Synergistic Illusions: Enhancing Perceptual Effects of Pseudo-Attraction Force by Kinesthetic Illusory Hand Movement

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***Abstract*—We investigated the enhancement of the perceived force strength in force feedback devices by combining the pulling illusion with kinesthetic illusions. The pulling illusion (i.e., a sensation of being pulled or pushed) is induced by asymmetric vibrations applied to the fingertips, enabling the implementation of small, lightweight, and ungrounded force feedback devices. However, the perceived force intensity is limited. We focused on the kinesthetic illusion, a phenomenon in which the movement of a limb in the direction of muscle extension is illusively perceived by presenting vibrations to tendons or muscles as an illusion that could enhance the perceived strength of the pulling illusion. Moreover, we investigated the perceptual characteristics of force sensation by combining a kinesthetic illusion induced by wrist tendon vibration stimulation with a pulling illusion. The findings demonstrate that the direction of the pulling illusion was accurately perceived, even with simultaneous wrist tendon vibration stimuli. Importantly, the results suggest that tendon vibration on the wrist, rather than cutaneous vibration on the wrist, enhances the perceived force intensity of the pulling illusion at the fingertips. These findings indicate the potential for expanding the expressive capability of the pulling illusion.**

***Index Terms*—Illusion, vibration, illusory force perception, kinesthesia.**

I. Introduction

The sense of force plays a vital role in our everyday lives. The ability to perceive force when touching or grasping an object enables precise manipulation. Recently, force feedback has gained increasing attention because of the prevalence of virtual reality (VR) and the expansion of remote work. This interest stems from the aspiration to enhance immersion in VR experiences and facilitate remote instruction by incorporating force feedback.

Various studies have been conducted on force feedback, with an emphasis on reproducing physical forces, including mechanisms using components such as a rod [1], [2] or a system utilizing wires [3]. However, these approaches have limited workspaces and require large devices due to the need for connections to fixed objects.

In contrast to these methods that physically generate forces, numerous scholars have used kinesthetic sensory illusions to provide a perceptual sense of force feedback. A device that uses skin shear deformation to provide a tangential force perception on the skin has been proposed [4]. Several approaches have leveraged the nonlinearity of human perception by presenting asymmetric vibration-acceleration patterns to induce illusory forces (i.e., to create the pulling illusion) [5], [6]. Although these systems are compact, lightweight, and ungrounded, they are limited in terms of the strength of the force feedback they can provide.

Intensifying physical stimuli to enhance the perceived force may cause discomfort or pain. A technique that enhances the strength of the perceived force feedback by combining different illusions, rather than increasing the physical intensity of the stimuli, has been proposed. Kawagishi et al. reported that integrating a pulling illusion and pseudo-haptics [7], presenting resistance using visual effects related to properties such as the position and velocity of the cursor on the screen, created a stronger perception of the illusory force [8]. However, this method requires the user to focus constantly on the cursor displayed on the screen, making it impractical for situations in which continuous visual attention to the hands or the manipulated objects is not feasible.

Therefore, in this study, we focused on a kinesthetic illusion that does not rely on visual cues and simultaneously presented the stimuli that induced pulling and kinesthetic illusions. The kinesthetic illusion is a perceptual phenomenon that induces a sense of movement without actual physical motion by stimulating the receptors responsible for perceiving deep sensations through external vibration stimuli [9]. In this study, we investigated the direction and magnitude of the perceived force feedback induced by a combination of pulling and kinesthetic illusions.

The rest of the paper is organized as follows. Section II introduces previous studies related to this work. Section III describes the implementation of the proposed method in which the vibration stimuli that induce pulling and kinesthetic illusions are simultaneously presented. Section IV describes a psychophysical experiment conducted to investigate the direction of the perceived force. Section V describes a second experiment performed to investigate whether a vibration-induced kinesthetic illusion enhances the pulling illusion more than similar vibration stimuli that do not induce a kinesthetic illusion do. We discuss the experimental results in Section VI and provide the conclusions and a summary of this study in Section VII.

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II. Related Work

A. Force Illusion

Various methods of presenting illusory forces, rather than reproducing physical forces, have been explored. We introduce methods of providing illusory force feedback to the fingertips (or hand), which are relevant to this study.

1) Skin Deformation: Researchers have explored the use of skin deformation to provide force feedback. Skin stretching, the deformation of the skin in the lateral or shear direction, is measured by various sensory receptors and utilized to perceive qualities such as texture, friction, slipperiness, and force [10]. Minamizawa et al. analyzed force feedback by using two motors and a belt to produce shear deformation of the fingertip [4], [11]. Quek et al. designed a system that incorporated tactile devices capable of inducing shear deformation of the skin into a pen-shaped end effector to provide force feedback [12]. Provancher incorporated tactile devices that could cause the shear deformation of the skin into a handheld device, enabling the presentation of haptic force and torque sensations [13]. However, these approaches face challenges in practical implementation because of the requirement for relatively large motors to achieve sufficient skin deformation.

2) Asymmetric Vibration: Recently, researchers have explored a method of using vibration to present intuitive force feedback. For the periodic translational motion (vibration) of an object, the integrated value of the acceleration or force acting on the object over one cycle becomes zero, resulting in no net force acting in a specific direction. However, humans who exhibit perceptual nonlinearity are more sensitive to rapid movements and less responsive to slow movements. Therefore, when asymmetric vibrations are presented with instantaneous changes in acceleration in one direction and gradual changes in the opposite direction, instantaneous changes are detectable, whereas gradual changes are less distinctly perceived, creating the perception of being pulled in one direction by the vibrations [14].

Amemiya et al. used a slider-crank mechanism to generate asymmetric vibrations [15], [14]. Nakamura et al. developed a device comprising two eccentric motors and demonstrated the induction of a traction force illusion by controlling the phase of each vibration [16]. Shima and Takemura designed a non-grounded device using a weight attached to a spring to induce a pulling force sensation [17]. However, despite the clear ability of these devices to induce a pulling illusion, their practical implementation is hindered by their relatively large size.

Researchers have also addressed this challenge. Rekimoto discovered that asymmetric vibrations are generated by inputting rectangular signals with different duty ratios into commercially available linear resonant actuators, leading to the occurrence of a pulling illusion [6]. Amemiya and Gomi designed a system that uses voice coil actuators to induce a traction force illusion [5]. Tanabe et al. generated asymmetric vibrations using vibration speakers to induce a pulling illusion [18]. These methods that use vibration actuators have significantly reduced the size and weight of devices in comparison to conventional methods, enabling greater portability. However, the perceived strength of the force feedback experienced by users also decreased. In this study, we enhanced the perceived force caused by the pulling illusion by combining it with a kinesthetic illusion.

B. Kinesthetic Illusion

In this study, a kinesthetic illusion was presented to the user. Two main methods of presenting kinesthetic illusions exist: electrical stimulation and tendon vibration.

1) Electrical Stimulation: Previous scholars have reported that applying electrical stimulation to tendons induces kinesthetic illusions. Gandevia reported the induction of kinesthetic illusions through low-current pulse stimulation applied to wrist tendons [19]. Kajimoto also reported the occurrence of kinesthetic illusions through electrical stimulation applied to the tendons of the arms, fingers, and legs [20]. Electrical stimulation involves pain and is limited in user acceptance, and the probability of inducing the illusion through electrical stimulation is low.

2) Tendon Vibration: Researchers have also explored the use of vibration to induce kinesthetic illusions, as vibrations are accompanied by less pain than electrical stimulation methods. The primary afferent neurons of the muscle spindles are activated when tendons or muscles are subjected to vibrations. The illusion of limb movement in the direction of muscle stretching is induced by vibration stimulation [9], as muscle spindles serve as position and motion sensors [21]. Methods exist for applying vibrations to tendons, such as placing the tendon in contact with a grounded vibration device [22] or using bands to secure vibrators at the location of the tendon [23]. In this study, this vibration method was used to present a kinesthetic illusion.

C. Combination of Illusion

Attempts have been made to enhance perceived force sensations by combining a pulling illusion with another illusion. Kawagishi et al. strengthened perceived force sensations by combining pseudo-haptics with the pulling illusion [8]. Pseudo-haptics is the phenomenon in which users experience haptic feedback by observing a visual stimulus that is designed to distort based on user input [7]. As pseudo-haptics requires the user to focus visually on an object that the user manipulates for force perception, it is challenging to apply in tasks in which the location of the force feedback is not necessarily stared at.

In this study, not relying on visual sensation, we presented participants with illusory deep sensations: the pulling illusion by asymmetric vibration and the kinesthetic illusion by tendon vibration and using small lightweight vibrators. To date, no systematic investigation into the combined effects and characteristics of simultaneously presented perceptual illusions induced by vibrations has been conducted. Additionally, the mutual influence between these phenomena remains unexplored. The objective of this study was to investigate the characteristics of the perceptual force sensations of a combination of the pulling and kinesthetic illusions.

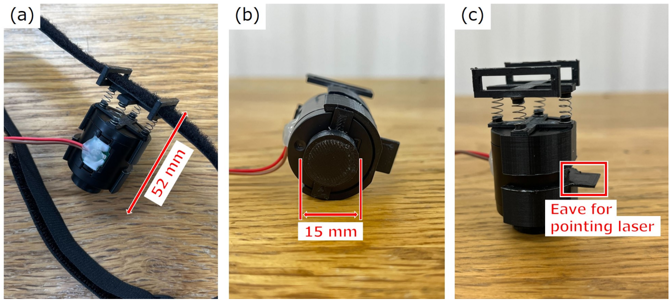

Fig. 1. Device to apply vibration. (a) Appearance of the device. (b) Skin contact side. (c) Eave for measuring the acceleration of the device holding a vibrator by a laser displacement sensor. Acceleration measurements were taken with participants wearing the device and a laser of a laser displacement sensor pointed on the eave

III. Implementation

In this study, we employed asymmetric vibration to induce the pulling illusion and tendon vibration to induce the kinesthetic illusion. We also aimed to consolidate the overall system with fewer devices using the same type of vibrators and a shared control mechanism and to manipulate the input signals separately to induce both illusions.

To present the pulling and kinesthetic illusions simultaneously, the experimental setup included a pulling illusion induction vibrator, kinesthetic illusion module, and driving unit to operate each module. As the pulling illusion induction vibrator, we employed a vibratory actuator (ACOUSTICHAPTIC 639897, Foster Electric Co., Ltd.) capable of operating within the frequency range confirmed to induce a pulling illusion in prior works [24], [18]. The chosen vibrator was a voice coil actuator with a size of ϕ 25 mm $\times$ 27 mm, mass of 28.0 g, and a resonant frequency of 65 Hz. The kinesthetic illusion module had a vibrator, case for housing the vibrator, and band. To induce a kinesthetic illusion, contact between the vibrator and the skin of the participant is necessary. However, directly pressing the vibrator against the arm would cause the entire arm to be driven by the vibrator, resulting in a weak perception of vibration and making inducing a kinesthetic illusion difficult. Therefore, referring to a previous study [23], we designed a vibrator case with a built-in spring (Fig. 1) to apply vibrations to the target area. A kinesthetic illusion was induced by limiting the area driven by the vibrator to the vicinity of the contact point. The driving unit has PC software (Unity) that outputs the signals, an audio interface (ICUSBAUDIO7D, StarTech.com), and a 15 W output Class D audio amplifier (PAM8610, DIODES). The vibration wave output from the PC was input into the vibrators through an audio interface and audio amplifier to activate them. Multiple vibration waves were prepared as the output from the PC, enabling the individual and arbitrary activation of each vibration actuator at various timings. Vibration waves were created using the audio editing software Audacity[1].

As the vibration waveform was input into the pulling illusion induction vibrator, we adopted an asymmetric waveform, that is, a two-cycle sine wave that was inverted for half a cycle

[1]https://www.audacityteam.org/

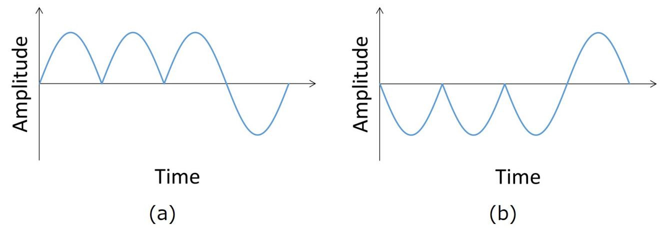

Fig. 2. One cycle of the input sound signal waveform. (a) Input signal creating more positive half-cycles. (b) Input signal creating more negative half-cycles

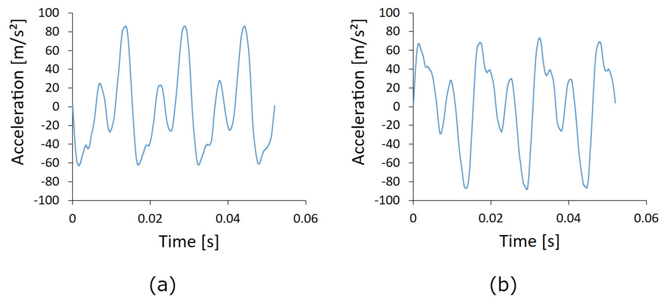

Fig. 3. Acceleration waves of the vibrator. (a) Acceleration of the vibrator whose input is shown in Fig. 2 (a). (b) Acceleration of the vibrator whose input is shown in Fig. 2 (b)

(Fig. 2), confirmed to induce a pulling illusion in the previous study [18]. The frequency range for inducing the pulling illusion ranges from several Hz to several hundred Hz. Particularly, frequencies of several tens of Hz, such as 40 Hz, are more effective for eliciting a pulling illusion [14]. We selected a frequency of 65 Hz as the asymmetric vibration wave input to the vibrator, considering the frequency characteristics of the vibrator used and the frequency range in which a pulling illusion is more likely to occur. An asymmetric vibration pattern characterized by momentary changes in acceleration, followed by gradual changes in the opposite direction, was observed when measuring the acceleration of the vibrator to which the asymmetrical vibration waves were input, as shown in Fig. 3. The maximum amplitude of the asymmetric acceleration vibration was set within $90 \pm 10\ \mathrm{m/s^2}$ based on a previous study [18] in which the induction of a pulling illusion was confirmed. The acceleration amplitude was adjusted while the participants wore the device. The acceleration was measured using a laser displacement sensor (LDS, Keyence LK5000), and the output vibration intensity was adjusted within the specified range.

The vibration waves input into the vibrator in the kinesthetic illusion module were in the form of sine waves. A frequency range of 70-80 Hz is effective for inducing the kinesthetic illusion [25]. A previous study [26] reported that the illusion of the fastest motion was observed at 70 Hz. Therefore, a frequency of 70 Hz was used in this study. The acceleration amplitude was set in the range of $90 \pm 10\ \mathrm{m/s^2}$, based on previous studies [22], [27] in which the kinesthetic illusion was vividly induced. The amplitude was adjusted using the same method as that employed for the pulling illusion induction vibration. Vibrations were applied to the assumed positions

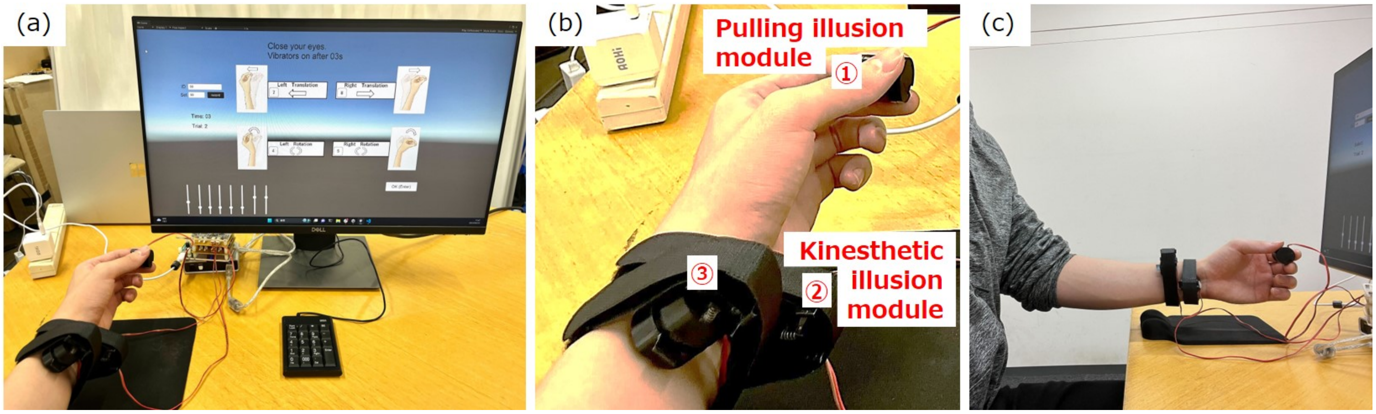

Fig. 4. (a) Overview of the experimental system used in experiment 1. The participants answered the perceived direction of illusory force with a numeric keyboard. (b) ①Vibrator applying asymmetric or symmetric vibration to the fingertips. ②Band-type vibrator-embedded device applying vibration to the tendon of the wrist. ③Band-type vibrator-embedded device applying vibration to the area slightly away from the tendon of the wrist. (c) Posture during vibration

of the tendons on the inner side of the wrist, specifically targeting the tendons of the flexor carpi radialis, palmaris longus, and flexor carpi ulnaris muscles. The objective was to induce a kinesthetic illusion simulating wrist dorsiflexion. This choice was based on the ease of visually confirming the position of the tendons and the direction similarity between the induced illusory motion and pulling illusion. The effect of the force pushing the vibrator into the tendon on the kinesthetic illusion is controversial. A previous study [28] suggested that the threshold amplitude required to induce the kinesthetic illusion decreases as the vibration device is pressed more firmly, and other previous studies [29], [30] provided evidence that stronger pressing force leads to more vivid illusory perception. On the other hand, Honda et al. reported that a more distinct illusion occurred at a weaker pressing force when wrist tendons were vibrated [22]. We decided to adopt a relatively weak pressing force, as the vibrated tendons, frequency, and acceleration amplitude of vibration in the study by Honda et al. were similar to those in this study. Following previous research [23] aimed at inducing a more distinct illusion based on a similar consideration, the pressing force was set within the range of 1.5-2.5 N. The vibrator case was equipped with four springs, each with a spring constant of $0.25\ \mathrm{N/mm}$. The overall spring constant of the device was $1.0\ \mathrm{N/mm}$. The pressing force was adjusted by visually observing the spring displacement.

IV. Experiment1: Direction discrimination

An experiment was conducted in which participants were instructed to indicate the perceived direction of the force sensation and elucidate the direction of the force illusions induced by the proposed system. The experimental procedures were approved by the local ethics committee (Graduate School of Information Science and Technology, The University of Tokyo; approve number UT-IST-RE-230905).

A. Participants

A required sample size of 14 participants was estimated using G*Power 3.1.9.7[2][31], based on a desired power of 0.8, $\alpha = 0.05$, a one-tailed binomial test (one sample case) that examines the difference from constant, and an effect size $g = 0.35$. Fourteen participants (12 male and two female, aged 22 to 25, all right-handed) participated in the experiment. All participants provided written informed consent and were unaware of the purpose of the study.

B. Apparatus

The experimental setup shown in Fig. 4 (a) was prepared. The vibration presentation system had a vibrator for presenting a pulling illusion, band-type vibrator-embedded device that applied vibration to the tendons of the wrist (tendons of the flexor carpi radialis, palmaris longus, and flexor carpi ulnaris muscles), and band-type vibrator-embedded device that presented vibrations to the arm (not to the tendons of the wrist) (Fig. 4 (b)). The timing of the vibration presentation and options for selecting the response direction were displayed on the monitor. The participants entered their responses using a numeric keypad.

C. Procedure

1) Experiment explanation and preparation: First, the participants were seated in a chair and instructions regarding the experimental posture and an overview of the experimental procedure were provided. The participants were instructed to assume an experimental posture with their left arm forward. Throughout the experiment, they put their left hand on a mouse pad with a wrist rest to relax their left arm. They slightly lifted their left arm only when vibration was applied (Fig. 4 (c)). The hand of the participant should not be in contact with a stationary object, such as a desk, due to the potential inhibition of the kinesthetic illusion induction due to haptic cues [32]. A previous study indicated that active manual

[2]https://www.psychologie.hhu.de/arbeitsgruppen/allgemeine-psychologie-und-arbeitspsychologie/gpower

movement boosts the precision of the perceived direction of an illusory force induced by asymmetric vibration [33]. The pulling illusion could be induced more strongly without any physical constraints than with the arm immobilized. Therefore, we did not immobilize the left arm of the participant and had the participant lift their arm slightly during vibration.

2) Device mounting: The participants were equipped with these devices, and they were all right-handed. Based on a previous report [34] suggesting that providing vibrations to the nondominant arm can induce a more distinct kinesthetic illusion with shorter latency, the devices were attached to the left (nondominant) arm of each participant. The vibrator for inducing the pulling illusion was grasped such that it allowed the fingertips of the thumb, index finger, and middle finger to contact each other. The participants were instructed to bring the pads of their thumbs and little fingers together, thereby locating the target tendons to position the vibration device for providing vibrations to the wrist tendons. The vibration device for applying vibrations to the arm was slightly offset from the vibration device for providing vibrations to the wrist tendons. In addition, to reduce auditory cues, the participants were equipped with noise-canceling headphones, and white noise was played.

3) Acceleration amplitude and vibrator positions adjustment: Subsequently, the acceleration amplitudes were adjusted for each vibration device while measuring the acceleration of the attached vibration devices using the LDS. To confirm the occurrence of the pulling illusion in both the left and right directions through asymmetric vibration stimulation, the induction of a kinesthetic illusion in the direction of wrist dorsiflexion through vibration stimulation of the wrist tendons, and the absence of a wrist dorsiflexion illusion through vibration stimulation of the arm were verbally conducted. To confirm the occurrence of the pulling illusion, the participant was presented with vibration on his or her fingertips with his or her eyes closed and arm slightly lifted, and the participant stated the direction of the perceived force. The participant was asked to adjust the grasping force and the position of the vibrator and to perform the confirmation task again when he or she was not sure of the direction or the direction the participant answered was different from that intended by the experimenter. The participant was not informed of the direction the experimenter intended to make the participant feel. In the confirmation of the induction of the kinesthetic illusion, the participant was provided vibration on the wrist with his or her eyes closed and arm slightly lifted and stated whether the wrist dorsiflexion movement occurred or not. The experimenter adjusted the positions of two vibrators such that vibration applied to the wrist tendon induced illusory wrist dorsiflexion and vibration applied to the area slightly away from the wrist tendon did not induce the illusion. The participant was not informed which vibration was intended to induce the illusion. After adjusting the positions of the vibrators, the acceleration amplitude of each vibrator was measured using the LDS and was confirmed to be within the specified range.

4) Force direction response: The participants performed practice trials to familiarize themselves with the vibrations and method of answering the direction. Subsequently, an experimental session was conducted in which participants were instructed to indicate the direction of the force illusion induced by the vibration stimuli. During the vibration stimuli, the participants were instructed to minimize visual and tactile cues by closing their eyes and slightly lifting their forearms to avoid contact with the desk or their bodies. They were also instructed to refrain from resisting the perceived passive movement and rather focus on the movement of their left hand.

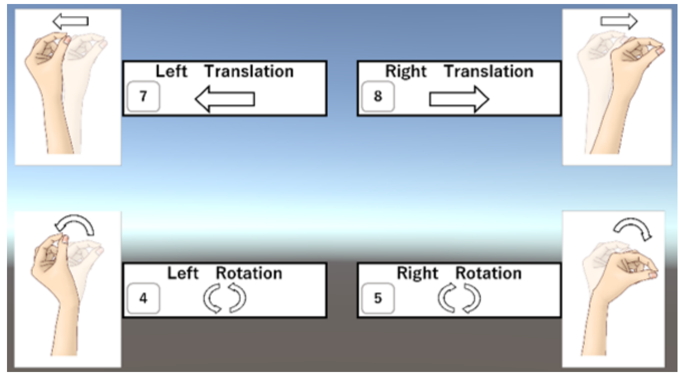

Fig. 5. Screen capture of UI for choosing the perceived force direction

D. Conditions

In the experiment, the participants were presented with six different vibration patterns (three patterns applied to the fingertips $\times$ two patterns applied to the arm). The three patterns applied to the fingertips had asymmetric vibrations that induced the leftward pulling illusion (*left*), asymmetric vibrations that induced the rightward pulling illusion (*right*), and symmetric vibrations (*symmetric*). The two patterns applied to the arm consisted of vibrations targeting the tendons of the wrist (*tendon*) and vibrations applied slightly away from the tendons (*skin*).

Whereas the pulling illusion generates a translational force sensation, the kinesthetic illusion in this experiment was designed to evoke a sense of movement in the direction of wrist dorsiflexion. A rightward or leftward translational force may be felt if only the pulling illusion occurs, a leftward wrist-bending force may be felt if only the kinesthetic illusion is produced, and a rightward or leftward wrist-bending force may be felt if the two illusions are combined when presented with a vibration stimulus that induces the pulling illusion and one produces the kinesthetic illusion simultaneously. Therefore, the options for the participants to answer the perceived direction were "Left Rotation," "Left Translation," "Right Rotation," and "Right Translation" (Fig. 5). The participants were instructed to select "Rotation" when they felt a wrist-bending force or select "Translation" when they did not feel a wrist-bending force. When participants were uncertain of the perceived force direction or if it did not correspond to any of the four options, they were instructed to select one of the four choices randomly and not to bias their responses towards any one option.

The duration of each vibration stimulus was set to 6 s, considering the adaptation of vibration sensitivity and pre-

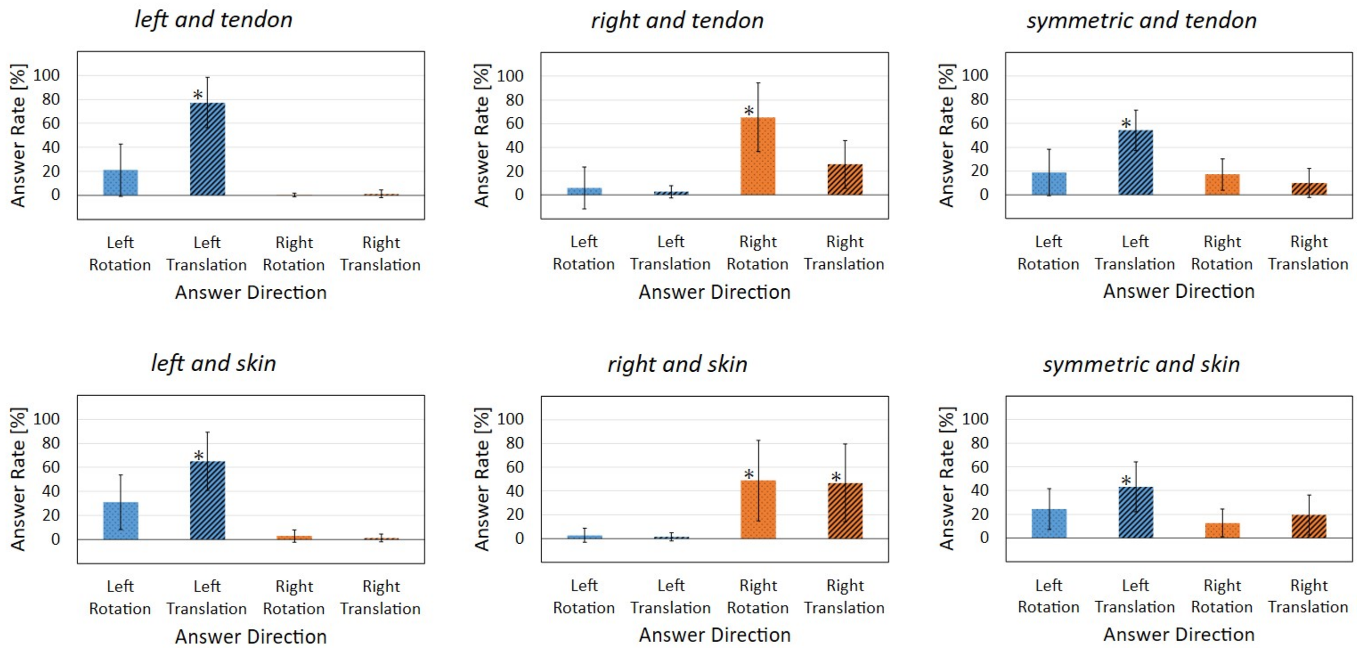

Fig. 6. Results of the direction discrimination task. The error bars are the sample standard deviation. Asterisks denote significant differences from the chance level of 25%. *: adjusted $p < 0.05$

TABLE I
RESULTS OF THE FRIEDMAN RANK SUM TEST

Fingertip vibration factor	Wrist vibration factor	p_{adj}	χ^2
left	*tendon*	< 0.001	34.156
	skin	< 0.001	30.786
right	*tendon*	< 0.001	26.173
	skin	< 0.001	29.488
symmetric	*tendon*	0.001	17.978
	skin	0.031	8.858

TABLE II
RESULTS OF THE WILCOXON SIGNED RANK TEST WHICH SHOWED A SIGNIFICANT DIFFERENCE. LR: LEFT ROTATION. LT: LEFT TRANSLATION. RR: RIGHT ROTATION. RT: RIGHT TRANSLATION

Fingertip vibration factor	Wrist vibration factor	Answer direction factor	p_{adj}
left	*tendon*	LR - LT	0.021
		LR - RR	0.014
		LT - RR	0.004
		LT - RT	0.004
left	*skin*	LR - RR	0.031
		LR - RT	0.014
		LT - RR	0.004
		LT - RT	0.008
right	*tendon*	LR - RR	0.032
		LT - RR	0.008
		LT - RT	0.013
right	*skin*	LR - RR	0.017
		LR - RT	0.008
		LT - RR	0.013
		LT - RT	0.007
symmetric	*tendon*	LT - RR	0.012
		LT - RT	0.012

vious studies [35], [36], because this duration is short and sufficient to induce the perception of a kinesthetic illusion. Each trial had a 6-s vibration stimulus, participant response, and subsequent 6-s interval. During the practice trials, six trials were conducted in random order, with each vibration pattern presented once. The main session had six sets with a 1-min break provided between each set. In each set, 18 trials were conducted in random order, with each vibration pattern presented three times. In total, 108 trials were conducted.

E. Analyses

First, the proportion of answer directions was converted into a z-score and used as the evaluation value. The z-score is a standardized value obtained using the mean and standard deviation. The proportion was converted into a z-score when the proportion was 0 or 1, assuming that the proportion was $1/(2N)$ or $1 - 1/(2N)$ respectively, with the number of trials for each condition $N = 18$. Second, an aligned rank transform (ART) [37], which enabled us to conduct an ANOVA for non-parametric data, was performed. We conducted a three-factor repeated measures ANOVA (3 levels of the fingertip vibration factor (*left*, *right*, and *symmetric*) $\times$ 2 levels of the wrist vibration factor (*tendon* and *skin*) $\times$ 4 levels of the answer direction factor (“Left Rotation,” “Left Translation,” “Right Rotation,” and “Right Translation”)). In this analysis, the significance level was 0.05.

In addition, the response directions of the participants were separated into left or right, without distinguishing between rotation and translation, and a binomial test was conducted to examine whether the proportion of responses in each direction for each condition was significantly higher than the chance level of 50 %. Further, the response directions were divided into left/right and rotation/translation, and a binomial test was performed to determine whether the proportion of responses in each direction for each condition was significantly higher than the chance level of $25\ \%$. In binomial tests, the significance level was 0.05, and the Bonferroni correction was used for a multiple-testing correction.

F. Result

The response directions of the participants for each vibration pattern are shown in Fig. 6.

The results of a three-factor repeated measures ANOVA revealed a significant three-way interaction effect ($F(6, 78) = 5.263$, $p = 0.001$, *partial* $\eta^2 = 0.288$). Then, we tested for a simple two-way interaction between the wrist vibration factor and the answer direction factor at each level of the fingertip vibration factor. The results showed a significant simple two-way interaction effect at level *left* ($F(3, 39) = 4.399$, adjusted $p = 0.009$, *partial* $\eta^2 = 0.253$), at level *right* ($F(3, 39) = 4.907$, adjusted $p = 0.005$, *partial* $\eta^2 = 0.274$), and at level *symmetric* ($F(3, 39) = 3.371$, adjusted $p = 0.028$, *partial* $\eta^2 = 0.206$). Subsequently, conducting the Friedman rank sum test with the Holm correction, we tested for a simple-simple main effect of the answer direction factor at each level of the fingertip vibration factor and each level of the wrist vibration factor. The results revealed a significant simple-simple main effect of the answer direction factor at all combinations of levels of the fingertip and wrist vibration factors, as shown in Table I. Subsequently, we conducted the Wilcoxon signed rank test with the Holm correction to examine a significant difference between levels of the answer direction factor at each level of the fingertip vibration factor and each level of the wrist vibration factor, and the results showed a significant difference in some cases (Table II and Supplementary Table 3).

The results of the binomial tests revealed the directions whose response rates were significantly higher than the chance level as follows: left (adjusted $p < 0.05$, relative risk (RR)$= 1.97$) under the *left and tendon* condition, left (adjusted $p < 0.05$, $RR = 1.92$) under the *left and skin* condition, right (adjusted $p < 0.05$, $RR = 1.83$) under the *right and tendon* condition, right (adjusted $p < 0.05$, $RR = 1.91$) under the *right and skin* condition, left (adjusted $p < 0.05$, $RR = 1.46$) under the *symmetric and tendon* condition, left (adjusted $p < 0.05$, $RR = 1.36$) under the *symmetric and skin* condition when the responses were categorized as left or right, “Left Translation” (adjusted $p < 0.05$, $RR = 3.10$) under the *left and tendon* condition, “Left Translation” (adjusted $p < 0.05$, $RR = 2.60$) under the *left and skin* condition, “Right Rotation” (adjusted $p < 0.05$, $RR = 2.62$) under the *right and tendon* condition, “Right Rotation” (adjusted $p < 0.05$, $RR = 1.95$) and right translation (adjusted $p < 0.05$, $RR = 1.87$) under the *right and skin* condition, “Left Translation” (adjusted $p < 0.05$, $RR = 2.17$) under the *symmetric and tendon* condition, and “Left Translation” (adjusted $p < 0.05$, $RR = 1.73$) under the *symmetric and skin* condition when the responses were categorized as left/right rotation/translation.

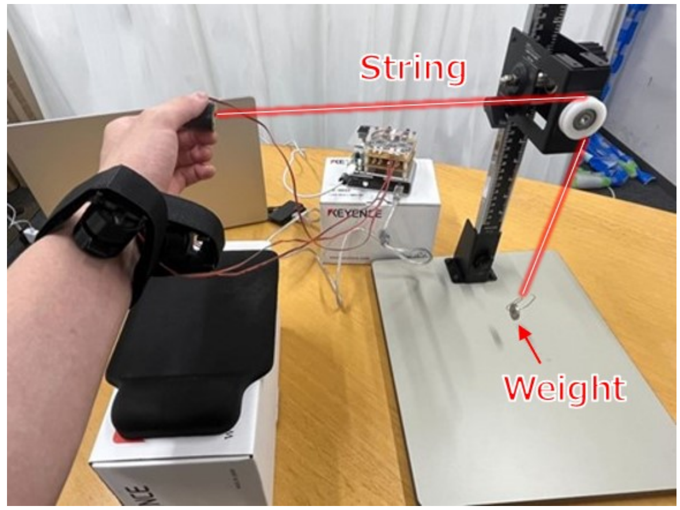

Fig. 7. Overview of the experimental system used in experiment 2. A physical (not illusory) force was presented using a string and weights. The vibration devices mounted on the left arm were the same as in Section IV.

V. EXPERIMENT2: MAGNITUDE COMPARISON

In this experiment, we investigated the influence of a combination of the pulling and kinesthetic illusions induced by tendon vibration on the perceived force sensation. We compared the perceived force magnitude under two conditions: the pulling illusion with the tendon vibration (the proposed method) and that with cutaneous vibration applied at a location not directly on the wrist tendons. The perceived force intensity was measured using the staircase method at the point of subjective equality (PSE) between the weight and the perceived force strength. The experimental procedures were approved by the local ethics committee (Graduate School of Information Science and Technology, The University of Tokyo; approve number UT-IST-RE-230905).

A. Participants

Eleven male participants (aged 22 to 25, all right-handed) participated in this experiment. Five participants continued in the second experiment from the first experiment. All participants provided written informed consent and were unaware of the purpose of the study.

B. Apparatus

The experimental setup is shown in Fig. 7. The vibration presentation system had a vibrator for inducing a pulling illusion, a band-type vibrator-embedded device that applied vibration to the tendons of the wrist (tendons of the flexor carpi radialis, palmaris longus, and flexor carpi ulnaris muscles), and a band-type vibrator-embedded device that presented vibrations to the arm (not to the tendons of the wrist). It was the same as those described in Section IV (Fig. 4 (b)). The vibrator used to present the pulling illusion was equipped with a string and clip that could suspend the weight attached to the opposite end of the string. The string was hung on the pulley attached to the stand and weights were placed on the clip, presenting a physical (not illusory) force to the participants.

When illusory forces were induced, the weight was lifted to loosen the string, avoiding the presentation of a physical force.

C. Procedure

1) Experiment explanation and preparation: First, each participant was seated in a chair and provided with instructions regarding the experimental posture and an overview of the experimental procedure. The instructed experimental posture and physical constraints of the left arm of the participant were the same as those described in Section IV.

2) Device mounting: Subsequently, the participants were equipped with these devices. All the participants in this experiment were right-handed. The devices were attached to the left (nondominant) arm of each participant. The vibrator for inducing the pulling illusion was grasped such that the fingertips of the thumb, index finger, and middle finger were allowed to be in contact. A vibrator for tendon stimulation was placed after visualizing the tendon location. The tendons were easily visible when the participants brought the pads of their thumbs and little fingers together. The vibration device for applying vibrations to the arm was slightly offset from the vibration device for providing vibrations to the wrist tendons. In addition, to reduce auditory cues, the participants were equipped with noise-canceling headphones, and white noise was played.

3) Acceleration amplitude and vibrator positions adjustment: Subsequently, the acceleration amplitudes were adjusted for each vibration device while measuring the acceleration of the attached vibration devices using the LDS. After acceleration adjustment, the following three prerequisites were confirmed in the same manner as in Section IV: First, the asymmetric vibration produced the illusion of a traction force in the left and right directions. Second, the vibration of the wrist tendons produced the illusion of wrist dorsiflexion. Third, the arm vibration did not produce a wrist dorsiflexion motion illusion.

4) Measurement of PSE using a staircase method: The following describes the perceptual force measurement method.

The flow of each trial consisted of a 6 s presentation of illusory force by vibrations, 3 s interval, 6 s presentation of physical force with vibrations and weights, participant response, and 6 s interval. The vibration duration was consistent with that of the previous experiment.

In each trial, the weight varied based on the staircase method [38]. If the response was “stronger” (indicating that the force sensation from the weight was stronger than the illusionary force sensation), the mass of the weight in the subsequent trial was reduced. Similarly, if the response was “weaker,” the mass of the weight in the next trial was increased. Until the first reversal of responses occurred (where the response changed from “strong” to “weak,” or vice versa, between a trial and the previous one), the mass of the weight was varied in increments of 12 g. Subsequently, the weight was varied in increments of 4 g. Two distinct series with different initial values were prepared for each vibration pattern. One series was an ascending series starting from a sufficiently small initial value of 0 g (without a weight), whereas the other series was a descending series starting from a sufficiently large initial value of 48 g.

We followed a previous study [39] and implemented four distinct series concurrently to prevent bias in the responses caused by the anticipation of stimulus intensity changes by the participants. For instance, in the left condition group, ascending and descending series for both the *left and tendon* and *left and skin* conditions were conducted in parallel. Specifically, the participants completed the trials from the four series randomly and then moved on to the next four trials in another randomized order.

Before the main session, a practice session was conducted to familiarize the participants with the vibrations and the required response. Each trial with a weight of 48 g and without weight under each condition was tested once during a practice session. In the main session, each set included four trials: two trials (for the ascending and descending series) of each condition in random order. A total of 14 sets (56 trials) were conducted with a 1 min break after every two sets. A total of 112 trials, including the left and right condition groups, were performed. Note that when each participant completed the 14th trial, the staircase could determine the mass of the weight for the 15th trial.

The participants were instructed to close their eyes and slightly lift their arms during the vibration stimuli. They were also instructed to refrain from actively moving their arms to the left or right.

D. Conditions

In this experiment, four vibration pattern conditions were applied (i.e., two patterns to the fingertips $\times$ two patterns to the arm). The two patterns applied to the fingertips consisted of asymmetric vibrations that induced a leftward pulling illusion (*left*) and asymmetric vibrations that induced a rightward pulling illusion (*right*). The two patterns applied to the arm consisted of vibrations targeting the tendons of the wrist (*tendon*) and vibrations applied slightly away from the tendons (*skin*). We reproduced the vibration accompanying the pulling and kinesthetic illusions when presenting the force sensation using weights. The cutaneous sensation was reproduced by presenting symmetrical vibrations at the fingertips and a position slightly away from the tendons of the wrists.

The participants provided verbal responses indicating whether they perceived the force, resulting from both vibration and weights, as “stronger” or “weaker” in comparison to the (illusory) force perception solely induced by vibrations. The participants were instructed to provide a random response if they could not determine either response. They were not informed of which force sensation was presented by weights or vibrations alone to prevent bias based on prior knowledge. The participants were instructed to indicate whether the second force perception was “stronger” or “weaker” than the first force sensation in each trial.

This experiment was divided into two trials: one presented a leftward force sensation (left condition group), and the other presented a rightward force sensation (right condition group). The left condition group included the *left and tendon* and *left*

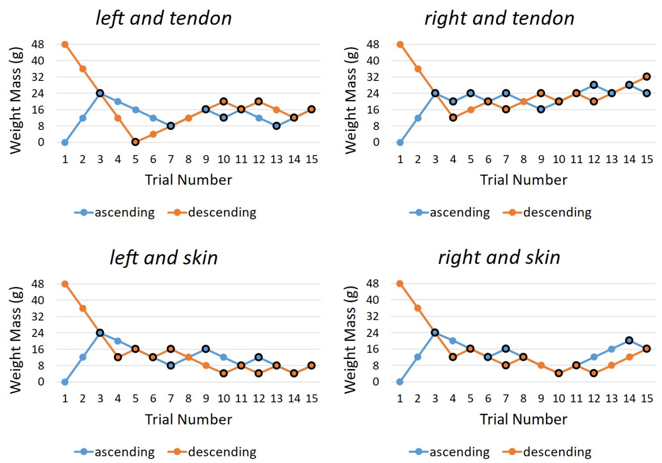

Fig. 8. Example of data obtained in the magnitude comparison task. The vertical axis indicates the mass of the weight corresponding to each trial number. The data points used to estimate the PSE are outlined in black.

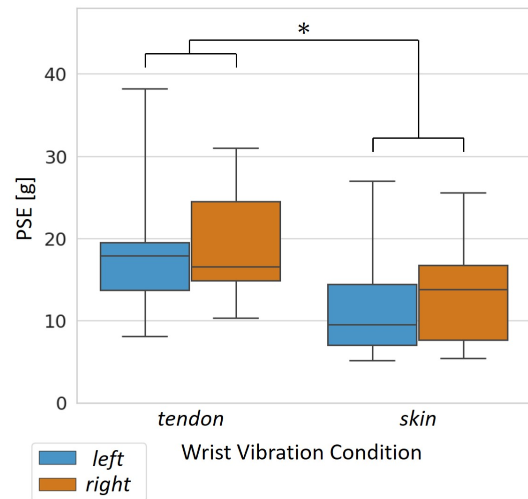

Fig. 9. Results of the magnitude comparison task. The vertical axis indicates the PSE calculated from the obtained data. *: adjusted $p < 0.05$.

and skin conditions. The right condition group included the *right and tendon* and *right and skin* conditions. The order in which the left and right condition groups were performed was randomly determined to balance out the participants.

E. Data processing

Examples of the data obtained from each participant are presented in Fig. 8. The obtained data were processed based on a previous study [39], and the PSE of each participant was calculated for each vibration pattern. The average of the reversal points (the points where the responses switch from "stronger" to "weaker" or vice versa), including the 15th data point, was calculated for each ascending and descending series of each vibration pattern. The PSE of each participant under each condition was determined by averaging these two values from the ascending and descending series.

F. Analyses

We performed ART and conducted a two-factor repeated measures ANOVA (2 levels of the fingertip vibration factor (*left* and *right*) $\times$ 2 levels of the wrist vibration factor (*tendon* and *skin*)). The significance level was 0.05.

G. Result

The values obtained for each condition were as follows: Under the *left and tendon* condition, the average was 18.1 g with a sample standard deviation of 7.8 g; Under the *left and skin* condition, the average was 11.2 g with a sample standard deviation of 6.3 g; Under the *right and tendon* condition, the average was 19.1 g with a sample standard deviation of 6.9 g; Under the *right and skin* condition, the average was 13.3 g with a sample standard deviation of 6.4 g (Fig. 9).

The results of the ANOVA revealed a significant difference in the wrist vibration factor ($F(1, 10) = 44.491$, $p < 0.001$, *partial* $\eta^2 = 0.816$). We did not find any significant difference in the fingertip vibration factor ($F(1, 10) = 0.575$, $p = 0.466$, *partial* $\eta^2 = 0.054$) or the interaction effect ($F(1, 10) = 0.408$, $p = 0.537$, *partial* $\eta^2 = 0.039$).

VI. DISCUSSION

A. Direction Discrimination

In experiment 1 (Section IV), we investigated the direction of the perceived force generated by a system that simultaneously presented pulling and kinesthetic illusions.

In the results of the binomial tests when categorizing the responses of the participants in the left or right direction, a significant preference existed for pulling illusion direction responses compared with the chance level for the *left and tendon*, *left and skin*, *right and tendon*, and *right and skin* conditions. This finding implies that a distinct pulling illusion was induced, even when vibratory stimulation was applied to the arm. The results for the *symmetric and tendon* condition revealed a significantly higher rate of responses, indicating the direction of the kinesthetic illusion. This finding demonstrated that a kinesthetic illusion was induced even with symmetric vibratory stimulation on the fingertips. The above findings are consistent with the assumptions underlying this study: ① that a pulling illusion occurs with asymmetric vibratory stimulation on the fingertips but not with symmetric stimulation, and ② that a kinesthetic illusion is induced by vibratory stimulation of the tendon but not when the stimulation is applied away from the tendon. In contrast, the results for the *symmetric and skin* condition demonstrated a significantly higher proportion of leftward responses, despite the intention of the vibratory stimulation being designed to elicit neither a pulling illusion nor a kinesthetic illusion. Considering the confirmation of these two assumptions during the attachment of the vibratory stimulation device to the participants in the experiment, a potential influence of the weight illusion induced by symmetric vibratory stimulation could have existed [40], [41]. During the experiment, the vibrator held by the participants frequently slightly tilted to the left of the horizontal position. Although this state did not significantly impact the occurrence of the pulling illusion, the weight illusion could have been induced by symmetric vibration stimulation, leading to its interpretation as a leftward downward force sensation. On the

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other hand, the post hoc ANOVA tests showed no significant difference between each answer direction under the *symmetric and skin* condition, suggesting that the proportion of responses in the left translation was higher than the chance level, but each response direction could be simply dispersed in a scattered manner.

Although the direction of the kinesthetic illusion was consistent with the wrist dorsiflexion (leftward direction) under all conditions, the perceived direction of the force reported by the participants mostly aligned with the direction of the traction force illusion. Previous scholars have reported that when kinesthetic illusions are induced through tendon vibration, the illusion can be weakened or even abolished by passive movements of the limb in the opposite direction to the perceived motion of the illusion [9], [42]. Furthermore, the perceived direction of the illusory motion was observed to be aligned with the direction of the passive movement by performing passive movements with relatively slow and small displacements [43]. Based on these previous studies, the traction force illusion is considered to have played a role similar to that of passive motion in the present system. Consequently, the motion illusion may have been weakened, eliminated, or altered, potentially aligning the perceived force direction with that of the traction force illusion.

Another possible cause may be the simultaneous presentation of asymmetric vibration to induce a pulling force illusion, and tendon vibration to present a kinesthetic illusion. The pulling illusion immediately occurs after vibration stimulation, whereas the kinesthetic illusion emerges seconds later [36], [35]. Therefore, in the direction discrimination experiment, the bias toward the perceived direction of a pulling illusion, which was perceived earlier, could have influenced the responses of the participants. Further research is required to investigate the relationship between the timing of inducing each illusion and the direction of the perceived force. For example, examining cases in which the timing of presenting asymmetric vibrations is shifted to an earlier or later time than the time at which vibrations are applied to the tendons could result in different contributions.

Regarding the results of the binomial tests when categorizing the responses of the participants into left/right rotational/translational directions, the "Left Translation" force perception is suggested to arise under the *left and tendon* condition, whereas the "Right Rotation" force perception is proposed to arise under the *right and tendon* condition. In support of these suggestions, the post hoc ANOVA tests showed significant differences between "Left Translation" and each of the other three answer directions under the *left and tendon* condition and between "Right Rotation" and each of the leftward answer directions ("Left Rotation" and "Left Translation") under the *right and tendon* condition. Under the *left and tendon* and *right and tendon* conditions, the influence of wrist dorsiflexion motion illusion was hypothesized to lead to a significantly high proportion of responses indicating "Rotation" in both left and right directions. However, the results had a low rate of responses indicating "Left Rotation." A previous article [32] reported that motion illusions occurred in the context where tactile cues to the fingertips were not fixed

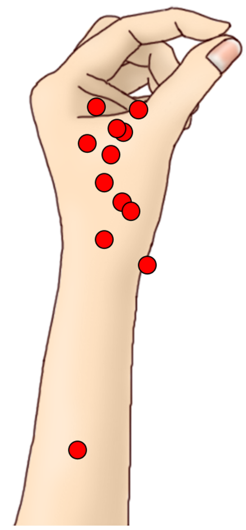

Fig. 10. Plot of axes of rotation when the participants perceive "Right Rotation". Two out of 14 answered that they were not sure where the axis of rotation was.

to the environment. Therefore, tactile cues to the fingertips from the pulling illusion are unlikely to eliminate the induction of motion illusions.

In addition, the participants were instructed to indicate the position of the axis of rotation when they perceived a rotational force sensation, and the results were plotted on an illustration depicting the arm and hand (Fig. 10), revealing that a common response when perceiving right rotation was to locate the axis of rotation between the wrist and fingertips. This finding suggests that a torque sensation, which is a combination of the wrist dorsiflexion moment from the kinesthetic illusion and the force from the pulling illusion, was perceived, or at least that the motion illusion contributed to a certain extent to the overall force perception. As the motion illusion is unlikely to disappear only when the pulling illusion is in the left direction, a possible explanation for the presence or absence of rotational perception in the left or right direction may be the initial hand posture when receiving vibratory stimulation. In this experiment, the initial posture was deliberately set to maintain a natural wrist position without flexion. However, in this posture, the range of motion in the dorsal flexion direction of the wrist (corresponding to the left direction in this experiment) was smaller than that in the palmar flexion direction (corresponding to the right direction) [44]. This situation may have led to a low rate of interpreting the direction of the force perception as "Left Rotation." A sense of rotation could occur in the left direction by adopting an initial posture in which the wrist was flexed to make the range of motion equal in the dorsal and palmar flexion directions, albeit an unnatural posture.

The perception of rotation may also be more likely to occur when the direction of the pulling illusion is opposite to that of the kinesthetic illusion. Further investigation of the combination of motion illusion in the palmar flexion direction of the wrist and the pulling illusion could contribute to a deeper understanding of the conditions under which torque

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sensation is induced.

B. Magnitude Comparison

In experiment 2 (Section V), we compared the strength of the force perception elicited by the combination of the pulling and kinesthetic illusions induced by tendon vibration with the force sensation presented by the combination of the pulling illusion and vibration stimuli that did not induce the motion illusion.

First, the results suggest that the presentation of the pulling and kinesthetic illusions (induced by wrist tendon vibrations) leads to a stronger perception of force than the combination of the pulling illusion and vibration stimulation (positioned away from the wrist tendon). A previous article [18] reported that pinching the basal bone of the finger grasping the transducer decreased the force intensity of the traction force illusion. The discussion in that report stated that this result could have been caused by the attenuation of the vibration transmitted to the tendon at the pinched position. The presented vibration frequency was within the range of the frequencies reported to produce kinesthetic illusions. This finding suggests that the kinesthetic illusion caused by tendon vibration is related to the traction force illusion. The activation of the muscle spindles by the finger and wrist tendons vibration could have contributed to the increase in the force intensity, as the muscle spindles (Ia afferent fibers) signal during vibration-induced kinesthetic illusions [21], [9].

In addition, considering the questionnaire regarding the axis of rotation in the direction discrimination experiment, the participants perceived a stronger force sensation possibly because of the combined effect of the wrist dorsiflexion moment from the kinesthetic illusion and the force from the pulling illusion.

Second, the results indicate that no difference in the strength of the perceived force exists between the case in which the directions of the pulling and kinesthetic illusions are the same and that in which the directions are the opposite. When the pulling and kinesthetic illusions are in opposite directions, the two force sensations may cancel each other out, weakening the perceived force. However, the perceived force was strengthened to the same extent as that under the condition in which the illusions were in the same direction in this study. The reason could be that the enhancement of the perceived force was attributed to muscle spindle firing whether the muscle was agonist or antagonist or that the force sensations induced by the illusions were on different points or axes and did not cancel out each other.

Earlier results revealed that an asymmetric-vibration-induced pulling illusion increased the perceived magnitude of force by amplifying the vibration amplitude [18]. The novelty of this study lies in the fact that a combination of the pulling illusion and kinesthetic illusion was used to enhance the intensity of force perception. The proposed method can also enhance the perceptual force through the conventional approach of increasing the vibration amplitude. Therefore, it can yield a stronger force perception than the maximum perceptual intensity achieved by the pulling force illusion independently. However, additional investigations are required to increase the perceived force intensity further because a force sensation as strong as that of a large actuator still cannot be presented using the developed approach. For instance, optimizing the frequency and amplitude of the vibration stimulus, incorporating a kinesthetic illusion induced by vibration stimulation of the wrist tendons and tendons located in the forearm and elbow, and combining the proposed system with other modal illusions, such as visual illusions, could result in various contributions.

C. Other Methods Inducing Illusion

In this study, a combination of pulling and kinesthetic illusions was presented using vibration-based techniques. However, studies involving the perception of force illusions through methods other than vibration, such as skin deformation [45], [46], [47], and the induction of kinesthetic illusions through non-vibration methods, such as electrical stimulation [20], have not yet been conducted. Further research must be performed to ascertain whether the results obtained in our experiment are solely attributed to the combination of pulling and kinesthetic illusions or to the methods employed to induce each illusion independently.

D. Application

The use of asymmetric vibration of the actuator to induce a pulling illusion has been explored in applications such as pedestrian navigation systems [48], [6] and string-based fishing simulations in VR [49], due to the limited intensity of the perceived force. The proposed system enables the presentation of stronger force feedback compared to conventional methods, and it can be applied in VR training for racket sports or sportive sword-fighting (Sports Chanbara), where the load is exerted up to the wrist, because of the positioning of the vibrator.

E. Limitations

The study faced several limitations, which should be considered when interpreting the results. One may be related to the arm posture of the participants during the experiment. In this study, the arm of each participant was not immobilized and slightly lifted during vibration to enhance the perception of the pulling illusion, as reported in previous studies [33], [18]. However, this posture could have led to the variability of the proprioception by the participants because the lifted arm positions could have differed between trials and individuals. Therefore, we cannot rule out that the participants could have felt the kinesthetic illusion slightly differently across trials. Another concern related to the experimental posture is muscle fatigue. Fatigue causes a slowing of the illusory movements of kinesthetic illusion when muscles are loaded, but not when muscles are relaxed [50], [51]. In this study, we instructed the participants to rest their arms with their arms down except during the vibration periods and they took breaks between trials to minimize the effect of muscle fatigue. However, when the arm is in a floating position, the vibrating muscles are in a state of voluntary contraction to maintain the wrist posture. In addition, the arms of the participants could have become fatigued as the experiment progressed. Therefore, the kinesthetic illusion may have occurred more weakly than if the muscles had been completely relaxed and could have been perceived even more weakly in the last trials.

The second issue is related to the design of experiment 2, for which a limited number of participants were recruited. The achieved power of the main effect of the wrist vibration factor computed using G*Power 3.1.9.7 was 0.9999651.

In our experiment, we only stimulated the tendons causing the wrist extension illusion, limiting the number of tendons stimulated. We did not investigate the impact of stimulating other tendons, such as the tendons causing wrist flexion illusion.

When attempting to enhance the perceived force further by increasing the number of stimulated tendons, the tendons that can contribute to enhancement from the perspective of the direction of kinesthetic illusions are limited. Therefore, an upper limit to the ultimate intensity of the perceived force of the pulling illusion is likely to exist.

Although the proposed method that employs the vibration stimulation of the fingertips and wrist can induce a stronger traction force illusion, its applications are limited. In particular, the method may only be useful when force is applied to the finger, and skin sensation at the wrist does not interfere with the illusion. Further research is needed to explore and expand the potential applications of the proposed technique.

VII. CONCLUSION

In this study, we designed a system that simultaneously presented pulling and kinesthetic illusions through vibration stimulation and investigated the direction and intensity of the resulting force sensation. Regarding the direction, we found that we could manipulate the overall left-right direction of the force feedback by controlling the direction of the pulling illusion, and under specific conditions, a torque sensation is suggested to occur. Regarding the intensity, the kinesthetic illusion is suggested to contribute to an increase in the perceived force strength of the pulling illusion on the fingertips, regardless of whether the (illusory) motion direction is consistent with or opposite to that of the pulling illusion. The findings of this study could expand the expressive capability of the pulling illusion, which has been difficult this far.

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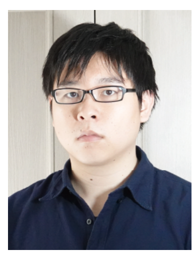

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