Increasing Perceived Weight and Resistance by Applying Vibration to Tendons during Active Arm Movements

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Abstract. We proposed to use kinesthetic illusion to achieve wearable/portable haptic devices for kinesthetic feedback in VR experiences. The kinesthetic illusion is the illusion of limb movement typically induced by vibratory stimulation. We investigated how the kinesthetic illusion affected the perceived weight and resistance of the handheld object. We designed vibration patterns that simulate constant gravity and velocity-related resistance. Two experiments were conducted to measure changes in perceiving weight and resistance when wielding cylindrical weights and hand fans. The results of the experiments indicated that the designed kinesthetic illusions enhanced these sensations; the real weight was perceived heavier, and the real resistance was perceived larger. However, we could not find the explicit difference between the two stimulation patterns, and the resistance sensation induced by the illusion differed from the actual sensation of using the hand fans.

Keywords: Heaviness, Kinesthetic Illusion, Resistance, Tendon Vibration

1 Introduction

Haptic feedback is essential for enhancing the quality of virtual reality (VR) experiences. By focusing on the physical interaction with an object, many ungrounded haptic devices have been proposed to provide force and tactile feedback in VR environment [1–3].

Conversely, haptic devices that simulate such forces, in general, tend to be complex and cumbersome. Many researchers have tackled this problem and proposed methods that employ haptic illusions induced by tactile or visual stimulation [4, 5]. Because the weight and length of a handheld object are related to the moment of inertia [6], Zenner et al. developed Shifty, which is a device that changes the position of the center of gravity to simulate the weight and length of handheld VR objects [7].

In the paradigm of kinesthetic feedback for VR objects, the illusion of proprioception, the sensation of force and movement of a body was rarely included. Because proprioception is known to contribute to the perception of the weight, length, and shape of a handheld object [6, 8], such an illusion can also realize and enhance the kinesthetic feedback from a handheld VR object.

One such proprioceptive illusion is kinesthetic illusion, which is typically induced by applying low-frequency vibrations of approximately 100 Hz to tendons [9]. The illusion can induce a sensation of limb movement even when it is not moving and cause errors in the perception of movement velocity [9–11]. This effect has been studied since Goodwin et al. rigorously documented this phenomenon [12]. The basic mechanism of the kinesthetic illusion induced by tendon vibration is caused by changes in the firing rate of the muscle spindle afferents that are receptors in the muscles and contribute to the perception of limb position and movement [13].

The kinesthetic illusion is frequently used to generate the illusion of bodily movement. The illusion may also lead to the illusory deformation of the object being touched [14]. Though the kinesthetic illusion has the potential to modulate perception of the object's properties, the effects of the illusion on physical properties such as weights are still unclear. We previously reported that the heaviness of a handheld bar could be modulated through a preliminary experiment [15].

Following the previous report, this study investigates the possibility of modulating the virtual properties of a handheld object by the kinesthetic illusion. We conducted experiments to confirm the effect of tendon vibration on perceptions of heaviness and resistance.

2 Experiments

We conducted two experiments to investigate how much the kinesthetic illusion can independently increase the perceived weight and resistance through physical props. Twelve people (11 males, one female, ten right-handed, 21-26 years old) participated in the experiment. The experiment was conducted with the approval of the ethics committee of The University of Electro-Communications (No. 20067).

Prior to the detailed procedure for each experiment, common apparatus and stimulation conditions will be described.

2.1 Apparatus

Overview of the experimental environment is shown in **Fig. 1** (a, b). An acrylic board was placed to hide the participant's arm. A glove was used to prevent perceiving the weight through tactile cues. Retroreflective markers for optical motion capture (OptiTrack V120 Duo) were fixed to the hand and elbow to track the arm's movements.

Four voice-coil-type vibrators (Acouve Lab, VP210) were mounted at the elbow and wrist by using supporters (**Fig. 1** (b)). These vibrators were placed on the distal tendons of the biceps and triceps brachii and the radial side (abductor pollicis longus, extensor carpi radialis longus, and extensor carpi radialis brevis) and ulnar side (flexor and extensor carpi ulnaris) of the wrist. Although the loading force was not controlled, the supporters fixed vibrators with enough loading force to prevent them from slipping from the positions.

The vibrator was driven by a signal output from PC-based software (Cycling'74, Max 8) via an audio interface (Roland, OCTA-CAPTURE) and audio amplifiers (FX-AUDIO- FX202A/FX-36A PRO).

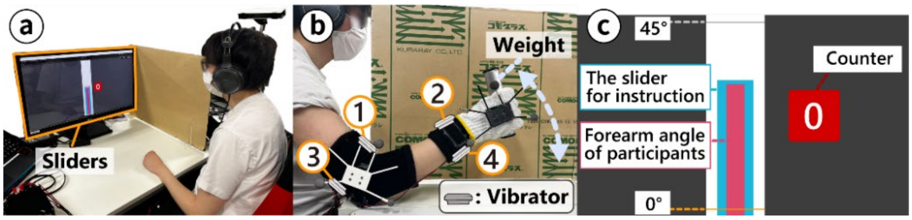

Fig. 1. (a) An overview of the environment as for Experiment 1. (b) Positions of the vibrators and the markers. (c) Screen display of the sliders for movement control.

2.2 Tendon Vibration during Active Movements

We set three vibration conditions: Weight, Resistance, and Control (not applying stimuli). **Fig. 2** (c) illustrates the vibration patterns for the Weight and Resistance conditions during the lifting movement. Under the Weight condition, the tendons of the biceps and wrist abductors were constantly stimulated during the exercise. Under the Resistance condition, the tendons of the biceps and wrist abductors were stimulated during flexion, and the tendons of the triceps and wrist adductors were stimulated during extension.

The two stimulation conditions were selected to increase the apparent heaviness of a handheld object by the following mechanisms. The Resistance condition was set based on the previous report [15] that participants tended to perceive a handheld object as heavy when proprioceptive stimulation was applied to suppress velocity of the movement. The vibration pattern of this condition aims to represent resistance to the movement by evoking the movement illusion in the opposite direction. The Weight condition was set to induce the illusion of extension constantly, considering that the weight is affected by gravity.

The vibration frequency and amplitude were set to 70 Hz and from 70 m/s^2 to 100 m/s^2 for each vibrator based on a previous literature [9]. The amplitudes were adjusted within the range where the participants did not feel a tonic vibration reflex (the vibration-induced reflex of the muscle of which the direction is opposite to that of the illusion) and could still perceive the illusion strongly. The amplitude of the rise and fall was changed linearly to avoid vibration noise.

2.3 Experiment 1: increasing the weight of a handheld object

Fig. 2 (a) shows the weight samples used in the experiment. The samples were created by using a cylindrical aluminum pipe 32 mm in diameter (29 mm inside diameter) and 150 mm in length, filled up by mixing salt and water, or sand (approx. 1.2 g/cm^3) and iron sand (approx. 2.8 g/cm^3) in several mixing rates. The samples weighed between 160 g and 330 g prepared in 10 g increments.

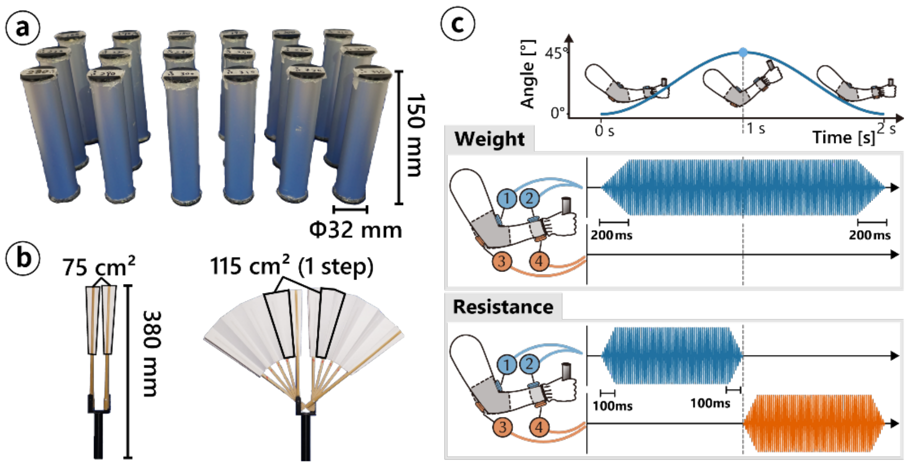

Fig. 2. (a) Weight samples used in experiment 1. (b) Hand fan samples used in experiment 2. (c) Vibration patterns of the Weight and Resistance conditions during the lifting movement.

Procedure. Two vibrators were placed at the participant's wrist and two at the elbow. When placing the vibrators, the experimenter confirmed the positions of the tendons of the targeted muscles by touching the participants' arms. The vibration amplitude was calibrated using an accelerometer (Sparkfun, LIS331). Whether participants could perceive the illusion was checked after calibration by applying the same vibratory stimulation as in the experiment.

The participants were asked to lift the objects following the sliders displayed on the screen (**Fig. 1** (c)). One slider was for movement instruction, and the other was for informing participants of the forearm angle calculated from the hand and elbow positions. The vibration timing for each condition was pre-programmed based on the instruction slider (i.e., the vibration was applied regardless of the participant's movement). The timing to start the movement was notified with the counter. The participants braced their elbows on the desk, grasped the weight, and lifted it to 45° by a forearm movement (**Fig. 1** (b)). The weight was then lowered to the desk again. This movement was practiced for each stimulation condition until the participants could confidently perceive heaviness while moving in response to the instruction slider.

The double staircase method using the Parameter Estimation by Sequential Testing (PEST) [16] was adopted to measure the subjective equivalent points of the perceived weight. PEST is a rule for deciding the step size for changing the compared stimuli (in this experiment, the weight of the sample). For each comparative trial, we randomly selected an ascending series from 160 g or a descending series from 330 g to prevent the participants from predicting the answers. The participants raised the reference sample (200 g) for each vibration condition and then lifted a sample for comparison without vibratory stimulation. They were then asked whether the comparison sample was lighter or heavier than the reference sample. Based on the answer, the subsequent step size was determined by PEST. The initial step size was set to 80 g for both series, and the series was completed when the step size was reduced to 10 g.

When participants answered beyond the range of samples prepared (for example, if the participant answered "heavy" even if the comparison sample was 330 g), the sample was presented again, and if the identical answer was given three consecutive times, the value was adopted as the series' result. The presentation order of the three conditions was counterbalanced between participants.

During the experiment, while lifting the weights, the participants wore headphones that emitted pink noise and metronome sounds. The metronome was presented at the lower and upper limits of the motion and was used as an additional cue in the exercise.

Result. Statistical analysis was carried out using SPSS (Statistics 24 Advanced, IBM). The results were the averages of the ascending and descending series for each stimulus condition for each participant. One-way repeated measures ANOVA (RM-ANOVA) was applied to analyze the perceived weight differences between the stimulus conditions. A post hoc test using the Bonferroni method was also conducted to investigate the differences between conditions.

Fig. 3 (left) shows boxplots of the average subjective equivalent points of all participants for each stimulus condition. The main effect of the vibration conditions was significant ($F(2, 22) = 15.133$, $p < 0.001$). The post hoc test revealed significant differences between the Weight and Control conditions ($p = 0.001$) and the Resistance and Control conditions ($p = 0.011$). Conversely, there was no statistically significant difference between the Weight and Resistance conditions ($p = 0.246$).

The average weight in the Weight condition was 250 g, and the average weight in the Resistance condition was 235 g. The differences from a reference weight (200 g) were 25% and 17.5% respectively for the Weight and Resistance conditions.

2.4 Experiment 2: increasing resistance of a handheld object

Since the Resistance condition is intended to enhance resistance to the movement, the perception of a handheld object's resistance should be more affected than weight. Experiment 2 was carried out to investigate the effect of the kinesthetic illusion on the sensation of resistance. Two samples were prepared using hand fans based on Drag:on [17] to represent the sensation of resistance (**Fig. 2** (b)).

This experiment was conducted with the same participants using an almost identical apparatus, experimental conditions, and procedure as in experiment 1, but the velocity of the movement was increased to facilitate perception of the hand fans' resistance. The participants flapped the hand fans three times at 1 Hz. Following the changes of the exercise, the duration of each vibration pattern was scaled to one-half time. The fan has ten width steps, and the area of the fan increases by 115 cm^2 per step. A fan opened four steps (535 cm^2) was used as the reference stimulus. The ascending series started from the completely closed state (75 cm^2), and the descending series was started from the opened state at the maximum (1225 cm^2). The initial step size in PEST was set to four steps, and the series ended when the step size was reduced to one. When changing the state, the hand fan was opened and closed symmetrically to avoid unnecessary torque.

In the preliminary experiment, we found that resistance was difficult to perceive when the same sample was continuously wielded. Therefore, the order of presentation of the reference and the comparison samples was randomized in this experiment. During the intervals between the trials, the participants wielded a completely closed sample to feel the lowest resistance to facilitate evaluation.

The sound of the metronome was not presented in this experiment because the sound tended to disturb participants' concentration during rapid movement.

Result. The results of the experiment are shown in **Fig. 3** (right). Four participants reported greater than fully opened resistance with Weight and Resistance conditions: One participant for the Weight condition only, one participant for the Resistance condition only, and two participants for both conditions.

The RM-ANOVA showed the significant main effect of the vibration conditions ($F(2, 22) = 26.134$, $p < 0.001$). A post hoc test revealed significant differences between Weight and Control ($p = 0.001$) and Resistance and Control ($p < 0.001$). Conversely, there was no statistically significant difference between Weight and Resistance ($p = 1.000$).

The mean values of the Weight, Resistance, and Control conditions were 935 cm^2, 921 cm^2, and 572 cm^2, respectively. The difference from the reference area (535 cm^2) was 75% and 72% respectively for the Weight and Resistance conditions.

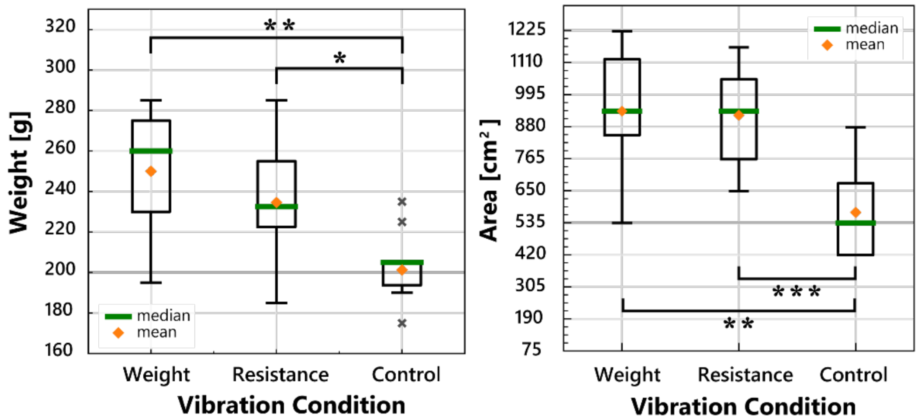

Fig. 3. Boxplots of all participants under each stimulus condition: weight (experiment 1) and resistance (experiment 2). The reference samples were 200 g and 535 cm^2 for each. ***: $p < 0.001$, **: $p < 0.01$, and *: $p < 0.05$.

3 Discussion

In experiment 1, although no significant difference was observed between the Weight and Resistance conditions, seven participants commented that it was easier to perceive weight under the Weight condition than under the Resistance condition. In addition, under the Weight condition, the sample was felt to be heavier than under the Resistance condition. Therefore, the Weight condition may enhance the sensation of weight more than the Resistance condition.

Conversely, in experiment 2, resistance was enhanced under both the Weight and Resistance conditions with no difference between them. Several participants commented that the resistance sensation of the hand fans and the kinesthetic illusion were different, and therefore the comparison was difficult. Some participants commented that they compared the sensation of resistance using the sensation only while lifting up the sample, especially under the Weight condition. Therefore, there is a high possibility that the sensation evaluated to compare resistance differed among participants. On the other hand, there was a comment that the Resistance condition more closely represented a sensation of resistance than the Weight condition.

The main reason that the comparison became difficult was that the tendon vibration was applied to the forearm and upper arm while the resistance of the hand fan was mainly sensed in the wrist and forearm. Since the wrist and elbow vibrators were set using the same parameters, the vibration for the Resistance condition elicited a sensation that resistive force was being exerted on the forearm and upper arm as if the arm were moving under water. In addition, the strong vibration may have masked the resistance sensation from the hand fans and made the comparison difficult.

4 Conclusion

We investigated the effect of the kinesthetic illusion on the sensations of weight and resistance perceived while wielding handheld cylindrical weights and fans. Two vibration patterns that induce the kinesthetic illusion were designed to enhance the sense of weight and resistance; one was to simulate constant gravitational force, and the other was to simulate velocity-related resistance. The results of the experiments indicate that the designed kinesthetic illusions enhanced these sensations; the real weight was perceived heavier, and the real resistance was perceived larger. However, we could not find explicit difference between the two stimulation patterns. Our next step is to reconsider the position and parameters of the vibrators and to conduct the experiment using the haptic device that simulates the physical characteristics of the handheld object more accurately.

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