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Paper:

Influence of Combined Vibration and Electrical Stimulation on Latency of Kinesthetic Illusion

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The application of vibration stimulation to muscles, via the skin surface, can generate the sensation of movement, when actually there is no motion. This phenomenon is called kinesthetic illusion. Recently, in the fields of rehabilitation and virtual-reality technology, research has been conducted to utilize kinesthetic illusions to feel body movements, when there are none. To apply kinesthetic illusions in the above fields, it is necessary to develop techniques to improve the occurrence rates of the kinesthetic illusions and shorten the latency, which is the time lag from the onset of stimulation to the occurrence of the illusion. In a previous study, the authors reported that the occurrence rate of kinesthetic illusion could be improved by simultaneously applying vibration and electrical stimulations to the antagonistic muscles. In this study, the influence of this technique on the latency of the generated kinesthetic illusion is investigated by applying a combination of vibration and electrical stimulations. Three different electrical-stimulation voltages are used in the combined stimulation to induce the kinesthetic illusion, and the latency is studied for each voltage condition and the vibration-only condition. The effects of the voltage change on latency are evaluated from a regression analysis performed using the generalized linear mixed model. The results suggest that the change in the electrical stimulation voltage can shorten the latency of kinesthetic illusion.

Keywords: vibration stimulation, electrical stimulation, kinesthetic illusion, latency

1. Introduction

Humans generate articular movement based on various sensory feedbacks from sight, hearing, somatic senses, etc. [1]. A receptor known as the muscle spindles in the muscles is regarded as one of the sources of the sensory feedback that generates kinesthesia [1]. As a muscle is stretched during movement, the muscle spindle in the muscle is also stretched. This transformation causes the firing of the muscle spindle, which transmits the afferent input to the central nervous system. This afferent input contributes to the generation of human kinesthesia. The muscle spindle is fired not only by the stretching of the muscle during human movement but also by external mechanical vibration stimulations via the skin [2]. When the afferent input induced by vibration is transmitted to the central nervous system, an illusion of body movement is generated, although there is no actual movement. This type of illusion is termed vibration-induced kinesthetic illusion. Vibration stimulation generates the afferent input via the primary endings of Ia afferents in the muscle spindle. Because the primary endings respond to the speed of stretch of the muscle [1], the brain recognizes the kinesthetic illusion as an illusion of the speed of stretch of the muscle, i.e., the angular velocity of the joint. Previous studies in the field of neurophysiology clarified that when applying vibration stimulation to the antagonist muscle to produce a kinesthetic illusion in articular movement, the illusion is induced as if the antagonist muscle is stretched; moreover, the kinesthetic illusion is the illusion of the angular velocity of the joint. It has been clarified that the kinesthetic illusion is induced in the elbow joint, wrist joint, and ankle joint [3–6].

In the early studies in the field of neurophysiology, studies on kinesthetic illusion were conducted as basic studies in the field of human kinesthesia. On the other hand, recent studies have been conducted to apply kinesthetic illusions in various fields. For example, in the field of rehabilitation, studies have been conducted to restore motor and sensory functions in paralyzed patients [7–9]. In the field of virtual reality, studies have been conducted to share the movement of the avatar with the user or make the user feel the illusion as if the user moved with a hang-glider which is shown in the head-mounted display [10–12]. However, some problems must be solved before the illusion can be used in rehabilitation and virtual-reality technology.

The main problems include individual differences in terms of experiencing the kinesthetic illusion and latency, which is defined as the time lag between the onset of stimulation and the occurrence of illusion. First, we will explain the problem of individual differences in experiencing the kinesthetic illusion. Even if the magnitude of the stimulus, such as the frequency and amplitude, is set as the same when applying vibration stimulation to different human subjects, some may experience the illusion easily while others experience it with difficulty. This is the individual difference in terms of kinesthetic illusion. Previous studies in the field of neurophysiology have reported that the perceived sensation of illusion could be adjusted by changing the frequency of the vibration stimulation [3, 4, 13]. According to Roll et al. and Naito et al., the perceived sensation of illusion was the largest when the frequency of vibration stimulation was 70 Hz in some parts of the body [3, 13]. However, even if the frequency of vibration stimulation was set as 70 Hz, in some cases, the perceived sensation of illusion was less for those who experienced the kinesthetic illusion with difficulty. To use kinesthetic illusions in rehabilitation and virtual-reality technology, in addition to the adjustment of vibration-stimulation frequency, it is necessary to make the illusion more intense for those who feel it with difficulty. Recently, more attention has been paid to methods that increase the perceived sensation of illusion by providing other sensory inputs in addition to vibration stimulation to human test subjects. According to Collins et al. and Shehata et al., the perceived sensation of illusion can be increased by applying tension to the skin in addition to vibration stimulation [14, 15]. When humans move their bodies, skin tension, which induces tactile feedback, is generated by the body movements. In their methods, tactile feedback caused by skin tension is combined with vibration stimulation to reproduce the state of sensory feedbacks when humans move their bodies. As a result, the perceived sensation of the kinesthetic illusion is improved. On the other hand, Franc et al. reported that the perceived sensation of kinesthetic illusion could be increased by providing visual feedback from the head-mounted display to enable the user to recognize the image of body movement [12]. The methods proposed by Shehata et al., Collins et al., and Franc et al., aimed to increase the perceived sensation of vibration-induced kinesthetic illusion by simultaneously providing sensory inputs, such as tactile sensation and visual feedback, that accompany the sensation of movement when the human body moves.

Based on the abovementioned studies, the authors proposed a method in their previous work to increase the perceived sensation of illusion. Humans use both the agonist and antagonist muscles during actual movement. During the movement, the agonist muscle is contracted, and the antagonist muscle is stretched. If the sensory feedback from the contraction of the agonist muscle and the extension of the antagonist muscle can be reproduced, it may be possible to improve the kinesthetic illusion. In the authors' proposed method, the authors tried to increase the perceived sensation of the kinesthetic illusion by stimulating both agonist and antagonist muscles [16]. As mentioned above, applying vibration stimulation to muscles provides humans with the feeling of stretching the stimulated muscle. In the proposed method, the application of vibration stimulation to the antagonist muscle induces the feeling of stretching the antagonist muscle. Moreover, by applying electrical stimulation to the agonist muscle via an electrode pasted on the skin, the motor nerve of the muscle is fired, which causes isometric contraction of agonist muscle. This electrical stimulation is like that used in studies of functional electrical stimulation [17, 18]. The isometric muscle contraction generates the sensation of contraction of the agonist muscle. A combination of the sensation of muscle stretching caused by vibration stimulation and muscle contraction caused by electrical stimulation can simulate a sensory state close to that of the sensory inputs from the antagonist muscle and agonist muscle during the movement, increasing the perceived sensation of kinesthetic illusion. In the authors' previous study, the results indicated that the occurrence rate of kinesthetic illusion was improved for the experimental participants who had difficulty experiencing the illusions induced by vibration stimulation alone [16].

Another problem to be solved for the proper application of the kinesthetic illusion is its latency. The latency of kinesthetic illusion is defined as the time lag from the onset of stimulation to the occurrence of the illusion. When only vibration stimulation is provided to the participants, even if the frequency is adjusted to 70 Hz, a latency of a few seconds remains [13, 19]. To the best of the authors' knowledge, no previous study has focused on the effect of multisensory stimulation on the latency of illusion. In studies on visually induced illusory self-motion, which is not induced by vibration stimulation but caused by visual input, the latency is shortened when wind is blown upon human skin while the image is being presented as visual information to create the sensation of movement [20, 21]. However, according to the results of a preliminary experiment conducted by the authors, wherein a vibration-induced kinesthetic illusion was induced by the combination of vibration and electrical stimulations, some participants lost the direction of the kinesthetic illusion. The results of these studies suggest that it is unclear whether electrical stimulation in addition to vibratory stimulation lengthens or shortens the latency of the illusion. Therefore, it is necessary to investigate how the latency of the illusion is affected by electrical stimulation in addition to vibration stimulation.

This study aims to evaluate the effects on latency when a kinesthetic illusion is induced by providing combined electrical and vibration stimulations, as the authors proposed in their previous study. In the previous study, the statistical significance of increasing the voltage of electrical stimulation in improving the occurrence rate of kinesthetic illusions was recognized. In this study, the effects on latency are evaluated by applying electrical stimulation in three stages to each participant while providing vibration stimulation simultaneously. The latency under the condition of vibration-only stimulation (wherein only vibration at a frequency of 70 Hz, which is considered to induce the shortest latency, is applied) is also studied for comparison with the case of the proposed combined stimulation.

2. Experimental Setup

2.1. Psychophysical Experiment

In this study, a kinesthetic illusion is induced in the dorsiflexion of the wrist joint of the participants. Dorsiflexion of the wrist joint is selected because the rehabilitation of wrist-joint movement is conducted for upper-limb-paralyzed patients and because the movement of each upper-limb joint is utilized in virtual-reality technology.

The verification of the induction of kinesthetic illusion and the measurement of latency are performed through psychophysical experiments. In the previous studies on kinesthetic illusion based on psychophysical experiments, the illusion of articular movement was triggered on one side of the body, while the perceived sensation of illusion the subject experienced was reproduced on the other side of the body. For example, the perceived sensation of illusion was evaluated using a method wherein a kinesthetic illusion was induced in the elbow joint on one side of the body of the participant, while the perceived kinesthetic illusion was reproduced in the elbow joint on the other side of the body [2, 22, 23]. Similarly, in this study, a psychophysical experiment is adopted to evaluate the latency of the kinesthetic illusion. Namely, a kinesthetic illusion is induced in the wrist joint of the right hand of the participants, and they are asked to reproduce the perceived kinesthetic illusion in the wrist joint of the left hand. The vision and hearing of the participants are blocked using sleeping masks and headphones, respectively, so that they can evaluate the illusion based on the kinesthesia of the wrist joint of the right hand alone.

Hereafter in this study, the right arm is termed the "vibrated arm," and the left arm, the "reference arm."

2.2. Measuring Device for Illusory Movement

Figure 1(A) shows a complete view of the experimental device used in this study. The participant sits on a chair in front of the experimental device, lays both hands on the experimental device and grips the handles of the experimental device lightly with both hands. As shown in **Fig. 1(C)**, the handles are connected to the encoder for measuring the angle of the wrist joint, and the rotation shaft. This wrist joint angle measuring device consisting of the handle and the encoder is termed the goniometer. The position of the forearm is adjusted such that the stylion ulnare, which is located near the center of rotation of the wrist joint, and the center of rotation of the goniometer match. As shown in **Fig. 1(C)**, a slider is set beneath the handle. After adjusting the center of rotation of the wrist joint, the position of the handle is adjusted using the slider to match the hand size of the participant. The handle of the goniometer rotates smoothly in the directions of dorsiflexion and flexion of the wrist joint. As mentioned in the previous section, the experimental participants are instructed to reproduce the perceived kinesthetic illusion through the articular movement of the reference arm after applying simultaneous vibration and electrical stimulations to the vibrated arm. The angular resolution of the encoder of the goniometer (E6B2-CWZ6C, 1000P/R, OMURON Co. Ltd.) is 0.36°. The pulse signal from the encoder is transmitted to the microcontroller (Arduino Due, Arduino). After converting the pulse signal into the corresponding angle, it is transmitted to the PC and recorded. In **Fig. 1**, the angle of the wrist joint of the participant is the initial condition of 0°. In this study, during measurement, the direction of dorsiflexion of the wrist joint is considered as the negative direction, and the direction of flexion is considered as the positive direction, during measurement.

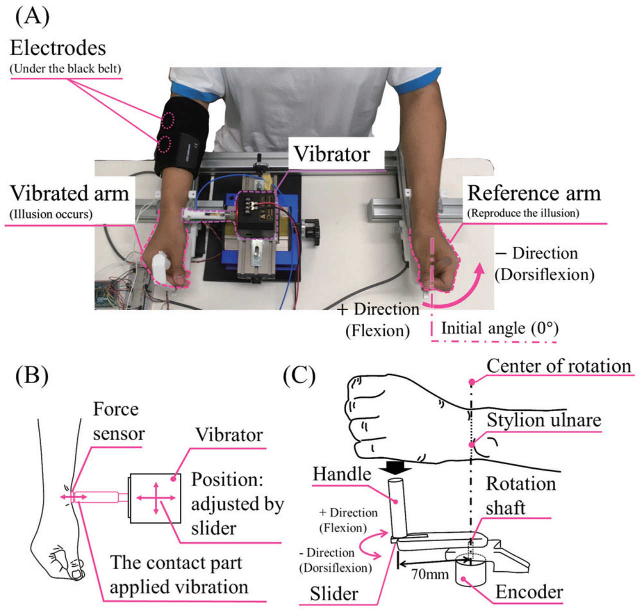


Fig. 1. Complete view of the experimental device. (A) Vibrator and device for electrical stimulation are attached to the forearm of the vibrated arm of the participant (left side of the picture). The participant reproduces the illusion perceived in the vibrated arm using the wrist joint of the reference arm (right side of the picture). (B) Enlarged drawing of the vibrator. The contact part applies the vibration. A force sensor is built into the tip of the contact part to measure the initial contact force. (C) The mechanism for measuring the angle of the wrist joint of the reference arm.

2.3. Vibration Stimulation

As shown in **Fig. 1(A)**, vibration stimulation is applied to the vibrated arm of the participant, using a commercial vibrator, Wavemaker 01 (Asahi Factory). The vibrator provides vibration stimulation at the set frequency to the vibrated arm of the participant using the feedforward control. The start signal of the vibration stimulation is transmitted from the PC, by an operator, to the microcontroller, and the start-of-stimulation command is transmitted from the microcontroller to the vibrator. To ensure that the vibration and electrical stimulations are applied simultaneously, the vibration stimulation is provided in sync with the start of the electrical stimulation.

As mentioned in Section 1, a kinesthetic illusion is induced by applying the vibration stimulation to the antagonist muscle, for an angular movement. In this study, wherein dorsiflexion of the wrist joint is induced as the kinesthetic illusion, the flexor carpi radialis, musculus palmaris longus, and flexor carpi ulnaris are considered as antagonist muscles. The tendons of these muscles are concentrated between the palm and forearm and around the rotating part of the wrist joint. For this reason, to induce the kinesthetic illusion of dorsiflexion of the wrist joint, vibration stimulation must be applied between the palm and forearm, and each muscle must be stimulated via the tendon of the muscle. In this study, the vibrator is arranged in the position shown in **Fig. 1(A)**. The position of the tendon is determined by palpating the examination participant, to contact the contact part of the vibrator.

In this study, vibration stimulation is applied at a frequency of 70 Hz. The frequency is determined according to the previous study where the latency was the shortest for a vibration-stimulation frequency of 70–80 Hz in other body parts [13]. As for the amplitude, in the previous studies on kinesthetic illusion, although the body parts to be stimulated were different from those in this study, the kinesthetic illusion was induced under amplitudes of 0.25 mm [24, 25], 0.5 mm [26], and 0.2–3 mm [13]. The vibrator, used in this study, cannot control the amplitude while touching the participant's skin and applying the stimulation. At a frequency of 70 Hz, the amplitude was measured at the free end of the vibrator's contact part without skin contact, employing a laser range finder (CD33-250NV, OPTEX FA Co. Ltd.). The recorded amplitude was approximately 1 mm. In a preliminary experiment, when vibration stimulation at the same frequency was applied to the participant, a kinesthetic illusion was induced. Therefore, the main experiment was conducted assuming the amplitude (under the condition of free end) as 1 mm and the frequency of the vibrator as 70 Hz. As shown in **Fig. 1(B)**, the contact force is varied by moving the position of the vibrator using the slider attached under the main part of the vibrator. Previous studies show that the initial contact force ranges from 0.5 N [24] to 3 N [26]. In this study, when the initial contact force was strengthened gradually, a participant experienced pain at 3 N. For this reason, the initial contact was set to range from 1 to 2 N. The experiment was conducted after measuring the initial contact force using the force sensor shown in **Fig. 1(B)** and confirming that the applied initial contact force ranges from 1 to 2 N.

2.4. Electrical Stimulation

Electrical stimulation is applied only under the experiment condition that the vibration and electrical stimulations are applied simultaneously. **Fig. 2** shows the waveform used in the electrical stimulation. A positive and negative bipolar rectangular wave is provided as the electrical stimulation. In a previous study, the authors clarified that the strength of muscle contraction could be changed by changing the voltage of the waveform [18]. **Fig. 3** shows the connection diagram of the electrical stimulation device. The waveform is generated by the microcontroller and transmitted to the amplifier (L298N motor driver control board, ACEIRMC). Then, electrical stimulation is applied from the amplifier to the muscle of the participant via an electrode (ELR-612, OG Wellness Technologies Co. Ltd.). The power-supply device (AD-8724D, A&D Co. Ltd.), which supplies the power to the amplifier, is earthed as shown in **Fig. 3** to prevent any electric shock to the participants or experimenters. In the method using the combined electrical and vibration stimulations, proposed by the authors in the previous study, electrical stimulation is applied to the agonist muscle for the inducing an illusion of articular movement [16]. Extensor carpi ulnaris is an agonist muscle involved in the dorsiflexion of the wrist joint. In this study, the location of extensor carpi ulnaris is determined by palpation, and the electrode is pasted on the location to apply the electrical stimulation.

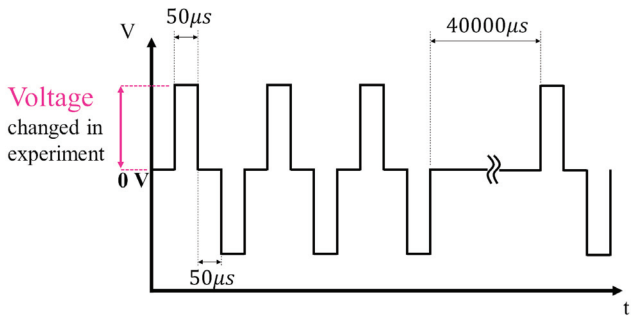


Fig. 2. Bipolar rectangular wave applied as electrical stimulation. In this study, the amount of electrical stimulation is changed by changing the voltage of the rectangular wave.

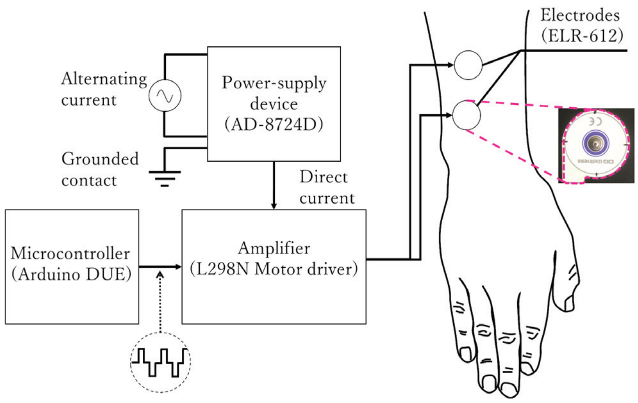


Fig. 3. Connection diagram of the electrical stimulation device.

In this study, the electrical stimulation is changed by changing the voltage in three stages: low, middle, and high. The value of voltage is determined in the preliminary examinations for each participant. In the preliminary experiment, the experimental participants were instructed not to apply force to the agonist muscle for the dorsiflexion of the wrist joint, and electrical stimulation was applied to extensor carpi ulnaris using the electrode, amplifier, and microcontroller. The voltage was increased gradually by applying the electric stimulation, and the value when the wrist joint of the participant began the dorsi-

Table 1. Values of voltage for each participant.

ID	Low voltage (V)	Middle voltage (V)	High voltage (V)
1	8	11	14
2	5	8	11
3	7	10	13
4	8	11	14
5	8	11	14
6	5	8	11
7	16	19	22
8	7	10	13
9	10	13	16
10	8	11	14

flexion was set as the middle voltage. When the electrical stimulation increased to 3 V above the middle-voltage condition, dorsiflexion was induced continuously in all participants. Accordingly, a voltage 3 V higher than the middle voltage was set as the high voltage, and a voltage 3 V lower than the middle voltage was set as the low voltage. The values of low, middle, and high voltage for all experimental participants are listed in **Table 1**. It was confirmed that the electrical stimulation would not cause pain to the muscle, under any voltage condition, in any experimental participant.

The preliminary experiment was conducted so the wrist joint could move freely, to confirm the voltage value at which the dorsiflexion would start. However, in the main experiment, to avoid confusing the kinesthesia caused by the movement of the wrist joint with the movement recognized by the illusion, the wrist joint of the vibrated arm was fixed and immovable.

Before both the preliminary experiment and the main one, the participants were informed that they could ask to stop the experiment if they experienced pain during the application of the electrical stimulation to the muscle.

2.5. Participants

Ten participants – seven male and three female – participated in the main experiment. The average age and standard deviation of the participants were 23 years and ± 3.2 years, respectively. None of the participants had previously experienced the kinesthetic illusion of wrist-joint dorsiflexion presented in this experiment. Neither did they have any anamnestic history causing obstacles to the movement of the wrist joint. Before the commencement of the experiment, the method of application of electrical and vibration stimulations used in the experiment was introduced and the safety measures were explained. Only the participants who received the explanation and signed the consent form participated in the experiment. The experiment was conducted according to the procedures recognized by the ethics committee of the School of Engineering, Kyushu University (Approved no. 2021-02).

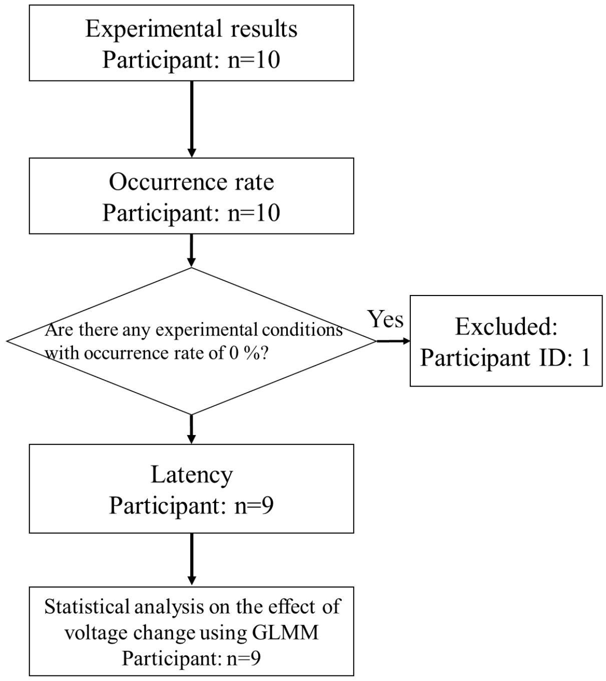


Fig. 4. Flowchart of analysis of the results of this experiment.

2.6. Trials Under Each Experimental Condition

The experiment was conducted under four conditions. In three cases, a combined stimulation of electrical and vibration stimulations was applied, where the low voltage, middle voltage, and high voltage determined in the preliminary experiment were applied. In the fourth case, only vibration stimulation was applied to the participants to research the latency under the vibration-only condition. As mentioned above, the frequency of the vibration stimulation was set to 70 Hz.

Three trials were performed under each experiment condition, and the latency from the application of the stimulation to the commencement of the occurrence of kinesthetic illusion was measured. The number of trials was determined with reference to the previous studies on kinesthetic illusions induced by vibration [2, 5, 13]. The application time of the stimulation was set as 5 s for both electrical and vibration stimulations.

3. Results

3.1. Flowchart of Data Analysis

Figure 4 shows the analysis procedures for the experiment results. The experiment was conducted on all participants under all experimental conditions. Three trials were conducted under each experiment condition. In the authors' previous study, when the frequency of vibration stimulation was set to 20 Hz, the change in the voltage of the combined electrical and vibration stimulation was confirmed to improve the occurrence rate of the illusion [16]. However, under the frequency of 70 Hz (the value in the experiments conducted in this work), it was unclear whether the change in voltage of the combined stimulation would improve the occurrence rate of the illusion. Therefore, first, we attempt to confirm, from the experiment results, how the occurrence rate of the illusion would change when vibration stimulation at a frequency of 70 Hz is applied. Next, the latency of the illusion is evaluated. In this experiment, to research the effects of the change in the voltage of the combined stimulation on the latency of the illusion, the latency is evaluated for the participants who experience at least one occasion of illusion in three trails for each of four experimental conditions. As mentioned below, because no illusion is induced in Participant 1 under the low-voltage condition, the evaluation is made on nine participants. Finally, to analyze the effects of the change in voltage on the latency of illusion, a regression analysis is conducted using a statistical model, the generalized linear mixed model (GLMM).

3.2. Occurrence Rate of Each Condition

The occurrence rate of a kinesthetic illusion expresses the value in percentage of how many times an illusion occurs in three trials, each under four experimental conditions. First, the following method distinguishes between whether the illusion occurs or not. If the dorsiflexion of the wrist joint of the reference arm occurs, the illusion of dorsiflexion of the wrist joint of the vibrated arm is judged to have been induced. If flexion of the wrist joint of the reference arm occurs, the illusion is judged to not have been induced because it is different from the expected direction of illusion from the stimulated muscle. Furthermore, if the dorsiflexion of the wrist joint of the reference arm is induced once, but it then turns to flexion and the movement stops at the angle of the flexion side instead of at the initial angle of 0°, the illusion is judged not to have been generated.

Based on the above criteria, we judge whether the illusion occurs in each trial under each experiment condition. The occurrence rate of the illusion is determined depending on how many times the illusion occurs in three trials. The occurrence rate of the illusion of each experiment under each experiment condition is shown in **Fig. 5**. First, under the condition of vibration-only, it is assumed in the previous studies on kinesthetic illusion that the strongest illusion is induced under 70 Hz. However, in this study, the illusion occurs only once in three trials (33%) for two participants of 10. On the other hand, in the combined stimulation, under the high-voltage condition, the occurrence rate of illusion is 100%, even for the participants in whom no illusion occurred under the condition of vibration-only. Contrarily, under the low-voltage and middle-voltage conditions, cases have been confirmed where the occurrence rate of illusion reduces, even for the participants with 100% occurrence rate under the condition of vibration-only. From the viewpoint of improvement of the occurrence rate of the illusion, the above results indicate that a relatively high voltage is desirable. The occurrence rate of illusion for the participant: Participant 1 is 0% under the low-voltage condition.

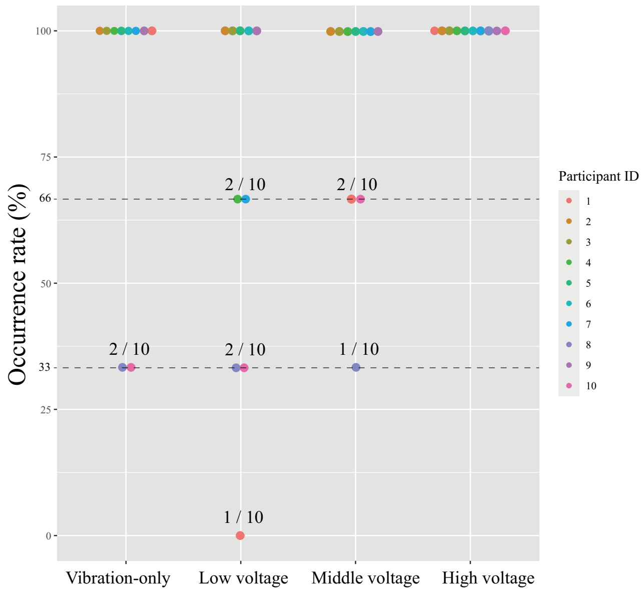


Fig. 5. Bee-swarm plot of occurrence rate of illusion. Occurrence rate for each participant under each condition of stimulation is plotted. Because there are multiple participants with the same occurrence rate, the plots are drawn in the horizontal direction. The figures above the plot indicates how many participants out of 10 exist at the concerned occurrence rate.

As mentioned above, only the test participants for whom the illusion occurs at least once under all of the four experimental conditions are eligible for consideration in the analysis of the latency of illusion. For this reason, Participant 1 was excluded from the analysis of latency.

3.3. Latency in Each Condition

The latency of the kinesthetic illusion is the time lag from the onset of vibration and electrical stimulations to the occurrence of illusion. As mentioned in Section 1, the kinesthetic illusion is the illusion of the angular velocity of the joint. Accordingly, in this study that focuses on the angular velocity of the reference arm as the criterion for the end of the latency, the time when the angular velocity of the wrist joint takes a negative value, and continuous dorsiflexion of the wrist joint of the reference arm starts to be generated (**Fig. 6**), is judged as the end of the latency.

Even under the same experiment conditions and for the same participant, variance is confirmed between the case of relatively long latency and that of relatively short latency, among the three trials. In this study, the longest latency among three trials is regarded as the representative value under a specific experiment condition. The effect of combined stimulation on latency was analyzed using the longest latency. Such an analysis is adopted because, in applying the kinesthetic illusion to the fields of rehabilitation and virtual reality, a longer latency would cause inconvenience and discomfort to a user. Therefore, the optimal condition of stimulation to shorten the longest latency as much as possible should be identified. In case the

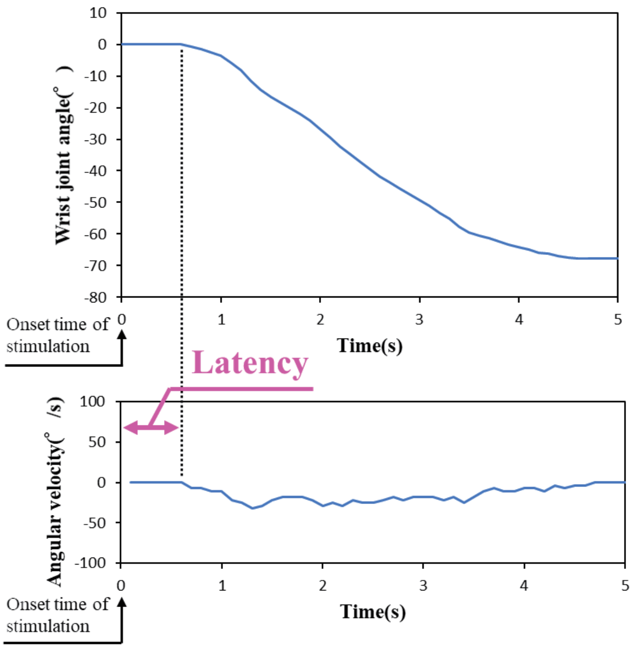
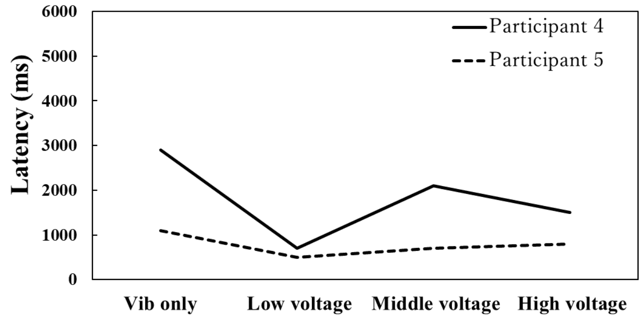


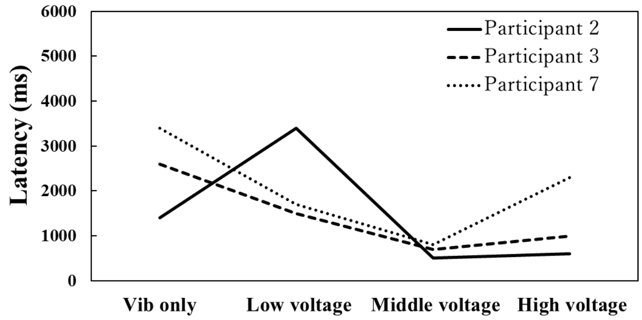
Fig. 6. Latency measured based on angular velocity of wrist joint of reference arm (results of Participant 2 under high-voltage condition).

illusion occurred once in three trials of a specific experiment condition, the latency of the trial was regarded as a representative value of the experimental condition. The longest latency under the experiment condition is termed "latency," hereafter. **Fig. 7** shows the latency of each participant under each experiment condition. In all participants, there are experiment conditions of combined stimulation in which the latency is shorter than that under the condition of vibration-only. For example, in **Fig. 7(a)**, the latency of Participant 4 under the low-voltage condition is the shortest, and the latencies under the middle-voltage and high-voltage conditions are shorter than that under the condition of vibration-only. On the other hand, for some participants, under a particular condition of combined stimulation, the latency is longer than that in the case of the vibration-only condition. For example, for Participant 2, in **Fig. 7(b)**, the latencies are shorter under the middle-voltage and high-voltage conditions than that under vibration-only condition, but the latency under the low-voltage condition is longer than that under the vibration-only condition. These results suggest that the combined stimulation of electrical and vibration stimulations may shorten the latency compared to vibration stimulation alone, but there are individual differences in which voltage conditions shorten the latency.

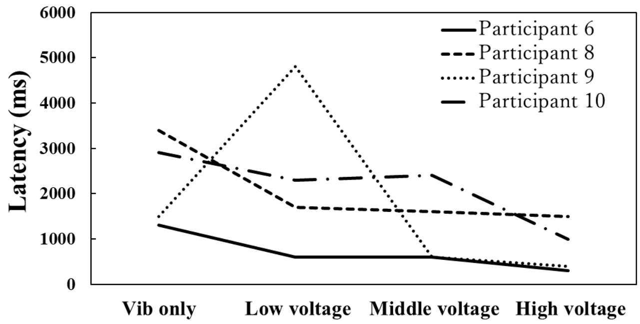
Figure 8 shows the latency distribution for all participants under each experiment condition. The symbol × indicates the mean latency for all the participants. Although the variance depending on the individuals can be recognized in the latency under each experiment condition, the mean latency of nine participants tends to shorten as the voltage value of the combined electrical and vibration stimulation increases. For such experimental result,



(a) Participants for whom latency is the shortest under low-voltage condition



(b) Participants for whom latency is the shortest under middle-voltage condition



(c) Participants for whom latency is the shortest under high-voltage condition

Fig. 7. Longest latency under each experiment condition.

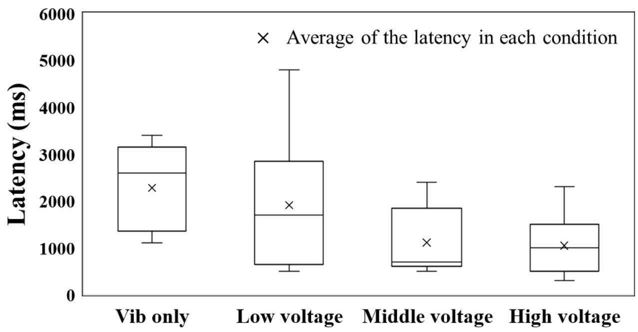


Fig. 8. Box plot of latency under each experiment condition.

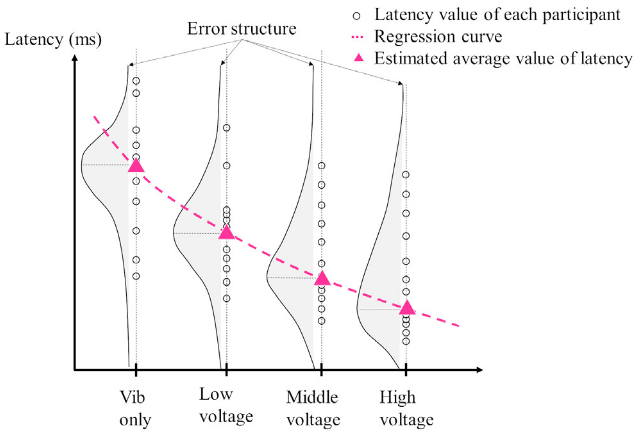


Fig. 9. Regression curve for mean value of latency under each experiment condition using the GLMM.

the GLMM can be used to statistically analyze how the explanatory variable (voltage condition) affects the variation of the response variable (latency), including the individual variance of latency. In the next section, the analysis on the effects of the voltage variation on the latency is explained using GLMM.

3.4. Statistical Analysis Using GLMM

3.4.1. GLMM of Latency and Voltage Change

As shown in **Fig. 8**, the latency of the kinesthetic illusion has a variance that depends on the individual differences of each participant, even under the same experiment condition. On the other hand, the mean of latency of each experiment condition tends to be shortened with the increase of voltage of electrical stimulation. GLMM is a method for analyzing changes in mean values in experimental data that include variation due to individual differences. In recent years, GLMM has been utilized in ecology and experimental psychology to assess the impact of manipulated variables on data, including accounting for variance due to individual differences [27–29]. To analyze the data of latency, the GLMM is used to evaluate the influences of the voltage change on the latency.

The conceptual diagram of the regression analysis using GLMM is shown in **Fig. 9**. The dotted line indicates the regression curve drawn by the regression analysis using GLMM. This curve passes through the expected values (▲) of the latency of the illusion under each experiment condition. If the curve is decreasing, the tendency is for the latency to be shortened with the increase in voltage. In GLMM, it is assumed that the latency contains the variance under a certain experiment condition in addition to the variance due to the individual differences.

First, for simplification, the generalized linear model (GLM), which does not consider the variance due to individual differences, is explained. In GLM, it is necessary to select the error structure, linear predictor, and link function according to the characteristics of the experimental data. In this experiment, the error structure is the probability distribution based on the latency under each experiment condition. Generally, the error structure is selected from among many types of probability distributions, such as the normal distribution, Poisson distribution, and gamma distribution, based on criteria such as whether the experimental data take continuous values or discrete ones, only the value of 0 or more, or both positive and negative values. In this study, the latency always takes the value of 0 or more and continuous ones. Because the variance of such data can be shown using the gamma distribution, and assuming that the experiment results of latency under each experiment condition would be distributed according to the gamma distribution, the gamma distribution is selected for the error structure. The gamma distribution is shown in the following equation:

$$p(y_i|s,r) = \frac{r^s}{\Gamma(s)} y_i^{s-1} \exp(-r y_i) \quad \quad (1)$$

where s is termed the shape parameter and r is the rate parameter. In the gamma distribution, the mean value is s/r and the variance is s/r^2. Furthermore, y_i indicates the value of latency under the experiment condition of i.

The mean latency, μ_i, under the experimental condition of i is expressed by the monotonically increasing function of the dummy variable of the voltage condition, d_i, as follows.

$$\mu_i = A d_i^{\beta} \quad \quad (2)$$

A on the right side is replaced by $\exp \alpha$ and the right side is arranged using the exponential function, as follows.

$$\mu_i = \exp(\alpha + \beta \log d_i) \quad \quad (3)$$

If the error structure follows the gamma distribution, the logarithmic link function is used as the link function in many cases; therefore, the logarithm is taken on both sides.

$$\log \mu_i = \alpha + \beta \log d_i \quad \quad (4)$$

As shown in the above equation, GLM with the error structure of a gamma distribution is a model where the linear predictor is $\alpha + \beta \log d_i$, and using the logarithmic link function, the mean latency μ_i as the response variable is predicted by the dummy variable of the voltage condition d_i as the explanatory variable. In this experiment, the electrical stimulation is changed in three stages. In the model equation (Eq. (4)), the explanatory variable d_i can be rewritten such that the categories of low-voltage, middle-voltage, and high-voltage are expressed by each dummy variable as follows.

$$\begin{aligned} \log \mu_i = {} & \alpha + \beta_{low} \log d_{low} + \beta_{middle} \log d_{middle} \\ & + \beta_{high} \log d_{high} \end{aligned} \quad \quad (5)$$

where the dummy variables d_{low}, d_{middle}, and d_{high} follow the following conditional expressions.

$$d_{low} = \begin{cases} 1 & \text{(under the low-voltage condition)} \\ 0 & \text{(under the conditions other than low-voltage)} \end{cases} \quad \quad (6)$$

$$d_{middle} = \begin{cases} 1 & \text{(under the middle-voltage condition)} \\ 0 & \text{(under the conditions other than middle-voltage)} \end{cases} \quad (7)$$

$$d_{high} = \begin{cases} 1 & \text{(under the high-voltage condition)} \\ 0 & \text{(under the conditions other than high-voltage)} \end{cases} \quad (8)$$

In the GLMM, by adding the variance due to the individual differences to the right side of the model equation (Eq. (5)), the variance of the data caused by the individual differences of the participants is also added to the prediction of the mean value. The model equation (Eq. (5)) is converted into GLMM as follows.

$$\log \mu_i = \alpha + \beta_{low} \log d_{low} + \beta_{middle} \log d_{middle} + \beta_{high} \log d_{high} + \varepsilon_i \quad \ldots\ldots\ldots (9)$$

where ε_i that expresses the variance of the data due to the individual differences is generally assumed to follow a normal distribution, as shown below.

$$p(\varepsilon_i|\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(\frac{-\varepsilon_i^2}{2\sigma^2}\right) \quad \ldots\ldots (10)$$

where the individual differences are supposed to follow the normal distribution with the mean value of 0 and dispersion of σ^2. the model equation (Eq. (9)) expresses GLMM which is used in this study. In the next section, the coefficients of α, β_{low}, β_{middle}, and β_{high} are estimated using the statistical software R (Ver.4.1.2) and the influences of the condition of voltage on the latency are reviewed based on the sign of the coefficient.

3.4.2. Estimated Parameters of GLMM

The analysis is conducted using the statistical software R (Ver.4.1.2). Using glmer, the function to estimate the GLMM, which can be used with Ime4 package of R, each coefficient of the model is estimated by means of the maximum likelihood estimation. The results of estimation of each coefficient are shown in **Table 2**.

As shown in **Table 2**, all the coefficients of the dummy variables in terms of the voltage condition, β_{low}, β_{middle}, and β_{high}, take the negative sign. Paying attention to the values of the parameters, the values increase in the negative direction in the order of low-, middle-, and high-voltage. Considering Eq. (9), if the change in the voltage condition increases the latency, these parameters should increase in the positive direction. As a result of the regression analysis, which shows that the parameters increase in the negative direction in the order of low-voltage, middle-voltage, and high-voltage, it can be assumed that the mean latency decreases in the transition from the low-voltage condition to the high-voltage condition.

Therefore, as a result of the analysis, in the case that the combined stimulation is applied to the participants, the tendency is for the latency to be shortened.

Table 2. Values of each parameter of GLMM.

α	β_{low}	β_{middle}	β_{high}
7.73	−0.176	−0.718	−0.780

4. Discussion

First, for the participants in this study, when only the vibration stimulation was applied to the vibrated arm, the latency did not deviate significantly from the latency in the previous studies. The mean latency of the nine participants in this study was 2,278±889 ms. In the previous studies, in which vibration stimulation was applied to the biceps brachii, the latency was reported to be approximately 4 s when vision was completely blocked [19, 30]. Naito et al. reported that the latency was less than 10 s when vibration stimulation at 70–80 Hz was applied to the biceps brachii [13]. Compared to the latency in the previous studies, although the group of participants in this study showed relatively short latency under the vibration-only condition, no participant showed a significant deviation in latency from that indicated in the previous studies.

Next, the relation between the occurrence rate of illusion and latency is considered. As mentioned in Section 3.2, all the participants experienced the illusion under the high-voltage condition. On the other hand, at low and middle voltages, for some participants, the occurrence rate of illusion was lower than that under the vibration-only condition (**Fig. 5**). Accordingly, from the viewpoint of increasing the occurrence rate of illusion, it is desirable to apply electrical stimulation under the high-voltage condition. Contrarily, from the viewpoint of reducing the latency of illusion, the regression analysis using GLMM indicates the tendency wherein the mean latency of illusion is reduced with the increase in voltage. However, as shown in Section 3.3 and **Fig. 7**, the voltage at which the longest latency (in three trials) becomes the shortest, varies according to the individual participant. It cannot be asserted that the application of high voltage would always lead to the shortest latency of illusion. Therefore, when applying kinesthetic illusions to rehabilitation and virtual reality, the objective – whether the occurrence rate of illusion should be increased or the latency of illusion should be reduced – must be decided first. If the objective is for the latency of the illusion to be reduced, the voltage has to be determined for each participant.

Furthermore, in this study, all experiments were conducted with 70 Hz vibration stimulation. However, when varying the intensity of the kinesthetic illusion, vibration stimulation is applied by modifying the frequency. The case wherein the frequency and voltage condition are varied simultaneously must be experimented upon and analyzed in detail to learn whether interactions between the effect of frequency change and that of voltage change on the latency would occur or not.

5. Conclusion

The effects of applying a combined stimulation of electrical and vibration stimulations on the latency of the kinesthetic illusion were studied in this work. The effects of the voltage conditions on the latency of illusion were evaluated by applying three different voltages for each participant, measuring the latency of illusion under the vibration-only condition, and applying the GLMM to the latency distribution under each stimulation condition obtained from the experiment. The parameters of the GLMM indicated a tendency wherein the increase in voltage reduced the latency of illusion.

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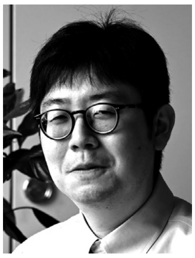

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