Illusory Directional Sensation Induced by Asymmetric Vibrations Influences Sense of Agency and Velocity in Wrist Motions

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***Abstract*— Illusory directional sensations are generated through asymmetric vibrations applied to the fingertips and have been utilized to induce upper-limb motions in the rehabilitation and training of patients with visual impairment. However, its effects on motor control remain unclear. This study aimed to verify the effects of illusory directional sensations on wrist motion. We conducted objective and subjective evaluations of wrist motion during a motor task, while inducing an illusory directional sensation that was congruent or incongruent with wrist motion. We found that, when motion and illusory directional sensations were congruent, the sense of agency for motion decreased. This indicates an induction sensation of the hand being moved by the illusion. Interestingly, although no physical force was applied to the hand, the angular velocity of the wrist was higher in the congruent condition than that in the no-stimulation condition. The angular velocity of the wrist and electromyography signals of the agonist muscles were weakly positively correlated, suggesting that the participants may have increased their wrist velocity. In other words, the congruence between the direction of motion and illusory directional sensation induced the sensation of the hand being moved, even though the participants' wrist-motion velocity increased. This phenomenon can be explained by the discrepancy between the sensation of active motion predicted by the efferent copy, and that of actual motion caused by the addition of the illusion. The findings of this study can guide the design of novel rehabilitation methods.**

***Index Terms*— Illusory directional sensation, illusory kinesthetic sensations, wrist motion, asymmetric vibration, haptic interface.**

I. Introduction

DIRECTIONAL cues are useful for guiding upper-limb motions, and have been generated using not only physical pulling forces but also illusory forces [1], [2], [3], [4]. Among these, an illusory directional sensation is induced by asymmetric vibration stimuli with different acceleration intensities on the outward and inward directions [5], [6], [7]. In this illusory phenomenon, the sensations of the hand being pulled in one direction are induced by pinching the vibrator, which generates asymmetric vibration stimuli on the fingertips [8], [9], [10]. A previous study reported that polarity-specific differences in acceleration intensity contributed to this illusion. [5]. Typically, the integral value of the vibration stimulus at a constant time is zero, which indicates that no force is applied in a particular direction. However, in the case of weak and strong accelerations in asymmetric vibration stimuli, the vibration is perceived as a pulling force. This is because weak accelerations are perceived vaguely, while strong accelerations are perceived distinctly [5]. Although the mechanism by which the illusion occurs is not entirely clear, previous researchers have discussed the role of mechanoreceptors [8], the influence of skin deformation [10], and cerebral functions [11] in relation to this illusion.

Typical applications of the illusory directional sensation were force feedback [12], navigation [13], [14], and motion guidance for upper-limb [15], [16]. We have specifically focused on the utility of motion guidance and have developed a training system utilizing this illusion for white-cane orientation in patients with visual impairment [17]. Moreover, other researchers have proposed rehabilitation as an application for guiding upper-limb motions using illusions [18]. Illusory directional sensation is changed by the interaction between upper-limb motions. Specifically, the sensitivity of the illusion increases with upper-limb motion [19], [20], and illusory directional sensations in the direction of gravity, while lifting objects, change the perceived weight of the grasped object [12], [21], [22]. However, the effects of this illusion on motor control remain unknown. We verified the effects of illusory directional sensations on motion to achieve better rehabilitation or training methods, based on scientific evidence.

In our previous study, several participants introspectively reported that guiding their motion with illusory directional sensations made them feel as if their hands were being moved [17]. In other words, their reports suggest that the agency of motion is not itself; rather, it is an illusory directional sensation. Therefore, the interaction between the illusory directional sensation and upper-limb motion may influence the sense of agency. In a typical active motion, self-motion is

Manuscript received 13 February 2024; revised 1 April 2024; accepted 22 April 2024. Date of publication 24 April 2024; date of current version 2 May 2024. This work was supported by the Japan Society for the Promotion of Science (JSPS) KAKENHI under Grant JP21K17796, Grant JP21H03474, and Grant JP23H03444. *(Corresponding author: Takeshi Tanabe.)*

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Institutional Review Board of the National Institute of Advanced Industrial Science and Technology under Approval No. HF2019-0966-B.

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Digital Object Identifier 10.1109/TNSRE.2024.3393434

determined by comparing afferent signals from proprioceptive sensations with efferent copies of motor commands [23], [24]. The discrepancy between the actual motion and that predicted by efferent copying decreases the sense of agency [25], [26]. When this illusion is induced during active motion, the illusory directional sensation may be added to the sensation of the motion, resulting in a discrepancy from the predicted sensation. Consequently, the sense of agency may decrease.

In addition, the sense of agency is important for shaping the body schema [27], which is a plastic and unconscious sensorimotor representation of the body used for planning and performing motions [28], [29]. The body schema is also known to be modified by kinematic illusions when stimulating the tendon and inducing a sensation of passive motion [30]. Because a sensation of passive motion can be induced not only by kinematic illusion but also by illusory directional sensation, the effects of the illusory directional sensation on motion control are possible to be interpreted by alteration of the body schema, which is used for motor planning [28], [29].

Based on the findings of previous studies, this study proposes the following hypotheses:

- The illusory directional sensation during active motion influences the sense of agency.
- The illusory directional sensation also alters the motion itself.

To determine the effects of illusory sensations on motion, we objectively and subjectively evaluated the effects of illusions induced during motor tasks involving wrist motions.

II. Methods

A. Participants

A total of 20 healthy participants aged 20–47 years (mean: 26.2 years ± 7.0 yeas (standard deviation); nine females) participated in this experiment. This study was approved by the Institutional Review Board of the National Institute of Advanced Industrial Science and Technology (approval number: HF2019-0966-B) and the experimental procedures were conducted in accordance with the Declaration of Helsinki. Informed consent was obtained from all the participants.

B. Experimental Setup

Fig. 1 shows the experimental setup of this study. Participants were seated with their right hand grasping a vibrator to induce an illusory directional sensation (Fig. 1(a)). The participants' forearms were placed on armrests and allowed to move freely from the wrists onward. In this study, we focused on examining the basic effects of illusion on motion, specifically targeting simple motions such as wrist flexion-extension. As shown in Fig. 1(b), illusory rotational sensations [31] were induced in the direction around the vertical axis. This direction is aligned with the flexion and extension of the wrist. The vibrator used to induce illusory directional sensations included two channels (L-ch and R-ch) of voice coils (639897, Foster Electric Co., Ltd.) placed in parallel. Opposing force vectors were produced using voice coils to induce rotational sensations (Fig. 1(b)) [31]. The control signals of the vibrator were generated using MATLAB R2020b (MathWorks Inc.)

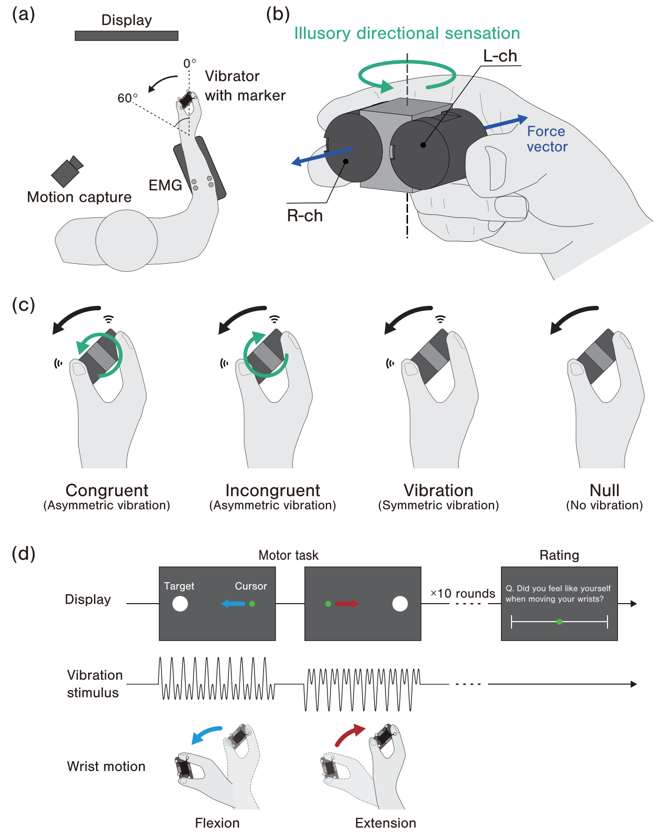

Fig. 1. Experimental setup. (a) Apparatus and participant postures. (b) Gripping method of vibrator (size: 53(w)×28(h)×27(d) mm and weight: 67.4 g). (c) Vibration stimulus conditions. The illustration shows the direction of the illusion during flexion motion. In extension motion, the direction of the illusion is inverted. (d) Timeline of the wrist motion, as well as visual and haptic feedback in a single trial.

and output as audio signals using Psychtoolbox, a library for psychophysical experiments. These signals were outputted from an audio interface (UAC-2, ZOOM Co.) and amplified using a D-class amplifier (PAM8403DR, Diodes Inc.). An accelerometer (pickup: Type-4517, Brüel & Kjær, amplifier: Type-2693-0S4, Brüel & Kjær) was used to measure the vibrations. An optical motion-capture device (OptiTrack V120 Trio, NaturalPoint Inc.) at a 120-frame rate was used to measure the flexion–extension motion of the wrist, and a rigid marker was attached to the vibrator. A display (LCD-GC242HXB, I-O DATA Device Inc.) was placed in front of the participant, showing the target position of the reaching motion and a cursor that moved horizontally in accordance with wrist motion (Fig. 1(d)). These drawings were developed using a visual design software (Processing Ver. 4.1.3), and the cursor drawing was updated to 120 fps to correspond to the rotation angle around the vertical axis of the vibrator, as measured by the motion-capture device. An electromyogram (EMG) sensor (Cometa Systems, Wave Wireless EMG) was used to measure the activities of the wrist flexor (flexor carpi radialis) and (extensor carpi radialis) muscles. A multifunctional data acquisition (DAQ) device (USB-6343, National Instruments Co.) was used to capture the measured accelerations and EMG readings at a sampling frequency of 20 kHz. The EMG signals were resampled offline at up to 2 kHz. The DAQ and motion-capture devices were synchronized using the synchronization signal output from the motion-capture device. A gamepad (JC-U3808TWH, ELECOM Co., Ltd.) was held on the left hand to indicate the subjective rating of the right wrist motions.

C. Vibration Stimulus Conditions

To test the effect of illusory directional sensations on wrist motion, a congruent condition, in which the wrist motion and direction of the cue matched, and an incongruent condition, in which the motion and direction were opposite, were set up (Fig. 1(c)). In other words, the congruent condition induced illusory sensation of left rotational direction during flexion and right rotational direction during extension, whereas, in the incongruent condition, the direction of the illusion was the opposite. For the asymmetric vibration stimulation to induce illusory directional sensations, we used the waveform of Eq. (1), as previously developed by our team [32].

$$\ddot{x}_{ref}(t) = A_1 \sin(2\pi f t) + A_2 \sin(4\pi f t + \phi_0) \quad (1)$$

This waveform consists of the fundamental and second harmonics, and the direction of the cue changes depending on the phase difference between two frequency components ϕ_0 [32]. Therefore, illusory left–right turning torques were induced by setting the phase difference to $-90°$ and $90°$, respectively. Based on the findings of previous studies [32], the amplitude of the acceleration $A_{1,2}$ and frequency f were set as 60 m/s^2 and 75 Hz, respectively. Prior to conducting the experiment, all participants were confirmed to be able to discriminate the direction of the illusory directional sensations (median correct response rate: 96.86%; interquartile range (IQR): 7.5%). Two control conditions were used. A vibration condition was established as the first control condition to examine the effect of simple vibration stimuli on wrist motion, and symmetric vibration (sinusoidal vibration) that could not induce illusory directional sensations was used. The sinusoidal vibration is the same as the asymmetric vibration stimulus for illusory sensations, with only A_2 being equal to zero in Eq. (1), and the other parameters were the same as those of the asymmetric vibration stimulus for illusory sensations. In the second condition, a null condition was established to evaluate baseline motion when the vibration stimulus was not applied.

D. Experimental Protocol

In this study, the effects of illusory directional sensations on the flexion–extension motion of the wrist were evaluated objectively and subjectively. For an objective evaluation, the trajectories of wrist motion and flexor and extensor EMG signals were used. The sense of agency was evaluated subjectively. The incongruent condition may not influence the sense of agency because feedback does not assist wrist motions. Instead, it was expected to influence the sense of effort because of the illusory sensation of pushing back against motion. Therefore, the sense of effort was also evaluated. Participants rated the following two questions between 0 and 100 points using a visual analog scale (VAS):

Agency

Q1. Did you feel like yourself when moving your wrists? (0 = The device moved it; 100 = I moved it myself).

Effort

Q2. How much effort is required to move your wrist? (0 = No effort at all; 100 = Maximum effort that can be exerted was required).

Fig 1(d) shows the timeline of the motor task. Participants were instructed to move the cursor toward the target on the display as quickly and accurately as possible by flexing and extending their wrists. The wrist motions were reaching motions between 0° that the wrist was straightened in a comfortable position and 60° on the adduction side (Fig.1(a)), and these motions were performed in reciprocal flexion (0° to 60°) and extension (60° to 0°). The next target was displayed when the cursor reached the target. Vibration stimulus was applied during these motions. Vibration stimuli were presented from the time the target was displayed until the cursor was reached. The above reciprocal motion of flexion–extension was handled as one round, and the participants performed ten rounds per trial. Subsequently, the participants answered the two questions described above and evaluated their subjective motion sensations. The aforementioned procedures (ten round motions and two subjective ratings) were considered in one trial, and eight trials were conducted for each vibration stimulation condition, amounting to 32 trials (four conditions $\times$ eight trials). The order of trials for the four vibration stimulation conditions was randomized. Considering the fatigue that arose during the experiment and the adaptation to the stimulus, all trials were divided into four blocks of eight trials each, and the participants were allowed 2-min breaks between successive blocks.

E. Data Analysis

1) Objective Evaluations: The time-series data (wrist trajectories and EMG signals) were preprocessed as follows. The trajectory of the wrist angle was time-differentiated and converted into angular velocity. EMG signals were processed using a Butterworth bandpass filter (order: 2, cutoff: 5–500 Hz) and a notch filter (cutoff: 50 Hz). The EMG signals were then converted into integrated EMG (iEMG) signals using a 50-ms sliding window centered at every sampling interval. While the time-series data include a total of 640 reaching motions (ten rounds $\times$ two motions (flexion or extension) $\times$ four vibration stimulus conditions (congruent, incongruent, vibration, or null) $\times$ eight trials) for each participant, angular velocity and iEMG time-series data of each reaching motion were extracted. Owing to the different durations of reaching motions, the time scale of time-series data for each reaching motion was normalized from 0% (the beginning of the reaching motion) to 100% (the end of the reaching motion). To obtain typical examples of the time-series data of angular velocity and iEMG signals for each vibration stimulus condition and each motion, the time-series data were averaged across the rounds and trials.

To determine the effects of vibration stimulus conditions and motions (flexion and extension) on wrist trajectories, the maximum angular velocities were compared using two-way repeated-measures analysis of variance (ANOVA). The maximum angular velocities for reaching motions were averaged for each participant, each vibration stimulus condition, and each motion; and then the averaged values were used for the statistical analysis. If Mauchly's sphericity test was significant, the Greenhouse–Geisser correction was applied. A paired-samples t-test with Bonferroni correction was performed as a post-hoc test. For iEMG data, the averaged activities of the agonist muscle during the entire period of reaching each motion (flexor iEMG signal in flexion and extensor iEMG signal in extension) were compared under vibration stimulus conditions using a one-way repeated-measures ANOVA. The average activity of the agonist muscle was normalized using the z-score because the amplitudes of the iEMG signals differed between participants. The z-scores for reaching motions were averaged for each participant, each vibration stimulus condition, and each motion; and then the averaged values were used for the statistical analysis.

To clarify the relationship between the angular velocity and iEMG signals, the correlation coefficients between the maximum angular velocity and averaged iEMG data for all trials for each participant were calculated for each motion. The normalities of the distribution of these correlation coefficients were not rejected by Shapiro–Wilk test. Therefore, a one-sample one-tailed t-test was performed for each motion to show that these correlation coefficients were not negative, assuming that the fast motion generated higher-amplitude iEMG signals (positive correlation).

2) Subjective Evaluations: In the subjective evaluation, the median VAS values of the sense of agency and effort were computed for each vibration stimulus condition. Because normality (Shapiro–Wilk test) was rejected for both agency and effort, a nonparametric analysis (Friedman's test) was used to compare the vibration stimulus conditions. The Wilcoxon signed-rank test with Bonferroni correction was performed as a post-hoc multiple comparison test. Kendall's rank correlation coefficients were calculated for each vibrational stimulus condition to validate the relationship between agency and effort.

3) Differences Among Participants: Differences in the effects of illusory sensations on wrist motion among participants were analyzed. The participants were instructed to move the cursor quickly toward the target, and the motion velocity was not controlled. Variations in the reaching time (time from the start of the motion until the cursor reached the target) were observed among the participants. The reaching time is not only directly related to the wrist velocity, but also to the load of motion, which is expected to influence the sense of agency. Therefore, analyses were conducted to demonstrate individual differences based on differences in the reaching time. Specifically, the correlations between reaching time and the effects of different directions of illusory directional sensations on the sense of agency (Kendall rank correlation coefficient) or angular velocity (Pearson correlation coefficient) were investigated. The differences in the VAS scores of the sense of agency between the congruent and incongruent conditions were used as subjective differences in wrist motion. The objective difference in motion was the difference in the maximum angular velocity between the congruent and incongruent conditions normalized by the average maximum angular velocity for each participant. In other words, this index indicates the ratio of the angular velocity difference between the illusion conditions to the average maximum angular velocity.

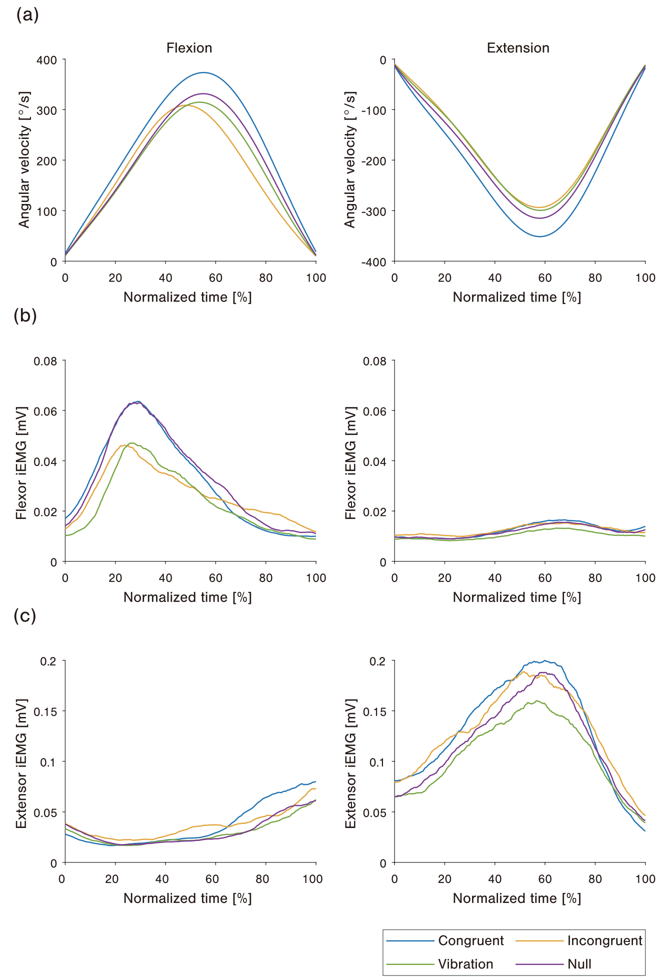

Fig. 2. Typical example of averaged wrist angular velocities and EMG signals in each motion (left line: flexion, and right line: extension). (a) Trajectories of angular velocity. (b) Flexor iEMG. (c) Extensor iEMG.

III. Results

A. Objective Evaluations

Fig. 2 (a) shows typical examples of time-series data of angular velocity. The angular velocity profiles were bell-shaped, which was consistent with the velocity trajectory of general ballistic motion. Fig. 3 shows the maximum angular velocities under each condition and motion. The results of the two-way repeated-measure ANOVA showed that the main effect of the vibration stimulus was significant ($F(2.31, 43.84) = 7.45, p < 0.001, \eta^2 = 0.19$); however, the main effect of motion ($F(1, 19) = 1.68, p = 0.21, \eta^2 = 0.03$) and the interaction between the vibration stimulus and the motion ($F(1.82, 34.65) = 2.36, p = 0.11, \eta^2 = 0.004$) were not significant. Multiple comparisons between the vibration stimuli showed that wrist motion under the congruent condition was significantly faster than that under the incongruent ($p < 0.001, d = 0.26$) and null conditions ($p < 0.01, d = 0.22$). In contrast, no significant differences between the congruent–vibration ($p = 0.06, d = 0.16$),

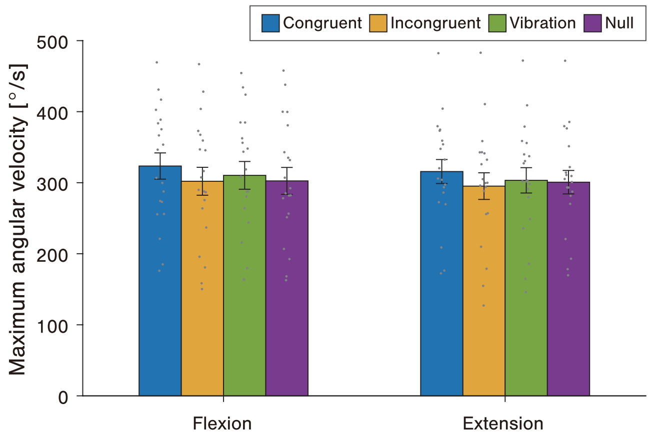

Fig. 3. Maximum angular velocities (absolute values of the peak of the bell-shaped velocity trajectories) of each vibration stimulus and motion. The bars indicate the means for all participants and error bars indicate standard errors. The dots indicate maximum velocities in each participant.

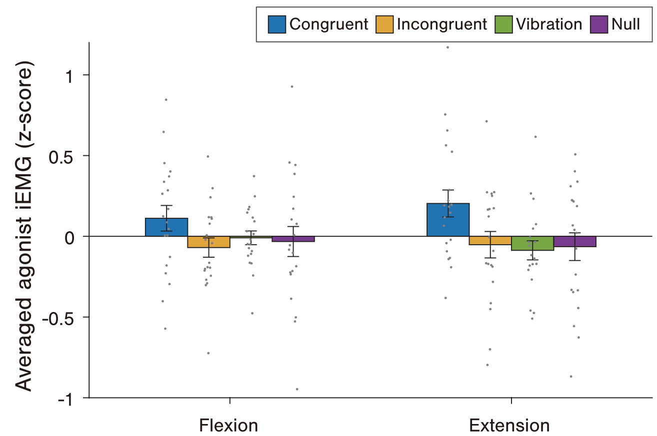

Fig. 4. Average iEMG (z-score) data during the entire reaching period for each motion. The bars indicate the means for all participants and error bars indicate standard errors. The dots indicate averaged iEMG in each participant.

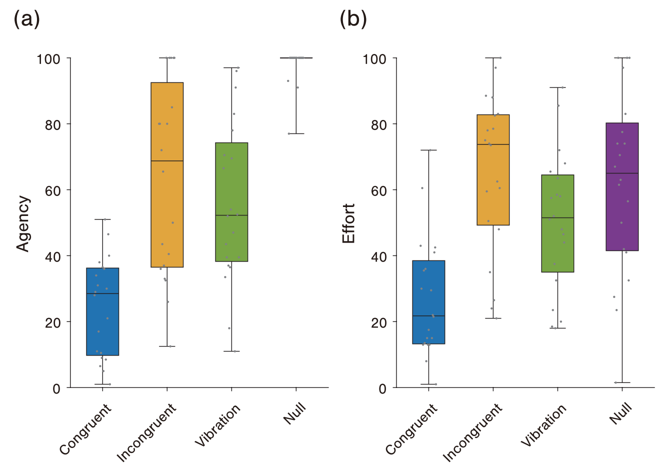

Fig. 5. Boxplots of subjective ratings using the VAS. The top and bottom parts of the box indicate the lower and upper quartiles of the score, whiskers indicate the minimum and maximum values of the score, and the horizontal bar indicates the median value of the score. The dots indicate VAS scores in each participant. (a) Sense of agency. (b) Sense of effort.

incongruent–vibration ($p = 0.55, d = 0.10$), incongruent–null ($p = 1.00, d = 0.04$), and vibration–null ($p = 1.00, d = 0.06$) were found.

The flexor and extensor iEMG signals had higher amplitudes in their primary motions, indicating that they were iEMG signals representing the activity of the agonist muscle (Figs. 2 (b), (c)). Fig. 4 shows the average iEMG signal during the entire reaching period for each motion. Although the mean z-score of iEMG signals was higher in the congruent condition than that in the other conditions, the main effects of the vibration stimulus on the iEMG signal during the activities of the agonist muscle were not observed in either flexion ($F(2.15, 40.84) = 0.91$, $p = 0.42$, $\eta^2 = 0.05$) or extension ($F(3, 57) = 2.28$, $p = 0.09$, $\eta^2 = 0.11$). Furthermore, the correlation coefficients between the maximum angular velocity and averaged iEMG data were 0.21 ± 0.05 (standard error) in flexion and 0.38 ± 0.04 (standard error) in extension. A one-tailed t-test indicated that these correlation coefficients were not negative (flexion: $t(19) = 4.30$, $p < 0.001, d = 0.96$; extension: $t(19) = 10.55$, $p < 0.001, d = 2.36$).

B. Subjective Evaluations

Fig. 5 shows subjective ratings of agency and effort. The Friedman test results showed that the main effect of the vibration stimulus on the agency was significant ($\chi^2(3) = 47.09$, $p < 0.001$). The sensation of the hand being moved by the vibrator (device) was induced during the congruent condition because the agencies were significantly lower in the congruent condition than in the incongruent condition ($p < 0.001, r = 0.73$), vibration ($p < 0.001, r = 0.70$), and null ($p < 0.001, r = 0.75$) conditions. Although the sense of agencies in the incongruent ($p < 0.001, r = 0.60$) and vibration ($p < 0.001, r = 0.75$) conditions were lower than that in the condition with no vibration stimulus, it should be noted they were significantly higher than in the congruent condition, as mentioned. No significant difference was found between the incongruent and vibration conditions ($p = 0.23, r = 0.32$). In terms of the effort, the main effect of the vibration stimulus was significant ($\chi^2(3) = 23.67$, $p < 0.001$). The results of the post-hoc test indicated that the congruent condition required significantly less effort than the incongruent ($p < 0.001, r = 0.70$), vibration ($p < 0.01, r = 0.58$), and null ($p < 0.01, r = 0.50$) conditions. Additionally, a significant difference was observed between the incongruent and vibrational conditions ($p < 0.05, r = 0.43$). In contrast, the incongruent ($p = 1.00, r = 0.07$) and vibration ($p = 0.46, r = 0.28$) conditions did not significantly change the effort compared to the null condition. Positive correlations between agency and effort were found for the congruent ($\tau = 0.62$, $p < 0.001$), incongruent ($\tau = 0.59$, $p < 0.001$), and vibration conditions ($\tau = 0.37$, $p < 0.01$), but not for the null condition ($\tau = 0.20$, $p = 0.32$).

C. Differences in the Effects of Illusory Directional Sensation

Fig. 6 shows the scatter plots between the reaching time and differences in agency between congruent and incongruent conditions. The lower the value on the vertical axis, the lower the sense of agency under congruent conditions.

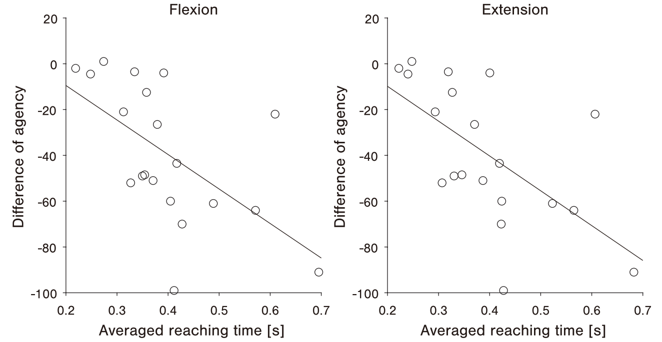

Fig. 6. Scatter plots between the reaching time and the difference in subjective motion (i.e., difference in agency) under congruent and incongruent conditions.

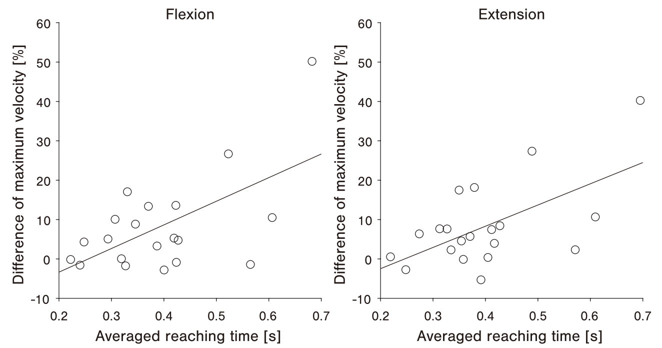

Fig. 7. Scatter plots between the reaching time and the difference in objective motion under congruent and incongruent conditions (i.e., ratio of velocity difference between the illusion conditions to the average maximum velocity).

Correlation analysis showed negative correlations for both motions (flexion: $\tau = -0.49$, $p < 0.01$ and extension: $\tau = -0.55$, $p < 0.001$). Fig. 7 shows the scatter plots between the reaching time and the difference ratio of angular velocity. The higher the value on the vertical axis, the higher the maximum angular velocity under the congruent condition. In contrast, the correlation analysis showed positive correlations for both motions (flexion: $r = 0.59$, $p < 0.01$ and extension: $r = 0.55$, $p < 0.01$).

IV. Discussion

A. Effect of Illusory Directional Sensations on the Wrist Motion

In this study, the wide variance observed under the incongruent and vibration conditions suggests that the agency of motion under these conditions was vague and that the participants faced difficulty in assigning ratings after performing the motion. In contrast, the sense of agency was consistent under the other two conditions, that is, higher and lower senses of agency were observed under the null and congruent conditions, respectively. These results suggest that the origin of the agency of motion is clear under congruent and null conditions. Moreover, the sense of agency in the congruent condition was significantly lower than that in the null condition. Therefore, the sensation that the hand is being moved is induced when the direction of the illusion coincides with wrist motion.

In terms of effort, although we expected a higher sense of effort owing to the application of illusory sensations to push back against the motion in the incongruent condition, no significant difference was observed between the null and incongruent conditions. Although previous studies have reported that the perceived weight of an object can be enhanced by an illusory sensation in the vertical direction [12], [21], [22], we could not find that the load could be enhanced by the illusion of horizontal motion. In contrast, because the sense of effort in the congruent condition was significantly lower than that in the null condition, it was possible to perceive it as a lighter load owing to the illusion. Although the agency distribution for the null condition was significantly concentrated at approximately 100 points, agency and effort ratings were correlated under other conditions. These conditions were not completely independent in this experimental motor task. Thereafter, the discussion was based primarily on the sense of agency.

Regarding the effect of illusion on motion, despite the ballistic reaching motion, the angular velocity of the wrist was significantly higher in the congruent condition than in the incongruent or null conditions. This difference in velocity was slight; however, it was statistically significant. Consequently, both the sense of agency and motion (angular velocity of wrist motion) were changed by illusory directional sensations, as hypothesized. Although the sense of agency under the incongruent and vibration conditions also decreased compared with that under the null condition, differences in velocity were not observed. Therefore, a decrease in the sense of agency and an increase in the velocity of motion were observed only when the directions of the motion and illusory sensations coincided.

Why did the velocity of motion increase in congruent conditions? We posit that the participants themselves increased their wrist velocity because no actual external force was applied to the hand to accelerate the motion; only the vibration stimulus was present. The muscle activity during wrist motion also provides evidence that there is no external force, as shown below. Generally, when an actual external force is applied to a hand that pushes back (i.e., the motion and actual force directions are opposite), the amplitude of the EMG signal increases with the contraction of the agonist muscle [33], [34]. In addition, when the motion is physically assisted (i.e., the motion and actual force directions are the same), the EMG signal may be small, because the wrist can be moved using a small torque. In contrast, in the case of the illusory sensation, it differed from the muscle activity described above. In the iEMG results of this study, no significant main effect was observed between the vibration stimulus conditions during the extension motion ($p = 0.09$). However, the effect size was not small ($\eta^2 = 0.11$). Specifically, we observed a trend where the iEMG signal under the incongruent condition (i.e., the motion and perceived force directions were opposite) was lower, while under the congruent condition (i.e., the motion and perceived force directions were the same), it was higher. Additionally, the correlation between the maximum angular velocity and average iEMG value, although weak, was not negative ($p < 0.001$ for flexion and extension). Because a higher motion velocity under each vibration stimulus condition tends to result in an EMG signal with a higher amplitude, the differences in motion velocity may have been caused by the adjustment of muscle activity by the participant. In summary, by presenting a congruent illusory sensation in accordance with wrist motion, the participants felt that the hand was being moved by the device, even though their own wrist-motion velocity increased.

In terms of the differences in the effects of illusory sensations on wrist motion among the participants, participants with longer reaching times tended to have larger differences between the congruent and incongruent conditions. This trend was also observed for agency (Fig. 6) and angular velocity (Fig. 7). Therefore, we inferred that an illusory sensation affects slow ballistic motion, whereas it is difficult to make fast motions faster. Considering that the illusory directional sensation affects the sensory system, we must assume that feedback from the illusion affects the motor control system and causes a change in velocity.

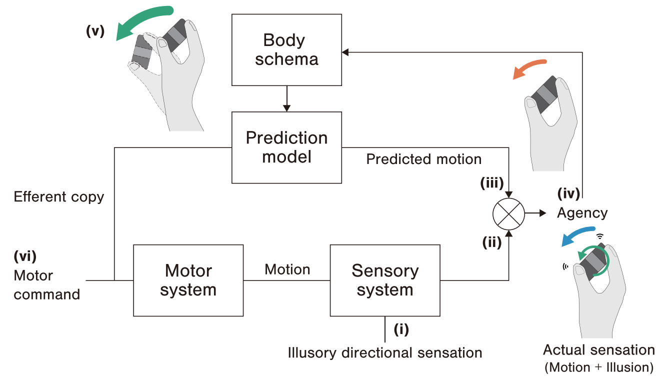

Fig. 8. Active motion and illusory directional sensations in the comparator model with an additional body schema [35]. (i)–(vi) indicate the events that occur during the active motion with the illusory directional sensation.

B. Mechanisms That Change the Sense of Agency and Wrist-Motion Velocity

The phenomenon of a decreased sense of agency, despite the participants speeding up the wrist motion by themselves, was examined based on the comparator model (Fig. 8), as outlined in [35]. This model incorporates the generation of a body schema, wherein the agency arises from a comparison of predicted and actual motions [23], [24], [25]. This model is deemed reasonable because the agency contributes to updating the body schema [27], which is recognized as an internal model in motor control [36]. This is shown in (i) Fig. 8, illusory sensations were inputted into the sensory system, inducing only the sensation of force, whereas physical external forces were inputted into the motor system in the comparator model [23]. When the illusory directional sensation coincided with the direction of the active motion, the sensations experienced were a combination of those caused by the motion and pulling force of the illusory sensation (ii). With the motor command to perform active wrist motion, an efferent copy of the motion is generated, and the sensation of the motion that is fed back is predicted (iii). However, because an illusory directional sensation was added to the sensation of wrist motion, a discrepancy was observed between the actual (ii) and predicted (iii) sensations. This discrepancy contributes to a reduction in the sense of agency (iv). With regard to the diminished effect of illusory sensations on participants with shorter reaching times (Figs. 6–7), we deduce that in cases of faster motion, the sensation of predicted motion outweighs the illusion, resulting in a smaller discrepancy at the comparator.

Next, we focused on the transformation of the body schematic to discuss the increase in wrist-motion velocity. The body schema is plastic and updated occasionally through various actions [28], [29]. In the illusory sensation congruent with motion (i), the body schema was updated to feel as if the wrist was flexed and extended to a greater degree than in the actual wrist motion (v). To increase the sense of agency in the updated body schema, the prediction model must be adapted to the current body schema, and the discrepancy between the sensations of the actual and predicted motions must be reduced. This required the sensation of a larger motion to be counteracted by participants' own motions. Strategies to counteract this sensation include increasing the stiffness of the wrist joint, or the motion generated to follow the sensation of a larger motion. However, the former strategy is not practical for performing a motor task because the participants must move their wrists quickly to the target. Therefore, in this study, the latter strategy, which strengthens the motor commands, may have been preferred, leading to faster motion (vi). However, even if a slightly faster motion is generated by the strengthened motor command, illusory sensations cannot be counteracted, because they are not directly affected by the motion output of the motor system (i). As a result, the discrepancy between the sensation of actual (ii) and predicted (iii) motions remained, and a low sense of agency (iv) and strengthened motor command (vi), that is, fast motion, were maintained. A previous study reported that interventions in the somatosensory system changed the sense of agency, with no significant impact on motion [37]. To the best of our knowledge, this is the first study in which motion changed with a change in sense of agency.

C. Limitations and Future Scope

The model shown in Fig. 8 is provisional, and, currently, knowledge whether the body schema has actually been updated is unclear. To clarify this, it is necessary to evaluate the subjective wrist angle during illusions [30]. In addition, we could not compare the illusory directional sensations with an external physical force. If we conduct such experiments using physical external forces consistent with wrist motion, we can expect the forces to decrease the sense of agency and increase wrist velocity. However, we expect EMG activity to differ between illusory directional sensation and physical external forces because wrist motion, when physically assisted, can be moved with a smaller torque exerted by muscles. In the future, a comparison between illusory sensations and physical external forces must be conducted to better understand the effects of illusions on motion.

V. Conclusion

This study investigated the influence of illusory directional sensations on wrist motion. The results showed that, when motion and illusory directional sensations were congruent, the sense of agency for motion decreased. In addition, the angular velocity of the wrist increased, and the EMG activity suggests that the increase in velocity might have been caused by the participants. In summary, the congruence between the direction of motion and illusory directional stimulation induced the sensation of the hand being moved, whereas the participants' wrist-motion velocity increased. It is possible that the illusory directional sensation during motion induced a reduction in the sense of agency associated with the discrepancy between the predicted and actual motions, and further caused the body schema to be updated. As the sense of agency and body schema play important roles in motor control [28], [38], the findings of this study may provide guidance for the design of a novel rehabilitation method. Therefore, future studies should explore specific rehabilitation targets.

Acknowledgment

The authors would like to thank M. Saitou of the National Institute of Advanced Industrial Science and Technology (AIST) for her support with the experiments.

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