Relationship between Force Sensation and Stimulation Parameters in Tendon Electrical Stimulation

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Abstract. Most haptic devices have the common problem of requiring a large hardware setup, because they must present actual force. To cope with this issue, we have proposed a method to present force sensation using tendon electrical stimulation. In this paper, we investigated whether it is possible to present force sensation by electrically stimulating the tendon through the skin surface at the wrist. We also investigated the relationship between the amount of sensation and the stimulation parameters. We found that a force sensation can be generated by electrical stimulation to the wrist, and the direction of the force sensation is opposite to the motion elicited by muscle electrical stimulation. We also found that it is possible to control the amount of the sensation by varying both pulse height and pulse frequency.

Keywords: Force sensation, Golgi tendon organ, Haptic Interface, Ib fiber, Tendon electrical stimulation (TES)

1 Introduction

To improve the sense of immersion in virtual reality, or the operability of telexistence or teleoperation systems, many haptic devices have been developed. However, most of them have the common problem of requiring a large hardware setup to mechanically generate actual force.

If there were a way to directly stimulate receptors related to force, or the sensory nerves extending from those receptors, it would be very energy-efficient, and thus dramatically smaller haptic devices could be achieved. There have been many studies on presenting the sense of touch via the electrical stimulation of the nerves extending from tactile receptors [1,2]. In regard to proprioception sensation, there are also studies that present the sense of gravity or acceleration by galvanic vestibular stimulation [3]. Meanwhile, it is known that motor illusions occur when applying vibrations to the tendon [4,5,6]. Moreover, it is suggested that electrical stimulation to the tendon (TES) also produces motor illusions [7], which is presumably because of the activity of Golgi tendon organs (GTOs) [8]. Compared with electrical muscle stimulation (EMS), which is also used to present force sensation by stimulating muscles [9,10,11], TES does not accompany actual body movement. This characteristic is suitable for some situations in which users' motion space is limited, such as in a cockpit.

adfa, p. 1, 2011.

The goal of this study is to realize a compact force presentation device using TES. In this paper, we investigated whether it is possible to present force sensation via electrical stimuli applied through the skin surface of the wrist, and the relationship between the amount of force sensation and stimulation parameters (i.e., the frequency and height of the current pulse).

2 Experimental Procedure

2.1 Apparatus

Electrical Stimulator: Fig. 1 (A) shows the electrical stimulator. This device controls pulse stimulus pattern and the amount of current from 0 to 25 mA (voltage is up to 300 V) with a micro controller (mbed NCP LPC 1768, NXP Semiconductors). The device has four channels, whose states can change to anode, cathode or isolated from each other through a circuit using photo MOS relays (AQW210S, Panasonic Corporation) (Fig. 1 (B)) on the device. The device realizes bipolar stimulation by changing the target-stimulating electrode; that is, a biphasic pulse train is applied to an electrode (Fig. 1 (C)).

Electrode: Two gel electrodes (1.9mm × 3.5mm, Vitrode F-150S, Nihon Kohden Corporation) were installed on the skin at the dorsal part of the left wrist (Fig. 1 (D)).

In preliminary trials, we have confirmed that a force sensation is induced by TES to the wrist and elbow. The direction of the sensation was to the opposite side of the electrodes (i.e., when the electrodes were on the dorsal part, the direction of the perceived force was inward (Fig. 2)). However, an actual movement was not accompanied with TES.

Measurement system for force sensation: We constructed a system to measure force sensation by TES. As shown in Fig. 2, it consists of a spring scale, a pulley, a wristband and string to connect them. The participants were asked to pull the wristband, which was attached to their right arm, until they felt that the force produced by the spring was close to the force sensation produced by TES. Thus, the illusory force was quantified.

We have preliminarily tested the system by presenting actual force to the left arm. Although there were differences between the measured force and actual force, and large variation among individuals, there was also a strong correlation between the two. Thus, we adopted this system in the main experiment.

2.2 Protocol

We applied TES to the left dorsal wrist. First, we obtained each participant's threshold of pulse height such that they barely felt force sensation. Pulse frequency was fixed to 40 Hz.

Then, we investigated the relationship between the amount of force sensation and electrical current parameters. Frequency conditions were 20 Hz, 40 Hz, or 80 Hz, and pulse height conditions were 1, $\sqrt[6]{2}$, $\sqrt[3]{2}$, or $\sqrt{2}$, relative to the previously obtained threshold. Combination of the conditions gave 12 trials. For each trial, we obtained the amount of perceived force sensation using the measurement system described in 2.1.

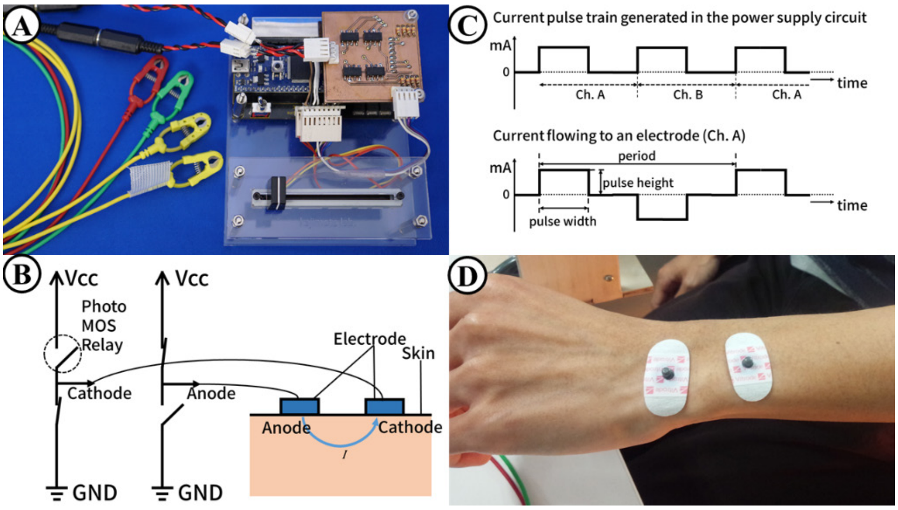

Fig. 1. (A) Electrical Stimulator. [2] (B) Two Photo MOS relays for one channel to allow a change of the channel state. (C) Monophasic current pulse train generated in the current control circuit is converted to biphasic pulses by switching the state. (D) Electrodes on dorsal part of the wrist.

Fig. 2. Measurement of perceived force sensation. (Left) Concept image. (Right) Actual system

We recruited eight laboratory members aged 21 to 24. All were male, and all confirmed that they could feel force the sensation produced by TES.

3 Results

Fig. 3 shows the results of the experiment. The vertical axis is the estimated mean of the force sensation. The bars indicate standard deviations. The transverse axis is the pulse height normalized by threshold values. The pattern of the bars represents pulse frequency. We used a two-way ANOVA, and found no interaction. Then, we did a multiple comparison (Tukey HSD test). Regarding frequency, we found significant differences at the 5% level between all frequency pairs. Regarding pulse height, we found a significant difference at the 5% level between almost all pairs except $\sqrt[3]{2}$ and $\sqrt{2}$.

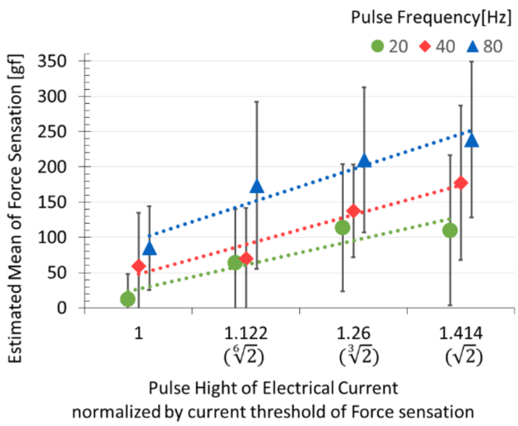

Fig. 3. Relationship between the amount of force sensation and the electrical current parameters.

4 Conclusion

We found that TES can induce force sensation, and that the amount of sensation can be controlled by both the pulse height and frequency of the electrical stimulation current. However, frequency is a better way to control the amount of sensation for the following reasons. First, the possible range of pulse height without pain sensation is small. Second, considering that there was no significant difference between $\sqrt[3]{2}$ and $\sqrt{2}$ in the pulse height condition, there seems to be a saturation, even at $\sqrt{2} = 1.414$ of the threshold current amplitude, which makes control quite difficult. Furthermore, we found that TES has the capacity to present a force sensation of around 250 gf. We must stress that this sensation was not based on muscle electrical stimulation, because if it was caused by muscle contraction, the direction of the force should be to the side of the electrodes (i.e., when the electrodes were on the dorsal part, the direction of perceived force should be outward), but the force that was presented this time was in the opposite direction. Furthermore, actual movement based on muscle contraction was not observed throughout the experiment.

In this experiment, participants are completely passive when presenting sensation. Hence, we will investigate whether the quality of sensation is variable when stimuli are presented interactively. Furthermore, the underlying mechanisms of force sensation must be clarified. Currently, we speculate that it is based on the activity of the Golgi tendon organs (GTOs), but the possibility of force illusion via cutaneous sensation cannot be fully excluded.

If the force sensation is mainly induced by the stimulation to GTOs, the reason why most participants felt the force on their arm to the direction such as Fig. 2 can be described as follows. TES on dorsal part of wrist (Fig. 1(D)) does not present the information of the muscles' length (since muscle spindle was not stimulated), but present the information of contraction of the dorsal muscles (since GTOs were stimulated). These situation is the same as "isometric contraction", which can be interpreted by that participants as an external force which attempts to move their arms inward, and they are competing against the force.

This hypothesis based on GTOs is supported by some indirect evidence, which was observed in another experiment that showed two patterns of participants; some felt force on their arm, and the others felt on their back of the hand, despite the stimulation is applied on the wrist. It could be explained that the former felt moving the arm was easier than bending their wrist when pseudo isometric contraction occurred. In our future research, we will see if the GTOs are the main factor by observing phenomena related to the GTOs such as the Ib reflection.

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