Modulation of a Hand-held Object's Property through Proprioceptive Stimulation during Active Arm Movement

Proprioceptive Modulation of a Hand-held Object's Property

Keigo Ushiyama
The University of Electro-Communications, Tokyo, Japan
ushiyama@kaji-lab.jp

Akifumi Takahashi
The University of Electro-Communications, Tokyo, Japan
a.takahashi@kaji-lab.jp

Hiroyuki Kajimoto
The University of Electro-Communications, Tokyo, Japan
kajimoto@kaji-lab.jp

ABSTRACT

The purpose of this study was to investigate whether stimulation of the proprioceptors in the arm during active movement can affect not only the proprioception of the arm but also the perception of the hand-held object. If it is possible to control the perception of a hand-held object through stimulation to the body, it can be applied to virtual-reality interfaces and controllers, which can be used in a wide range of situations. In the experiment, proprioceptive stimulation was based on the kinesthetic illusion induced by vibratory stimulation of muscle spindles and skin stretch near the joint. Participants were given a context in which they grasped an object and actively moved. They were asked to evaluate the perception of the object and the arm as the phase between movement and stimulation, and the conditions of stimuli were changed. Consequently, it was found that the perception of not only the arm but also the hand-held object could be changed, although there were large individual differences.

CCS CONCEPTS

• **Human-centered computing** → Human computer interaction (HCI); Interaction devices; Haptic devices; Human computer interaction (HCI); Interaction paradigms; Virtual reality.

KEYWORDS

Hand-held Object, Kinesthetic Illusion, Proprioception

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1 INTRODUCTION

Peripheral signals from proprioceptors in muscles, tendons, and skin are used to perceive the position, movement, and force of the body. Golgi tendon organs are mainly sensors of muscle tension, and muscle spindles are sensors of limb position and velocity. In addition, it has been reported that muscle spindles contribute to weight perception [1–3].

It is known that stimulating these proprioceptors can induce body illusions, and in many researchers have studied the illusion using methods to stimulate muscle spindles by vibration. Goodwin and his colleagues reported the kinesthetic illusion, that is a sensation of only kinesthesia without physical motion when applying approximately 100 Hz of vibration to tendons [4]. In addition, Lackner reported that body representation was modulated such as elongation of the nose and tilting of the body through vibrating distal tendons of flexor muscles located in the upper limb while touching the target part [5]. The vibration of the wrist while grasping an object can elicit the movement illusion of the hand and object [6]. Kinesthetic illusion can also be evoked by electrical stimulation of tendons and by stretching the skin of the subject limbs [7–9].

This illusory phenomenon is also influenced by vision [10], vestibular sensation, sound [11], and contexts of touch and body posture [12, 13]. The primary somatosensory cortex and motor cortex are activated by tendon vibration, indicating that this illusion is attributed to the processing of peripheral signals in the brain [14, 15].

Most previous studies on kinesthetic illusions have focused on illusory phenomena related to one's own body posture and movement. On the other hand, given that kinesthetic illusions strongly depend on the context and that proprioceptors contribute not only to the perception of one's own body, but also to the perception of the weight and length of the object being touched [16], it should also be possible to modulate the properties of the object being touched. In the paradigm of human-computer interaction (HCI), many virtual reality (VR) interfaces have been developed to change the weight, length, and stiffness of devices [17–19]. By stimulating the proprioceptors and controlling the perception of objects, it is possible to create interfaces that perceptually change the weight, length, and other physical properties of grasped objects in a similar manner.

In this study, we investigate whether the perception of the physical properties of a grasped object can be changed by inducing kinesthetic illusions or stimulating proprioception in the context of grasping and moving the object. As a first step, the sinusoidal

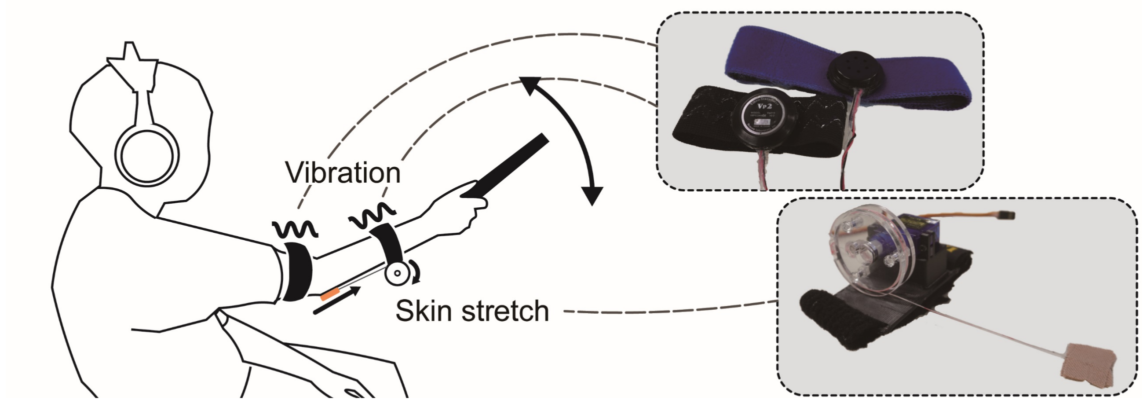

Figure 1: Movement image, and the vibrators and skin stretch device used in the experiment.

proprioceptive stimuli are applied during a simple sinusoidal movement in different phases, and the proposed method is considered through the subjective evaluation of the perception changes.

2 USER STUDY

2.1 Setup

In this experiment, we focused on the movements of the forearm which we make in daily life while lifting and using objects. A cylindrical rod of approximate length 30 cm and weight 157 g was used as a hand-held object, and the participant held the lower end of the rod and performed the sinusoidal movement of extension and flexion of the forearm with the lower limit in the horizontal plane (Figure 1). Simultaneously, vibration stimulation was applied to the tendons of the muscles related to movement around the elbow and wrist joints, and skin stretch was applied to the forearm side of the elbow. We adopted tendon vibration and skin stretch as proprioceptive stimuli because tendon vibration is a common method used to evoke kinesthetic illusions, and skin stretch can induce and enhance the illusion when combined with vibration [8, 9]. The movement cycle was set to 2 s (0.5 Hz) because there was a latency of several seconds for the illusion to occur [4, 20].

The stimulation timing was set to modulate the sensation at the time of swinging down during the sinusoidal movement. The vibrators were placed on the distal tendons of the biceps brachii and brachioradialis. The vibration frequency was set at 70 Hz, at which vivid illusions can be elicited [21], and a voice-coil type vibrator (Acouve Lab, Vp 210) was used. The input signal to the vibrators was generated using the personal-computer software (Cycling'74 Max8), and amplitude was modulated using a 0.5 Hz sine wave as the carrier wave and a 70 Hz sine wave as the modulation wave. The signal was input through an audio interface (Roland, OCTA-CAPTURE) and an audio amplifier (FX-AUDIO-FX-202 A/FX-36 A PRO). The skin stretch was performed by pulling a kinesio tape (20 × 25 mm) applied to the forearm ulnar side around the elbow joint via a 0.3 mm fine thread with a servo motor (Tower Pro pte ltd, SG -90) mounted on the forearm. An acrylic bobbin of diameter 39 mm was attached to the rotation axis of the servo motor to reel the thread (Figure 1). The skin stretch was performed in a sinusoidal manner at the same frequency as the movement. The rotation amplitude of the motor was 45 degrees, and the maximum amount of stretch from the diameter of the bobbin was approximately 15 mm. This amount of stretch was determined by the authors' preliminary experiments to perceive the sensation of forearm movement through the stretch.

2.2 Experiment

Stimulation parameters such as frequency and amplitude of vibration and skin stretch were fixed in the experiment, and we focused on the perception changes caused by shifting the phase of stimulation from the cyclic movement and changing stimulation types. The phase of the vibration stimulus was delayed by seven steps (0, 30, 60, ..., 180 degrees) based on the timing of the lower limit of the sinusoidal movement. The phase of skin stretch was set at -60 degrees relative to the vibratory stimulation (hence, positive phase values mean that the phase was delayed). In other words, the phase of the skin stretch shifted in relation to the motion as -60, -30, ..., 120 degrees. The phase difference between the skin stretch and the vibration was determined by the authors' preliminary experiments to perceive the grasped object as heavier. The timing relationship between the stimulation and the movement is shown in Figure 2. In addition to changing the phase of the stimuli, we conducted experiments with two conditions of whether the rod was grasped and three conditions under which stimuli were used (i.e., only skin stretch, only vibration, and combined stimulus) for each subject in a total of 42 conditions: 7 (phase) × 2 (bar) × 3 (stimuli).

The participants were asked to evaluate the changes in the perception of their arm and the hand-held object on 7-level Likert scales. The questionnaire items used are shown in Table 1. We designed items for weight, length, position of the center of gravity, external force, and sense of resistance/acceleration, using the arm and the hand-held object as subjects of the items. Each scale was labeled with a pair of sensations at both ends based on the sensation with no stimulus as four. For example, in the case of weight, both ends were set as lighter or heavier. To avoid bias in the participants' perceptions, we included not only items such as the weight and length of the object, which is the purpose of this study, but also items such as arms and external forces.

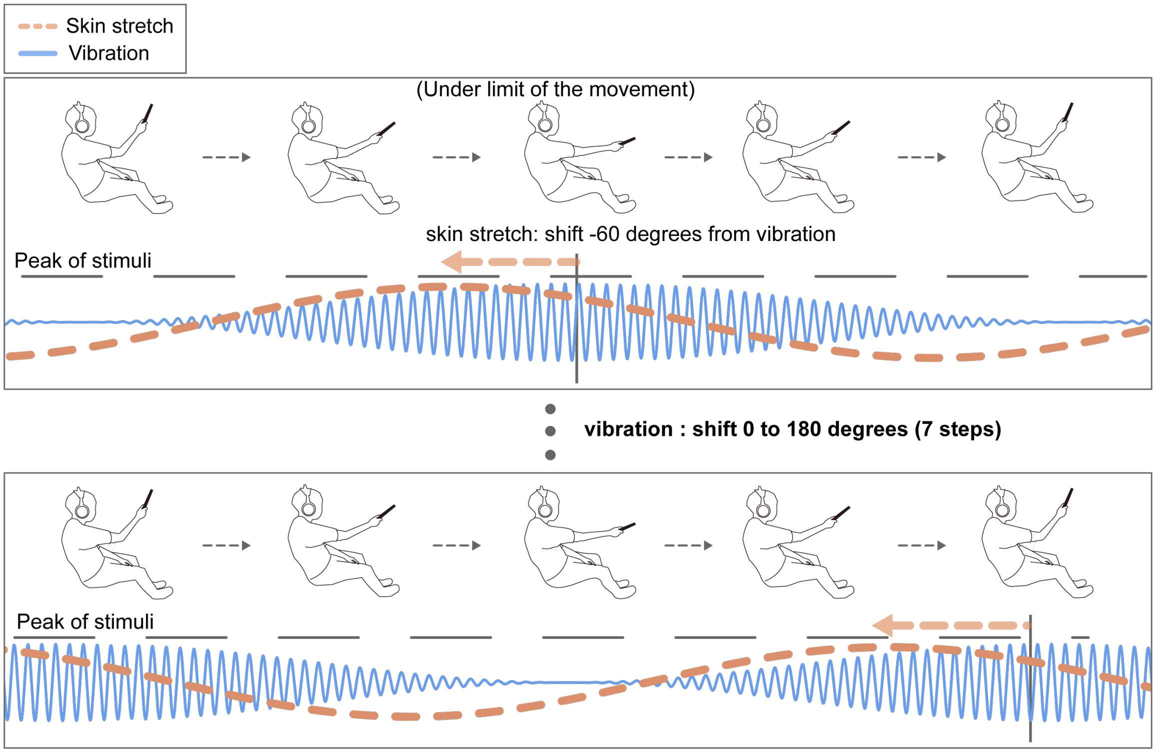

Figure 2: Timelines of the movement and the stimuli. The top timeline shows the condition where the phase of vibration is 0 degree (i.e., the vibration amplitude is maximum at the under limit of the movement). The bottom timeline shows the condition where the phase of stimuli is shifted 180 degrees. Skin stretch is always shifted −60 degrees from vibration.

Table 1: Items for subjective evaluation.

Item	Minimum (1)	Maximum (7)
Item1	The object became lighter	The object became heavier
Item2	The arm became lighter	The arm became heavier
Item3	The object became shorter	The object became longer
Item4	The arm became shorter	The object became longer
Item5	The center of gravity (CoG) of the object shifted backward	The center of gravity (CoG) of the object shifted forward
Item6	The center of gravity (CoG) of the forearm shifted backward	The center of gravity (CoG) of the forearm shifted forward
Item7	The object was pushed downward	The object was pushed upward
Item8	The arm was pushed downward	The arm was pushed upward
Item9	There was a resistance to the movement of the object	There was an acceleration in the movement of the object
Item10	There was a resistance to the movement of the arm	There was an acceleration in the movement of the arm

2.3 Experiment Procedure

Thirteen participants (21–26 years old, 10 males and 3 females, only one left-handed) were recruited for this experiment.

First, we told the participants that this experiment was intended to investigate the changes that would occur in their senses by stimulating their arms while they were performing arm movements.

Next, the vibrators and the skin stretch device were mounted on each participants' right arm. Each device was fixed using elastic bands. The position of the vibrators was adjusted by asking the participants to perform an isometric contraction of the target muscles. A kinesio tape was applied to the ulnar side of the forearm near the elbow, and the skin stretch device was mounted on the arm so that the thread was not loosened. In cases where the positions of the skin stretch device and the vibrator located in the forearm overlapped, a single elastic band was used to secure them.

After mounting, the position and amplitude of the vibrators and the position of the kinesio tape were calibrated. With the participants' arm in the air, we confirmed whether they could perceive the forearm being moved or the force on the forearm in the direction of extension through stimulation which is the same vibration and skin

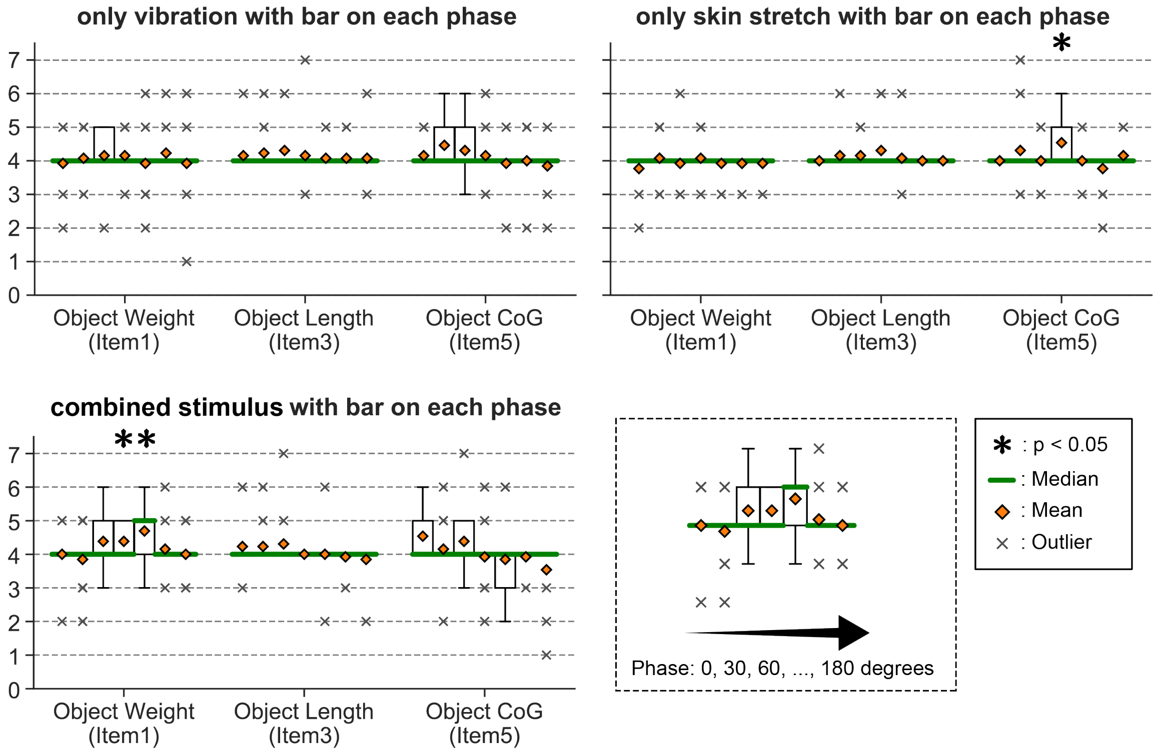

Figure 3: Phase changes in the perception of weight, length and center of gravity of the rod. For each data group, the condition of phase corresponds to 0 to 180 degrees from left to right (For only skin stretch, the phase difference corresponds to −60 to 120 degrees).

stretch as in the experiment. If not, the vibrators and kinesio tape were repeatedly adjusted in a position where the target sensation could be induced. After adjustment, the vibration amplitude was set to evoke a fully moving sensation. There was only one participant who could not perceive the sensation with the combined stimulus; however, the experiment was carried out, considering that perception changes would occur during active movement.

Next, sinusoidal motion of the arm was practiced without any stimulation. Participants were told the arm angle of the lower limit in which the forearm becomes parallel to the horizontal plane, and then they moved their arm at a comfortable amplitude. First of all, participants conducted the movement by looking at a slider moving in a sinusoidal manner on the display. Simultaneously, pink noise and metronome sound in the timing, which should be lower limit of the movement, were presented using the headphones. After the participants had become accustomed to the method of movement, they were asked to close their eyes and practice moving their arms, relying solely on sound. The practice continued until the experimenter confirmed that the participants' movement roughly corresponded to the movement of the slider.

After the practice, each questionnaire item and the evaluation method were explained to the participants, and then the experiment was started. The participants were asked to perform the movement continuously under each condition with eyes closed as well as in practice. The presence of stimulation was automatically switched every five cycles, and they evaluated the difference in perception with stimulation based on the perception without stimulation. Participants were allowed to perform the movement as many times as they wanted and were asked to answer the questionnaire when they were sure they could answer it. They were allowed to reconfirm the sensation even while answering the questionnaire. In addition, the participants were asked to comment on their sensation when they experienced a sensation that was not listed in the questionnaire.

Six conditions, which were the combinations of the presence of the bar (two conditions) and the stimulation method (three conditions), were set for each participant in random order (While pseudo random protocol was preferable to avoid any order effect, we considered that the number of participants is sufficient). Within these conditions, the phase of stimulation was randomly set (seven conditions). A one-minute break was provided for each of the seven conditions. In addition, participants could take a break at any time during the experiment when they felt tired.

3 RESULT

Figure 3 shows the graphs of the results of changes in the perception of the object's weight, length, and center of gravity (CoG) as shifting the stimulation phase for each stimulus.

Under the condition in which no box was drawn, the first and third quartiles were four because most participants did not perceive changes. Wilcoxon's signed-rank tests were used at a 5% significance level to statistically identify significant perceptual changes by testing the difference between the median of data of each phase and four, which is the value evaluated as no change. There was a significant difference in the perception change of the CoG under the condition where the stimulation was only skin stretch, and the phase was shifted by 90 degrees (p = 0.038), and the perception change of the weight under the conditions where the stimulation was combined stimulus and the phase was shifted by 90 degrees and 120 degrees (p = 0.025 and p = 0.021, respectively).

It can be observed from Figure 3 that the perception of the grasped rod changes with any combination of stimuli. The perception changes became clear by combining vibration and skin stretch. This tendency can be seen as distinctively in weight perception. Under the combined stimulus, the center of gravity and length perception seems to decrease along with the phase, i.e., the small phase tended to be perceived as shorter, and the large phase tended to be perceived as longer.

4 DISCUSSION

Figure 3 shows that there are some conditions where many participants could not perceive the changes in the grasped rod, and where both paired perception changes could occur; for example, the rod could be lighter or heavier under the same condition. It is considered that this is mainly caused by individual differences in the interpretation of the sensation between participants. Although most participants answered that the perception of the rod changed during the experiment, the optimal conditions of stimulus and phase, differed among participants. It can be understood that the appropriate stimulation timing is slightly different for each participant, because there are individual differences in the latency of the elicitation of the kinesthetic illusion [20].

It is considered that the difference in the cyclic movement of each participant and the fatigue in the experiment are also causes of the large distribution of the data.

Perception differences among participants could also be caused by differences in movement speed and amplitude, and by changes attributed to fatigue during the experiment for each participant. Because it is difficult to control the active movement of participants, the feedback system of stimulation depending on the users' motion would work better than controlling how to move.

Furthermore, most participants reported they felt sensations of resistance to the arm movement, their arm pulled or pushed more frequently than the hand-held object's perception change. This suggests that the proprioceptive stimulation itself worked for modulating arm proprioception for most participants.

4.1 Changes in physical properties of hand-held object

This experiment shows that the physical properties of the rod can be changed; in particular, the perception of weight and center of gravity, whereas the change in the length was not much perceived. It has been reported that muscle spindles can contribute to weight perception [2, 3], and the modulation of weight perception by tendon vibration would be reasonable. It was expected that the change in the center of gravity, that is, the change in the moment of the motion could also change the length perception [16]. However, many participants could not perceive the change in length. It might be challenging to perceive the change in the rod length when the length was known. There is still a condition in which the change becomes easy to perceive where the length of the rod would vary. We want to further investigate the change in length perception of the hand-held object under modified experimental conditions.

4.2 Phase differences between timings of movement and stimulation

Under the skin stretch only condition, the CoG sensation of the object was significantly shifted at a phase difference of 90 degrees. This phase difference was between the motion and the vibration (not presented), and the phase of the skin stretch was shifted by -60 degrees from the vibration; thus, the CoG often shifted forward when the phase difference between the motion and the skin stretch was 30 degrees. In other words, the skin stretch can work effectively when it is presented almost simultaneously or slightly delayed with the movement to produce an effective CoG perception change.

On the other hand, under the condition where the combined stimulus was presented, the hand-held object's weight became heavier significantly at phase differences of 90 and 120 degrees. Since weight perception did not change with skin stretch alone, and the responses with vibration alone condition had a huge variation, we can assume that combined stimulus enabled participants to comprehend the change in the weight perception steadily because of combining the perception change of CoG and weight derived from skin stretch and vibration.

A phase difference of 90 degrees with the motion means that it matched with the velocity (differential of position) peak of the motion. In other words, vibration might effectively change the weight perception when it is presented along with the velocity of the motion.

5 CONCLUSION

In this study, we investigated whether the physical properties of a hand-held object, such as weight and length, which can be related to proprioception, can be changed by vibrating tendons and stretching the skin of the arm during active movement. As an initial step, the simple cyclic movement of the forearm in the direction of extension and flexion were adopted, and cyclic stimulation was applied in accordance with the movement. Participants were asked to subjectively evaluate the sensation of the grasped object and their arm by changing the stimulation phase and stimulation conditions. It was found that the perception of not only the arm but also the object changed while performing a movement through stimulation. For the properties of the object, the perception of the weight and center of gravity were often changed relatively. However, there were individual differences in perception, and some participants did not experience any change in object perception; thus, there were few conditions that had statistically significant differences. In the future, we would like to quantitatively investigate the change in the weight and length perception under conditions narrowed down and investigate the effects of each stimulus in more detail by changing other stimulus parameters such as positions, amplitude, and the method to combine stimuli.

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