Combination of Mechanical and Electrical Stimulation for an Intense and Realistic Tactile Sensation

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Figure 1: Mechanical stimulation with electrical stimulation can present an intense and realistic tactile sensation safely.

ABSTRACT

Naturalistic tactile sensations can be elicited by mechanical stimuli because mechanical stimulations reproduce natural physical phenomena. However, a mechanical stimulation that is too strong may cause injury. Although electrical stimulation can elicit strong tactile sensations without damaging the skin, it is inferior in terms of naturalness. We propose and validate a haptic method for presenting naturalistic and intense sensations by combining electrical and mechanical stimulation. We validate the proposed method by verifying whether both enhancement of the subjective strength of mechanical stimulation through electrical stimulation and elimination of the bizarre sensation of electrical stimulation through mechanical stimulation can be achieved. We find that the proposed method increases subjective intensity by 25% on average across participants compared with mechanical stimulus alone and decreases the bizarre sensation compared with the presentation of the electrical stimulus alone. The method can be used to enhance the experience of virtual-reality content but has room for improvement especially in terms of intensity enhancement.

CCS CONCEPTS

• **Human-centered computing** → *Haptic devices.*

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KEYWORDS

Electrical stimulation, Mechanical stimulation, Tactile, Virtual reality

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1 INTRODUCTION

It is important to provide a user appropriate tactile feedback when he or she makes contact with an object in virtual-reality (VR) space in terms of improving the immersive experience. Additionally, when the VR experience is a form of entertainment, it is necessary to present not only a sense of grasping and tracing an object but also an appropriate tactile sense for tense situations; e.g., a sense of being slashed or slapped. In this case, the presented tactile sense must be strong and natural to maintain tension. Such a sensation must be safe so as not to damage the skin; otherwise, the sensation is not suitable for entertainment.

There are two main methods of presenting tactile stimulation; i.e., physical deformation of the skin through mechanical stimulation and direct excitation of nerves, such as through electrical stimulation.

Tactile stimulus by mechanical stimulation can closely mirror a natural tactile presentation because it reproduces the natural mechanical interaction between the skin and object. However, intense stimulation (e.g., acute stimulation such as that provided by a needle[Egekvist et al. 1999]) may carry a risk of injury.

During electrical stimulation, sensory nerves are stimulated by an electric current to the skin surface that produces a tactile sensation[Kaczmarek et al. 1994; Saunders 1983; Yem and Kajimoto 2017a]. The applications to entertainment include a touch display that can apply tactile sensations to fingertips[Matoba et al. 2011] and the presentation of pain sensations[Kataoka et al. 2014]. The induction of a tactile sensation via electrical stimulation directly activates sensory nerves, and an intense tactile presentation is thus possible without damage to the skin. While electrical stimulation also carries certain risks, especially in terms of possible electrical current pathways, it is a sure way of eliciting a strong sensation without leaving marks on the skin. However, the degree to which the sensation is perceived as natural is lower than that when touching real objects. Indeed, many existing entertainment applications using electrical stimulation have been found to produce a 'bizarre sensation'.

In summary, mechanical and electrical stimulation methods have advantages and disadvantages. A combination of the two strategies may therefore produce a natural yet strong sensation. Ideally, a 'natural' tactile feeling can be elicited by mechanical stimulation with sufficient tactile intensity achieved via electric stimulation.

We developed a haptic presentation method that combines electrical and mechanical stimulation to verify the proposed method and it was proved that subjective mechanical tactile intensity was enhanced via electrical stimulation[Mizuhara et al. 2019]. However, this paper did not evaluated changes in sensation quality by electrical stimulation.

The present paper verifies whether both enhancement of the subjective strength of mechanical stimulation through electrical stimulation and elimination of the bizarre sensation of electrical stimulation through mechanical stimulation can be achieved.

2 RELATED WORK

Several studies have investigated change in the sense of electrical stimulation in response to mechanical stimulation. Yem et al. tried to mask the vibration sense of electrical stimulation in presenting a pressure sensation[Yem and Kajimoto 2017b]. Kuroki et al. verified that mechanical stimulation changed the threshold of an electrical stimulus when simultaneously presenting electrical and mechanical stimulation using pins[Kuroki et al. 2007]. However, these studies did not consider the augmentation of tactile intensity by mechanical stimulation or the masking of the bizarre feeling of electrical stimulation. One example of an entertainment system that uses mechanical and electrical stimulation is PainStation[Reiff and Morawe 2001]. This system generates pain sensations using independently applied electrical and mechanical stimulation, and the two sensations do not affect each other's sensory quality. Lopes et al. combined mechanical stimulation via a solenoid with electrical muscle stimulation (EMS[Kono et al. 2018; Lopes et al. 2017]) to present strong impact and arm motion associated with a touching event in a VR environment[Lopes et al. 2015]. The electrical stimulation targeted muscle tissue in that case, while electrical stimulation was used to stimulate the nerves of Merkel cells which respond to mechanical pressure and Meissner corpuscles which respond to mechanical vibration in our method.

3 EXPERIMENTAL APPARATUS

Figure 2 shows the experimental apparatus[Mizuhara et al. 2019] used in the present study. The device used to present the mechanical stimulation comprised a mechanical tactile device with a design similar to that of a guillotine. This device was combined with an electric stimulation device. The mechanical stimulation device had a 3-mm-thick wooden board (36.5 g) that fell along the grooves of two vertical aluminum frames. Two photo reflectors were attached to one of the frames, and the falling speed of the wooden board was calculated so that the electrical stimulation could be given at a precise time relative to the mechanical stimulation. The wooden board was lowered and raised by a mechanical arm having a stepping motor and servomotor.

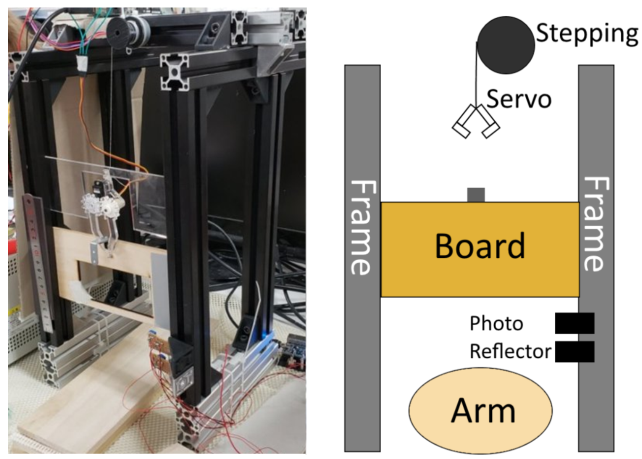

Figure 2: Experimental apparatus.

Figure 3 shows the electric stimulation kit[Kajimoto 2012] used for electrical stimulation. The kit comprised a microcontroller (NXP Semiconductors, mbed NXP LPC 1768), high-speed digital-to-analog converter, and voltage–current conversion circuit (see Figure 4) that controlled the waveform of the stimulation current. We used a piece of conductive gel (having a length of 0.5 cm and width of 3 cm) on a wire as the cathode and another piece of conductive adhesive gel (Nippon Koden Co., Ltd., Dispos electrode F Vitrode) as the anode. Electric current flowed from the anode to cathode.

4 EXPERIMENT

4.1 Experimental Purpose

We recruited participants and conducted an experiment to verify whether enhancement of the subjective intensity of the tactile sense and the masking of the peculiar sensation (hereinafter referred to as the electrical sensation) of electrical stimulation could be achieved simultaneously through simultaneous mechanical and electrical stimulation. The experiment was approved by the ethics committee of the author's institute.

4.2 Experimental Procedure

The experimental setting is shown in Figure 5. Each participant was asked to sit on the chair in front of the experimental apparatus with

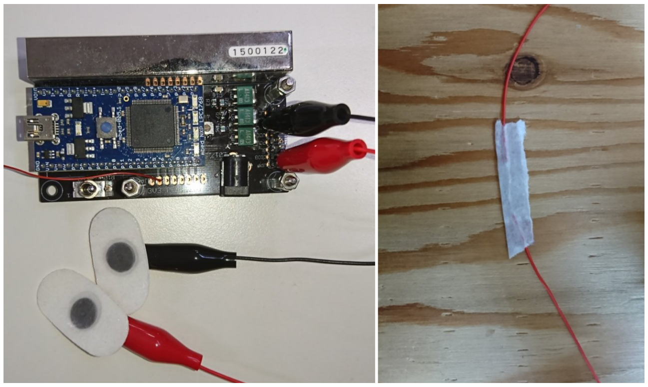

Figure 3: (a) Electrical stimulation kit and (b) electrode (cathode).

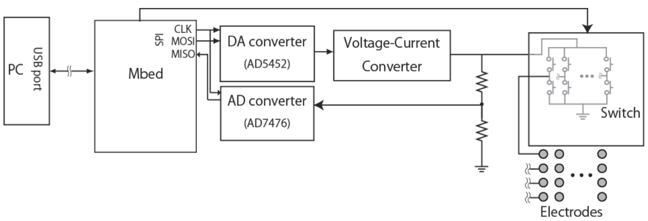

Figure 4: Electrical circuit of the kit.

their right arm on the wooden table and their right palm facing up. The arm was positioned such that the wooden board fell and hit the mid-point between the elbow and wrist. We drew a line on the skin at the position that the wooden board made contact, and then attached a cathode at this location. An anode was placed 5 cm towards the wrist. Electrical and mechanical stimulations were independently presented to the arm.

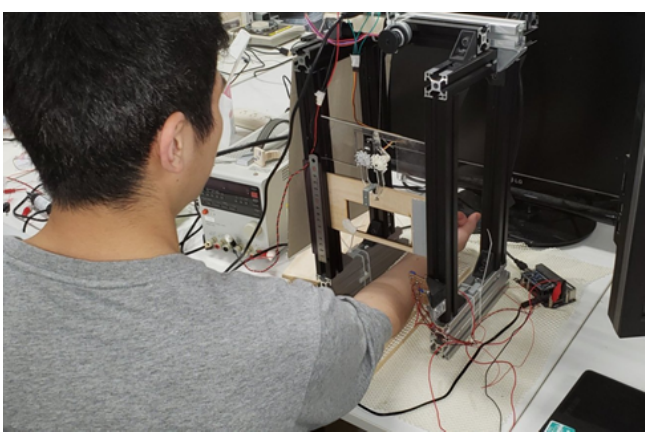

Figure 5: Experimental setting.

A reference stimulus and a comparison stimulus were then presented. Participants reported on

- the subjective strength (impact) of the comparison stimulus, assuming that of the reference stimulus was 10 and
- how strongly they felt the electrical sensation (on a seven-step Likert scale, 1: no electrical stimulation, 7: nothing but electrical stimulation).

The reference stimulus was a mechanical stimulus generated by the wooden board falling from a height of 4 cm. The following four conditions were used for comparison stimuli. Each stimulus was presented once in an order determined using a Latin square.

- Mechanical stimulation by the wooden board falling from a height of 4 cm (identical to the reference stimulation)
- Mechanical stimulation by the wooden board falling from a height of 6 cm
- Electrical stimulation
- Mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation

Electrical stimulation was the presentation of a 500-us square wave once with the same timing as the mechanical stimulation at an intensity of 10 mA. The participants were 12 men aged 21 to 25 years. The parameters of mechanical and electrical stimulation were determined based on the previous study[Mizuhara et al. 2019]. During the experiment, the participants were not able to see or hear the board fall.

5 RESULTS

The experimental results are presented below. Each result was statistically processed adopting a Friedman test and Holm multiple comparison procedure. In the following figures, M4 denotes mechanical stimulation by the wooden board falling from a height of 4 cm, M6 denotes mechanical stimulation by the wooden board falling from a height of 6 cm, E denotes electrical stimulation, and M4 + E denotes mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation. Error bar on each bar indicate its standard deviations.

5.1 Subjective Intensity

Figure 6 shows the subjective intensity under different stimulation conditions. Median values were 10 for M4, 11 for M6, 10 for E, and 12.5 for M4 + E. Statistical analysis reveals a significant difference at the 5% level between the following conditions.

- Mechanical stimulation by the wooden board falling from a height of 4 cm and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.013$)
- Mechanical stimulation by the wooden board falling from a height of 6 cm and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.049$)
- Electrical stimulation and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.031$)

5.2 Electrical Sensation

Figure 7 shows the electrical sensation under different stimulation conditions. The median values were 1 for M4, 1 for M6, 7 for E, and 3.5 for M4 + E. Statistical analysis reveals a significant difference at the 5% level between the following conditions.

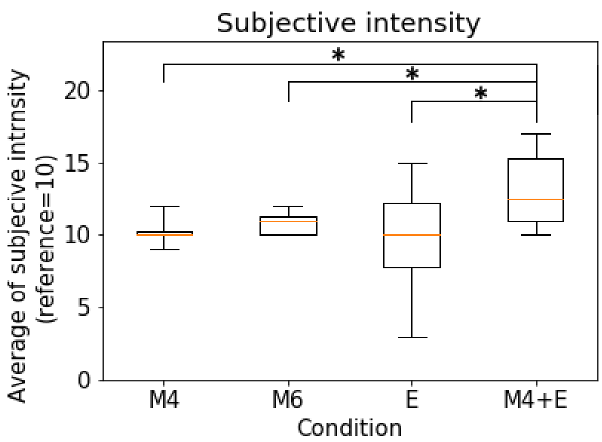

Figure 6: Subjective intensity for different conditions. "*" denotes a significant difference at p < 0.05.

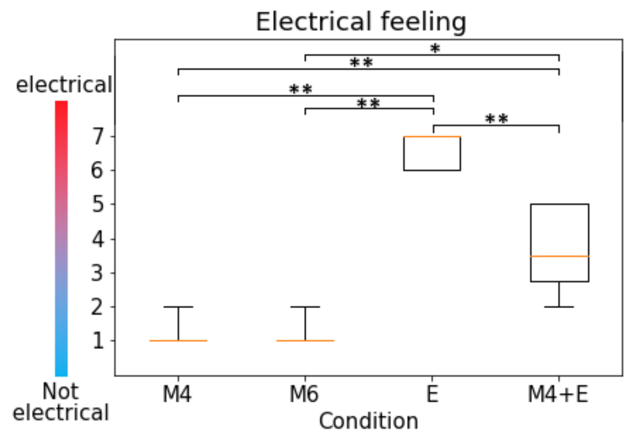

Figure 7: Electrical sensations for different conditions. "*" and "" respectively denote significant differences at p < 0.05 and p < 0.01.**

- Mechanical stimulation by the wooden board falling from a height of 4 cm and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.0092$)
- Mechanical stimulation by the wooden board falling from a height of 4 cm and electrical stimulation ($p = 0.0092$)
- Mechanical stimulation by the wooden board falling from a height of 4 cm and electrical stimulation ($p = 0.0092$)
- Mechanical stimulation by the wooden board falling from a height of 6 cm and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.0070$)
- Electrical stimulation and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.0048$)
- Mechanical stimulation by the wooden board falling from a height of 6 cm and mechanical stimulation by the wooden board falling from a height of 4 cm + electrical stimulation ($p = 0.010$)

6 DISCUSSION

6.1 Subjective Intensity

The subjective intensity of the simultaneous presentation of electrical stimulation and mechanical stimulation due to the wooden board falling from a height of 4 cm was significantly greater than that of each stimulation presented alone. In this case, the subjective intensity increased by 25% on average across participants.

However, some participants reported that the subjective intensity increased by about 70% while others reported that it did not increase at all. Among the 12 participants, only half reported that the subjective strength increased by more than 25% as a result of electrical stimulation. The rate of enhancement of the subjective intensity for these six participants was 55%.

In other words, there is the possibility that there is a group in which the sensation is enhanced by electrical stimulation and a group in which it is not. It is necessary to conduct further experiments on the effectiveness of the combining stimulations after reviewing the method of mechanical stimulation and the parameters of electrical stimulation.

6.2 Electrical Sensation

All participants reported that the electrical sensation of an electrical stimulus with mechanical stimulation due to the wooden board falling from a height of 4 cm was weaker than that of electrical stimulation alone.

The electrical sensation was therefore reduced through mechanical stimulation. However, the electrical sensation of the combined stimulation was significantly stronger than that of the mechanical stimulus alone. Our next step is to reduce the electrical sensation of the combined stimulus to that of mechanical stimulation.

Additionally, it is necessary to investigate how an electrical stimulus with mechanical stimulus is perceived and consequently how the electrical sensation is weakened.

7 CONCLUSION

We demonstrated a haptic presentation method that achieves sufficient naturalness and intensity via the simultaneous application of mechanical and electrical stimulation.

Although the study was successful in terms of reducing the electrical sensation, individual differences in the increase in the subjective strength were large, and further investigation is required to improve the presented method.

We plan to develop a method of presenting strong sensations by combining electrical and mechanical stimuli. Such an approach could be adopted to enhance realism and tension in gaming systems.

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