)

where, \( A_x \) is the total vibration amplitude and \( A_{x,x}, A_{x,y}, A_{x,z} \) are amplitudes for the vibration on each axis at time \( i \). T is the period of vibration. Variables \( \max(A_{y,i} - A_{y,i}) \) and \( \min(A_{y,i} - A_{y,i}) \) represent the maximum and minimum values of the vibration amplitude in time interval T (from i to i-T). The same method was used to calculate \( A_y \) and \( A_z \).
We used the same electrical stimulation kit as in our previous study to produce the electrical stimulation [19]. This kit uses a microcontroller (MBED LPC1768, NXP Semiconductors), a high-speed D/A converter, and a voltage-current conversion circuit to control the waveform and the intensity of the electric current. A switching IC (64-channel serial to parallel converter, HV507, Supertex Inc.) was used to select the electrode for stimulation. The intensity of the electric current (the height of the current pulse) was adjust from the keyboard of a PC.

The two microcontrollers communicated with each other via an interrupt port to synchronize waveforms for the electrical stimulation and mechanical stimulation.

B. Stimulation Conditions

As this type of vibration actuator cannot produce strong vibrations when the frequency is under 100 Hz, we set the frequency of the mechanical damped sinusoidal vibration to 100 Hz, the damping coefficient to 80 s⁻¹ and the maximum amplitude of vibration to 0.7 G. These were the values used to reproduce the sensation of tapping on wood by Okamura et al. [1]. The width of the current pulse for the electrical stimulation was 100 μs and the current intensity was adjusted between 0 and 5 mA. The stimulation electrodes are shown enclosed by a red rectangle in Figure 2. (left).

We used six kinds of electrical stimulation in the experiment and a mechanical vibration with fixed waveform parameters. Figure 4. shows the three levels of electrical intensity (Weak, Medium, and Strong) and two time intervals (100 ms and 150 ms) used for the electrical stimulation. We combined two values for the number of pulses per second (pps), 100 pps and 40 pps, for one stimulus to match the adaptation characteristics of the receptors shown in Figure 1. The time interval for the 100 pps stimulus was fixed at 50 ms and the time interval for 40 pps were 50 ms and 100 ms.

Figure 4. Conditions for the electrical stimulation combined with the mechanical damped sinusoidal vibration used in the experiment

C. Participants and Procedure

Seven participants took part in the experiment: six males and one female with ages ranging from 22 to 27 years old. All of them were right-handed.

The participants sat on a chair, cleaned the index finger of their right hand with alcohol, and placed it on the electrode film (Figure 3. (right) and Figure 5. ). The level of the mechanical stimulation voltage was adjusted to give a maximum vibration amplitude of about 0.7 G. For each stimulation condition, when the mechanical vibration stimulation was presented, the participants were asked to adjust the intensity of the electric current until they perceived it as being either weak, medium or strong. After they had experienced all the stimulation conditions, we asked them to compare the sensation experienced in each condition to the sensation they experienced when presented with only the mechanical vibration. Participants used the keyboard of the PC to turn the electrical stimulation on or off to compare the sensations. Figure 6. shows the Linkert scales for the two questions we used for the evaluation. Question 1 is designed to evaluate the effect of the cathodic electrical stimulation on their perception of softness and Question 2 was designed to examine whether their experience was a realistic tapping sensation or incompatible with tapping.

Figure 5. Overview of the experiment. Participants placed their index finger of the right hand on the stimulation device and turned the electrical stimulation on or off by pressing the keyboard of the PC with their left hand

Figure 6. Linkert scales showed on the PC screen for the two questions that used for evaluation in the proposed method

The stimulus was repeated every second. Subjects experienced all the stimulus conditions and then answered both of the above questions while receiving the stimulus.

D. Result

Figure 7. and Figure 8. show the results for each question. The vertical axis shows the answers of each participant expressed on the Likert scale. The horizontal axis shows the six stimulation conditions.
IV. DISCUSSION

The answers to Question 1 showed that almost all participants felt that cathodic electrical stimulation made the sensation softer than only mechanical damped sinusoidal vibration (Figure 7). We observed that the intensity of the perceived softness increased as the intensity of the cathodic electrical stimulation became stronger. This result is contrary to the belief that a higher pressure produces a harder sensation. Although a stronger electrical stimulation produced a higher pressure sensation [14], it did not make the sensation harder but softer. This was because the pressure-like sensation produced by cathodic stimulation mainly provides information on softness. We confirmed this by presenting all participants only cathodic electrical stimulation and they commented that they felt a very soft pressure on their skin. One participant, who was sensitive to hardness, interpreted a stronger electrical stimulation as being harder. The above result showed us that, in general, we can use the intensity of electrical stimulation as a parameter to control the perception of softness.

We did not observe any difference in the perception of softness when the electrical stimulation was presented for time intervals of 100 ms and 150 ms. One participant who was sensitive to hardness interpreted the stimulation as being harder when the time interval was 150 ms and the intensity was strong. This individual perceived hardness by the strength of the pressure and a longer presentation time provided a clearer sensation of pressure.

The answers to Question 2 showed that our proposed method reproduced a more realistic tapping sensation (Figure 8). Almost all participants felt a more realistic sensation when the pressure-like sensation was also presented to the skin on their finger pad by cathodic electrical stimulation. When the presentation time interval was 150 ms in particular they felt a realistic sensation even when the intensity of electrical stimulation was weak. Mechanical stimulation using a damped sinusoidal vibration mainly activates the Meissner corpuscles and Pacinian corpuscles. This method is not sufficient to provide the rich information of a tapping sensation in which the Merkel cells are also activated. One participant felt that the sensation was more incompatible with a tapping sensation when cathodic electrical stimulation was used than when only mechanical vibration was used. This participant commented that the contact area of the electrical stimulation was smaller than when tapping a real object’s surface and the sense of a mechanical impact became weaker. Some participants commented that they felt as if they were tapping on a rough surface. This is presumably because they perceived each separate electrode as a pressure point.

V. CONCLUSION

In this study, we proposed a method for using both cathodic electrical stimulation and mechanical damped sinusoidal vibration to reproduce tactile softness in the tapping process. Experimental results showed that most participants experienced the sensation as softer when the intensity was increased for cathodic stimulation combined with mechanical stimulation. Most of them experienced a more realistic tapping sensation with both electrical and mechanical stimulation than with only mechanical stimulation.

We plan to continue this study with two additional experiments. Firstly, we will investigate in more detail the effect of the time interval and the synchronization between the electrical and mechanical stimulations. Secondly, we will investigate the range of softness and hardness that our method can reproduce by comparing it to the experience of tapping real objects.

ACKNOWLEDGMENT

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REFERENCES


