The Effects of Simultaneous Multi-Point Vibratory Stimulation on Kinesthetic Illusion

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Abstract. Kinesthetic sensation is important for improving presence and immersion in VR environments. However, presenting kinesthetic sensation usually requires a large space so as to avoid users colliding with objects or other users. One of the ways to tackle this issue is to use kinesthetic illusion, which is a way of presenting kinesthetic sensation without physical motion. However, realizing dynamic motion and fast movement remains difficult. Considering that multiple synergist muscles are usually involved in a movement such as walking or even simple arm movement, stimulating multiple synergist muscles might enhance the illusion. Thus, we investigated whether multi-point vibratory stimulation to multiple synergist muscles enhances induced kinesthetic illusions. We found that stimulating multiple synergist muscles created more vivid illusions. Additionally, we found that our method was effective for inducing steady illusions. We also calculated the contribution of each proposed stimulation point to the illusion.

Keywords: Kinesthetic Illusion · Proprioception · Tendon Vibration

1   Introduction

Presenting proprioception and kinesthetic sensation is important for improving presence and immersion in VR environments. Usually, kinesthetic sensation is presented using equipment that incorporates actual user motion such as walking. However, this requires a large space. Otherwise users might collide with objects and other people.

These issues can be resolved by inducing only kinesthetic sensation without physical motion. Kinesthetic illusions, which are illusions of the position and movement of one's own body and induced by stimulating proprioceptors such as muscle spindles [1], can achieve this goal.

Kinesthetic illusions are often induced using about ∼100-Hz tendon vibrations [4]. Although skin deformation [2] and electrical stimulation of tendons [5] can induce movement illusion, tendon vibration is more effective, considering that muscle spindles contribute a great deal to kinesthetic sensation [7]. The intensity of the illusion depends primarily on the vibration frequency and amplitude [8,10]. The preload force of the vibrator is also known to affect the threshold of vibration amplitude for eliciting the illusion [3].

However, the intensity of the illusion induced by tendon vibration is not enough for realizing dynamic and fast movement. One reason might be that the stimulation point is limited. Yaguchi et al. [14] reported that kinesthetic illusion was enhanced by stimulating two synergist muscles or tendons at both ends. Even though previous studies have examined stimulating one or two synergist muscles, actual movement involves many synergist muscles. Therefore, stimulating multiple synergist muscles can induce the more natural and large kinesthetic illusion.

In our previous report [13], we preliminarily confirmed that multi-point vibratory stimulation induced more steady illusion than the illusion induced by one or two points of stimulation. In this paper, we investigate the effects of multi-point vibration in more detail as well as the contribution of each vibration position to the illusion.

2   Methods

Twelve participants (10 men and 2 women; aged 21 to 25 years old; all right-handed) took part in the experiment. We presented vibration stimulation to seven positions on the left chest, upper arm, and forearm to induce the arm extension illusion, and Fig. 1 (left) shows the vibrator positions (1 to 7) over the same tendons that we tested in our previous report [13]. We hypothesized that each vibratory stimulation would contribute differently to the illusion and illusions induced by each vibration could be composited linearly as the vector model of the illusion [9, 11].

Optical motion capture (OptiTrack V120:Duo) was used to measure participant movement. Fig. 1 (right) shows seven positions on the neck, shoulders, elbows, and wrists where we placed retroreflective markers. The marker positions were recorded in a left-handed coordinate system, as shown in Fig. 1 (center).
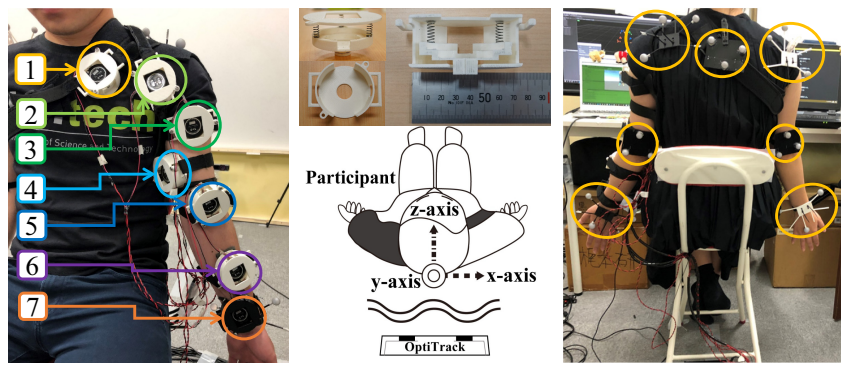

Fig. 1. (Left) Positions of vibrators. (Center) The design of the vibrator case, and the coordinate system (top view) used to record participants' movement. (Right) Positions of markers for measuring movement via optical tracking camera.

2.1 Vibratory Stimulation

The vibrator (Acouve Lab VP 210) was hung on three springs (overall stiffness: 1.2 N/mm) in the vibrator case (Fig. 1, center) The bottom of the vibrator case was covered by a sponge to avoid pain, and the case was mounted with rubber bands and a supporter (Fig. 1, left). The preload force of vibrators was adjusted from 1.2N to 2.4N by observing the displacement of the head contacting the skin. Based on a previous study [8], we set the vibration frequency to 70 Hz. The acceleration amplitude was adjusted to 90 m/s^2 with an accelerometer (Sparkfun LIS331). The input signal to the vibrators was generated with the same system as in our previous report [13]

2.2 Procedure

The experiments were carried out over two days by dividing the trials of presenting vibration in half so as to prevent participants' fatigue.

Participants were told the posture during the experiment and asked to wear the experiment devices. In particular, the vibrator cases were mounted on the target positions identified by touch. Each vibrator's acceleration amplitude and each OptiTrack marker were calibrated. After that, we measured the ability to express movement, and collected data of the vibration-induced illusions.

Measurement of the ability to express movement Preliminarily, we measured the ability to mirror the movement of the left arm with the right arm in order to screen out participants who cannot accurately evaluate the illusions by this method.

The experimenter moved the participant's left arm sinusoidally around the shoulder in two directions (flexion/extension and adduction/abduction) and participants mirrored the movement with their right arm. Six trials (three in each direction) were carried out randomly. The three trials in each direction included two trials of slow movement (about 3 deg/s) and one trial of fast movement (about 10 deg/s). The order of trials was different for each participant. The duration per one trial was 10 seconds.

Data collection of induced illusions We applied 127 vibration patterns (2^7-1), which included all combinations of the seven vibrators. Each vibration pattern was applied one time and the order of patterns differed across participants. Vibration was applied for 5 seconds with closed eyes. A 5-second interval divided each trial and a 1-minute interval separated every 10 trials. Participants were alerted to the timing of the next trial via headphones, which also served to mask sound cues via white noise.

During the vibration, participants were asked to express the perceived illusion by their right arm. After the vibration, participants answered three questions on a scale of 1 to 10 (Table 1), based on previous studies [6, 12]

Table 1. The evaluation scales of the illusion [6, 12].

Questions	(1) minimum and (10) maximum
Vividness	(1) The illusion was not vivid at all.
	(10) Perceived the illusion as if they were actually moving
Duration	(1) There was no illusion
	(10) The illusion evoked for stimulation
Magnitude	(1) The arm felt like it did not move very much
	(10) The arm felt like it moved as much as was possible

Prior to data collection, participants became accustomed to the measurement procedure through a practice stage in which the five trials were carried out. The order of vibration patterns differed from those in the actual measurement.

2.3   Data Analysis

We calculated the angular velocity by dividing the angle difference between the initial and the end arm position by the vibration duration. The arm angle was calculated using the arm vector from shoulder position to wrist position measured by OptiTrack. The flexion/extension (y-z plain; extension is the positive direction) and adduction/abduction (x-z plain; abduction is the positive direction) directions were used for analysis.

3   Results

3.1   Measurement of the ability to express movement

We calculated the error angle of right arm movement with respect to the left arm movement. In the flexion/extension direction, the average error was 1.92 $\pm$ 5.43deg. In the adduction/abduction direction, the average error was -5.79 $\pm$ 3.91deg.

There was no participant who was not able to mirror both arms at all. Thus, we used the data of all participants for analyzing.

3.2   Data collection of induced illusion

The 0.72% data (11 trials/1524 trials) was excluded from data analysis because tracking was lost during vibration. We analyzed the angular velocity of the right arm movement that expressed the illusory movement of the left arm.

The angular velocity in the extension/flexion direction is represented by ω_{yz} and the angular velocity in the adduction/abduction direction is represented by ω_{xy}. Fig. 2 shows the average angular velocity of each vibration pattern in each direction. Vertical vibration patterns on the horizontal axis indicate which vibrators used (1 to 7 from the top). The open circles indicate a vibrator was not used and closed circles indicate that it was.
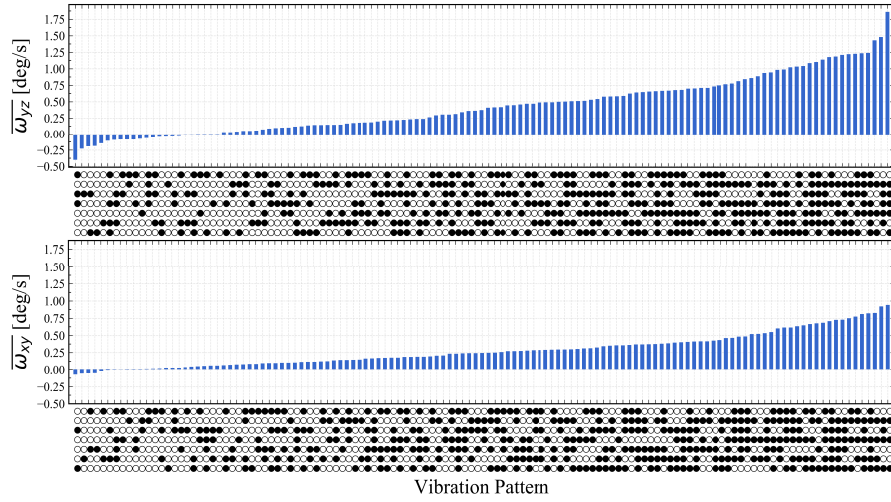
Fig. 2. (Above) Average ω_{yz} for each vibration pattern. (Below) Average ω_{xy} for each vibration pattern. vibration pattern corresponds to vibrators 1 through 7 (from the top).

A multiple regression analysis of the average angular velocity in each direction based on the vibration pattern (each vibrator was coded as ON=1, OFF=0) yielded the coefficients shown in Table 2. The regression equations for each angular velocity were statistically significant (ω_{yz} model: $F_{(7,119)} = 32.942$, $p < 0.001$, the adjusted $R^2 = 0.640$, ω_{xy} model: $F_{(7,119)} = 29.204$, $p < 0.001$, the adjusted $R^2 = 0.610$) and expressed as follows: $\omega_{yz} = -0.042v_1 + 0.385v_2 + 0.112v_3 + 0.254v_4 + 0.441v_5 + 0.138v_6 + 0.292v_7 - 0.347$, $\omega_{xy} = -0.005v_1 + 0.229v_2 + 0.038v_3 + 0.216v_4 + 0.023v_5 + 0.112v_6 + 0.171v_7 + 0.111$ (v_i: vibrator i).

Fig. 3 shows scatter plots of correlation coefficients between the average value of each evaluation scale and the applied vibration points. Subjective evaluation values were averaged for each vibration pattern.
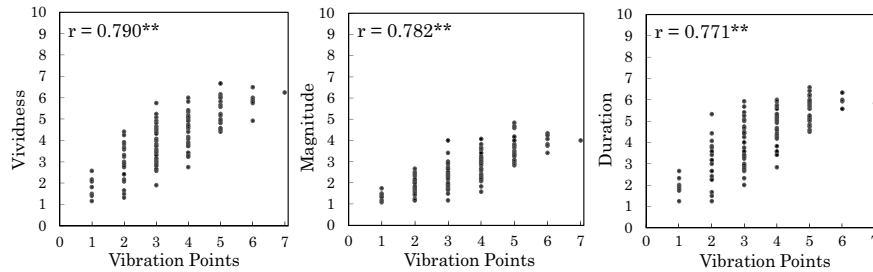

Fig. 3. Correlations (r) between vibration points and each subjective evaluation. **, $p < 0.01$

Table 2. The results of multiple regression analysis of each average angular velocity based on vibration patterns.

		Unstandardized Coefficients	Standard Error	Standardized Coefficients	t	p	Collinearity Statistics Tolerance	VIF
	(Constant)	-0.347	0.067		-5.20	<0.001		
	Vibrator 1	-0.042	0.046	-0.049	-0.913	0.363	1.000	1.000
	Vibrator 2	0.385	0.046	0.449	8.396	<0.001	1.000	1.000
	Vibrator 3	0.112	0.046	0.131	2.440	0.016	1.000	1.000
ω_{yz} model	Vibrator 4	0.254	0.046	0.296	5.537	<0.001	1.000	1.000
	Vibrator 5	0.411	0.046	0.479	8.958	<0.001	1.000	1.000
	Vibrator 6	0.138	0.046	0.161	3.003	0.003	1.000	1.000
	Vibrator 7	0.292	0.046	0.340	6.361	<0.001	1.000	1.000
	(Constant)	-0.111	0.038		-2.921	0.004		
	Vibrator 1	-0.005	0.026	-0.010	-0.179	0.859	1.000	1.000
	Vibrator 2	0.229	0.026	0.489	8.788	<0.001	1.000	1.000
	Vibrator 3	0.038	0.026	0.080	1.441	0.152	1.000	1.000
ω_{xy} model	Vibrator 4	0.216	0.026	0.460	8.275	<0.001	1.000	1.000
	Vibrator 5	0.023	0.026	0.049	0.883	0.379	1.000	1.000
	Vibrator 6	0.112	0.026	0.238	4.288	<0.001	1.000	1.000
	Vibrator 7	0.171	0.026	0.364	6.547	<0.001	1.000	1.000

4   Discussion

4.1   Multiple regression analysis of average angular velocity based on vibration pattern

In ω_{yz} model (Table 2), vibrators 5, 2, and 7 had the highest standardized coefficients, in that order. Actually, vibrators 5 and 2 were always included in the higher order patterns in Fig. 2 (above). In ω_{xy} model, vibrators 2, 4 and 7 had the highest standardized coefficients in that order. Vibrators 2, 4 and 7 were always included in the higher order patterns in Fig. 2 (below).

It was common for vibrators 2 and 7 to have large effects in each model. The main difference was that vibrator 5 had the largest effect in the ω_{yz} model and vibrator 4 had a relatively small effect, while in the ω_{xy} model, the vibrator 4 had one of the largest effects. This can be understood by considering a vector model of muscle spindles [9, 11], that is composed of the vectors of expected illusion directions and magnitudes when the muscle is stimulated. The coracobrachialis (vibrators 2 and 4), and the wrist flexors (vibrator 7) have vectors that point toward the compounded direction of extension and abduction, and the biceps brachii (vibrator 5) have a vector purely in the extension direction.

More interestingly, wrist flexors, which are not related to the motion of the shoulder joint directly, contributed a great deal to the illusion. We considered it is possibility because vibration applied to wrist flexors induced a motor image similar to what is experienced when the arm is moved by external force

exerted on the hand. This image could have enhanced the kinesthetic illusion. The participants actually commented that they felt passive arm movements.

In Fig. 2, the minus value means that participants expressed flexion. This is because tonic vibration reflex (TVR) was evoked in the experiment accidentally. In some participants, the reflex was induced even for the vibration patterns that induced strong illusions in others. These data decreased the accuracy of the models of multiple regression analysis.

4.2   Relationship between the strength of the illusion and the points of vibration

We found significantly positive correlations between each subjective evaluation scale and the vibration points (Fig. 3). This means that vivid and large kinesthetic illusions can be induced by multi-point vibratory stimulation. It also suggests that even though vivid illusions can be induced by strong vibration applied to single point, the same effect can be elicited by mild vibration distributed over several points.

4.3   Tendons and muscles of the stimulation points

In this experiment, the tendons were not stimulated directly in all positions. Albeit the tendons of the coracobrachialis were located under the deltoid (vibrator 2) and biceps brachii (vibrator 4), each position was effective for illusion. This result indicates that the illusion was elicited by indirect vibration to the tendon, and the muscle spindles can be stimulated effectively through coracoid process (located in vibrator 2). In particular, the vibrator 4 contributed differently to the direction of the illusion than vibrator 5 did. Kinesthetic illusion can be induced even by stimulating muscle belly [3,4]. This implies that the deltoid contributed to the illusion induced by vibrator 2 and the biceps brachii also contributed to the illusion induced by vibrator 4.

5   Conclusion & Future Work

The purpose of the present study was to investigate the effect that increasing the number of vibratory stimuli has on the kinesthetic illusion. Vibrators were placed at seven positions on the synergist muscles around the chest, upper arm, and forearm, and all vibration combinations were tested. We found that multi-point vibration induced illusions steadily and found the optimized vibration pattern which evoke more rapid illusion than the illusion induced by seven vibratory stimuli (Fig. 2).

In this experiment, the average angular velocity of the illusion was about 2 deg/s at most. Thus, we think that the limit of vibration-induced illusions is suggested. In future, further analysis of the data needs to be performed, and combinations with other modalities should be investigated.

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