PERCEPTION INTENSITY AND FREQUENCY OF PRESSURE AND VIBRATIONS ELICITED BY ELECTRICAL STIMULATION

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ABSTRACT

We investigated effects of the two stimulus parameters, the stimulation intensity represented by the pulse amplitude and the pulse frequency, on the tactile sensations elicited by single-channel transcutaneous electrical stimulation. Two types of experiments were conducted. In the current experiment, the current was modulated with the frequency fixed at 20 Hz and 200 Hz. In the frequency experiment, the stimulation frequency was modulated with the amplitude fixed at 2, 4, 6, 8 and 10 mA, respectively. In the current experiment, tickling, pressure and the low-frequency vibration were elicited at 20 Hz in more than 90% of the subjects, but the high-frequency vibration mostly appeared at 200 Hz. The frequency experiment showed that the perceived vibration frequency increased with the stimulation frequency. However, the frequency at which the vibration appeared was consistent regardless of the stimulation intensity, implying that the stimulation intensity did not affect the perception frequency of the vibration. On the other hand, pressure was perceived stronger as either the stimulation intensity or the frequency increased. Our observations suggested that the perception frequency and the intensity of the vibration sensations were directly related to the stimulation frequency and the pulse amplitude, i.e. the stimulation intensity, respectively, and the perception intensity of pressure was affected by both the stimulation frequency and the pulse amplitude.

Keyword: Tactile sensations, Electrical stimulation, Perception intensity, Pulse amplitude, Pulse frequency

INTRODUCTION

The tactile sensation provides us with a variety of information, one of the most common examples being the braille frequently used by the visually impaired. This means that our daily life would be very much limited without tactile sensations and thus it is necessary to ‘generate’ tactile sensations by means of external inputs, such as electrical stimulation. Researches have been done to induce some tactile sensations like tickling, pressure, and vibration, invasively [1, 2] or noninvasively [3-5]. The major applications include the prosthetic hand, where many different pieces of tactile information can be detected and measured using transducers, and then transformed into appropriate electrical stimulation applied to the user’s skin in order to enable the user to ‘feel’ the tactile sensation as if he/she were in contact with the object. Mechanical stimulation applied to the glabrous skin deforms the major mechanoreceptors, which creates and propagates action potentials along the afferent nerve path. The mechanoreceptors are classified into SA (slowly-adapting) and FA (fast-adapting) depending on their adaptation characteristics, and they are again divided into Type 1 (SA1 and FA1) and Type 2 (SA2 and FA2) based on the size of their receptive field. Most researchers agree that FA1 is responsible for light touch and fluttering, FA2 for high-frequency vibrations (HFV) such as buzzing, SA1 for pressure, and SA2 for skin stretch [2, 6]. Now that it is believed that electrical stimulation affects the afferent nerve fibers related to the above mechanoreceptors, creating and propagating action potentials toward the brain to induce corresponding tactile sensations, we investigated effects of the two stimulus parameters, the stimulation intensity represented by the pulse amplitude and the pulse frequency, on the tactile sensations elicited by single-channel transcutaneous electrical
stimulation.

**METHODS**

**Subjects**
Twenty healthy subjects at the age between 21 and 33 (24.05±4.07) participated in the experiments. All the subjects who participated in the experiments with a written consent were fully informed of the experimental procedure and any potential risk that might occur during the experiment.

**Preparation**
Before the experiment, the subject’s index fingerpad was cleaned with an alcohol swab, and then put in the room-temperature water for 30 seconds to decrease and keep the skin impedance as uniform as possible. After removing water with a tissue, we applied electrolytic gel on the fingerpad to provide a consistent contact condition between the skin and the electrodes to every subject. The fingerpad was then placed on the electrode in such a way that the center of the fingerpad’s swirl coincided with the distal electrode. A ten-minute break was taken without exception between two consecutive experiments to avoid any unnecessary effect from the previous stimulation.

**Electrical Stimulation System**
Fig. 1 shows the electrical stimulation system developed in our laboratory for this study. The electrical pulse trains were programmed in LabVIEW® (National Instruments Corporation, Austin, Texas, USA) to create and control the stimulus parameters; the pulse amplitude, width and frequency. NI 9263 (National Instruments Co., Austin, Texas, USA) generated the pulse train in voltage, and the voltage was then converted into the current by the 8-channel stimulator. The constant-current stimulation was employed to keep the stimulation intensity from changing due to the skin impedance variation during the experiment. The size of the source and reference electrodes was 10mmX1.5mm and 10mmX4.5mm, respectively, and they were placed along the longitudinal nerve path.

![Electrical Stimulation System](image)

**Electrical Stimulation System**
Two types of experiments were conducted; the current experiment and the frequency experiment, employing the pulse amplitude modulation and the frequency modulation, respectively. In the current experiment, the pulse amplitude was increased by 0.35 mA every 2.5 seconds at two frequencies, 20 Hz and 200 Hz. In the frequency experiment, on the other hand, the frequency was increased by 2 Hz in 1 second, from 0 to 300 Hz, at 5 different amplitudes, 2, 4, 6, 8, 10 mA. In both experiments, the catholic rectangular monophasic pulse train was employed with the pulse width fixed at 200 us.
**Sensation Description**
During the experiment, the subjects verbally described the sensation as specifically as possible. Their description included the kinds of the tactile sensation(s) they felt during the experiment, the starting/ending time of each sensation, the perception location, the perception intensity, etc. In this study, the tactile sensations were divided into tickling, pressure, low-frequency vibration (LFV) and HFV based on our previous research [3]. Tickling is a pleasant sensation, compared to that evoked on the skin by a soft fine feather. Pressure feels like a sustained indentation or compression on the skin. LFV can be expressed as beating or fluttering where two consecutive beats can be distinguished, whereas the subject cannot distinguish consecutive beats any more in HFV. HFV is again divided into vibrating and buzzing, depending on whether frequency change can be perceived. Whenever the subject felt any uncomfortable sensation or pain, we immediately stopped the electrical stimulation.

![Fig. 2. Elicitation ratio (%) in the current experiment](image)

**RESULTS**

**Stimulation Amplitude Modulation**
Fig. 2 indicates that tickling, pressure and LFV were elicited at 20 Hz in more than 90% of the subjects, but HFV appeared mostly at 200 Hz, not counter to our expectation. The stimulation frequency was generally close to the perception frequency. As for the sensation order, tickling was elicited earlier than any other sensation almost without exception. The second sensation was pressure or LFV at 20 Hz, while pressure or HFV at 200 Hz as shown in Fig. 3.

![Fig. 3. The second sensation in the current experiment](image)
Stimulation Frequency Modulation

Fig. 4 shows how the pulse amplitude affected the elicitation ratio of each sensation in the frequency experiment. The pulse amplitudes of 2 or 4 mA were not high enough to generate any tactile sensation in 50% and 30% of the subjects, respectively, and, if they did, the perception intensity was extremely low so that most of the subjects reported very weak tickling and/or some other sensation(s) they could not clearly describe. With the pulse amplitudes equal to or higher than 6 mA, almost all the subjects reported all the four major tactile sensations; pressure, LFV, vibrating, and buzzing.

![Fig. 4. Elicitation ratio (%) in the frequency experiment](image)

The subjects generally agreed that the perception frequency increased with the stimulation frequency when the pulse amplitude was higher than a certain value, 4 mA in this frequency experiment. Fig. 5 shows the averaged frequencies at which each sensation appeared during the frequency experiment, indicating that the sensation order was LFV → pressure → vibrating → buzzing at the pulse amplitudes above 4 mA in 90% of the subjects. Considering that pressure was the only noncyclic sensation, we can clearly see that high stimulation frequencies made the subjects feel high-frequency sensations. It was also found that each sensation began to appear almost at a constant frequency regardless of the pulse amplitude in each subject, as seen in Fig. 5, particularly for the pulse amplitudes equal to or high than 6 mA. Fig. 6 shows the frequency range of pressure, where the subjects began to feel pressure almost at the same frequency but the sensation for the lower pulse amplitude was over at the lower frequency.

![Fig. 5. Stimulation frequency at which the subjects began to feel a tactile sensation in the frequency experiment](image)
DISCUSSION

The experimental results suggested that the vibration sensation is frequency-dependent, i.e. the perception frequency increases with the (electrical) stimulation frequency like the mechanical stimulation. The low-frequency stimulation (20 Hz) primarily generated LFV, and the high-frequency stimulation (200 Hz) HFV. Talbot reported that 25 action potentials per second measured from a single FA nerve afferent for a 25 Hz mechanical stimulation [7], implying that increasing the frequency of the action potential increases with the stimulation frequency so that the brain perceives this firing rate. In case of the pressure sensation which is believed to be frequency-independent, on the other hand, the perception intensity increased with the stimulation frequency during the frequency modulation, which matched well with [8]. The SA I nerve afferents responsible for the pressure sensation may decode an increase in the action potential firing rate into an increase in the perception intensity as suggested in [9]. In this study, electrical stimulation altered the membrane potential of the sensory nerve afferents, affecting the firing rate of the action potential, and thus making the subjects ‘feel’ the perception intensity of pressure.

During the pulse amplitude modulation, tickling always appeared first, and then pressure or LFV/HFV followed. It can be interpreted that the sensation order can be generally determined by the anatomical position of the sensory nerve afferents so that the superficial region of the skin was affected by the electrical stimulation earlier than the deep region. That is, the deep region can be stimulated with a higher stimulation intensity (the pulse amplitude in this case) than the superficial region. It was reported by Talbot et al. that the perception intensity depended not only on the action potential firing rate but on the number of the affected nerve afferents [7]. As the pulse amplitude increased, therefore, the stimulation reached the farther (deeper) region, innervating more nerve afferents, and finally the subjects felt a stronger perception intensity. It was also suggested that this might be true to both FA and SA afferents; the perception intensity of the low/high-frequency vibration and pressure increased with the pulse amplitude.

It was observed that a continuous electrical stimulation weakened and finally made the sensation disappear, as shown in Fig. 6, primarily by reducing the action potential firing rate with time. Zigler et al. reported that the adaptation time, defined as the time taken for a sensation to disappear under a continuous stimulation, was proportional to the stimulation intensity and inversely proportional to the contact area in case of pressure [10]. This is in a good agreement with our experimental result that the high pulse amplitude caused the adaptation time of pressure to increase.

![Fig. 6. Frequency range of the pressure sensation](image-url)
CONCLUSION

It was possible for us to generate some tactile sensations via a single-channel transcutaneous electrical stimulation. Analyzing the experimental observations, the perception frequency and the intensity of the vibration sensations were directly related to the stimulation frequency and the pulse amplitude, i.e. the stimulation intensity, respectively, and the perception intensity of pressure was affected by both the stimulation frequency and the pulse amplitude.

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REFERENCES