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Weight Illusion Caused by Sinusoidal Vibration Correlates with Grip Force Adjustment

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Abstract: Our research team previously identified a weight illusion in which a lifted object feels heavy when it continuously presents a sinusoidal vibration to the fingertips. However, the mechanism underlying this illusion remains unknown. We thus hypothesized that the autonomous grip force adjustment against a vibrating object would be one of the factors underlying the weight illusion. The autonomous grip force adjustment increases the motor outputs of a human hand system, subsequently raising the sense of effort to keep holding the lifted object. The grip forces and perceived heaviness were evaluated using vibratory stimuli with five different frequencies (30 Hz, 60 Hz, 100 Hz, 200 Hz, and 300 Hz) and three different amplitudes (156 µm, 177 µm, and 203 µm). The results showed that the stimuli at lower frequencies or large amplitudes increased the grip forces more and felt heavier than the stimuli at higher frequencies or small amplitudes. Specifically, the 30 Hz stimuli felt the heaviest and increased the grip force the most. An increase in the grip force was positively correlated with the perceived heaviness. These results indicate that vibratory stimuli influence both the grip force and weight perception. Our findings can contribute to developing haptic displays to present virtual heaviness.

Keywords: weight illusion; vibration; grasp force; grip force adjustment; heaviness; mechanoreceptor

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1. Introduction

The weight of an object is defined as the product of its mass and gravitational acceleration. However, humans do not always perceive weight according to its physical definition. Instead, weight is often estimated based on generated motor commands and sensations during motions [1–4] and various types of physical quantities, such as density and inertia [5–7]. By controlling specific factors that affect weight perception, an object can feel heavier or lighter than its actual weight. These phenomena are referred to as weight illusions. Investigating weight illusions leads to an understanding of weight perception mechanisms.

The size-weight illusion is a representative example of weight illusions, in which an object with a smaller volume is perceived as heavier than an object with a larger volume, despite weighing the same [8]. The underlying principle behind this illusion however is still under debate. Nevertheless, a gap between the perceived weight of the lifted object and its expected weight before lifting is considered to be part of the reason for the illusion [1,9]. Furthermore, the material, color, and brightness also cause weight illusions, in which an object that is expected to be heavy from its appearance is perceived as being light [10–12]. As evident from the above examples, the appearance of an object is one of the factors underlying the weight illusion.

The presentation of tactile stimuli to the hand also leads to the weight illusion. Deep sensations primarily influence weight perception, but cutaneous sensations are also influential, especially for light objects [13–16]. When lifting an object, the skin deforms in the direction of the gravity or force acting on the held object. Therefore, an additional skin deformation in the direction of gravity makes objects feel heavier [15,17,18].

Some researchers have devised methods to increase the perceived weight using vibratory stimuli. When asymmetric vibration is presented to the hands, an additional force is felt in the direction of greater acceleration [19–22]. Therefore, asymmetric vibration in the direction of gravity makes objects feel heavier [20]. Furthermore, vibratory stimuli coinciding with the acceleration of moving hands can increase the perceived weight of an object [23,24].

Our research team previously identified a weight illusion caused by a continuous sinusoidal vibration to the fingertips [25]. When a vibrating object is lifted, it feels heavier than a still object with the same mass. In our previous study, 13 out of 15 participants reported this illusory weight perception [25]. We call this phenomenon the "vibration-weight illusion". Continuous vibrations over a wide range of frequencies from 30 Hz to 300 Hz generated the vibration-weight illusion [25]. As mentioned above, earlier studies used asymmetric vibration [19,20] or vibration coinciding with moving hands [23,24] to present the weight. In contrast, the vibration-weight illusion is caused by symmetric and continuous vibrations. The characteristics of the stimuli in the vibration-weight illusion differ from those of other weight presentation methods reported by earlier researchers. Therefore, investigating the mechanisms underlying this illusion may lead to new insights into the perceptual effects of vibratory stimuli and the mechanisms of weight perception.

We hypothesized that an increase in the grip force will be the main factor underlying the vibration-weight illusion. Humans feel their own motions and forces intensely when the related motor commands are large [26–29]. In the case of the vibration-weight illusion, an additional grip force may be used to stabilize the vibrating object, and the additional force may make the object feel heavier than its actual weight. Therefore, this study investigated the relationship between the grip force adjustment and vibration-weight illusion. Especially, this study confirmed how the grip force and perceived heaviness are changed by sinusoidal vibrations of different frequencies (Experiment 1) or amplitudes (Experiment 2).

2. Related Studies and Hypothesis of the Vibration-Weight Illusion

An asymmetric vibration is an example of force presentation by vibratory stimuli [19,20]. It comprises a faster motion of mass in one direction and a slower motion in the other, and the illusory force felt in the former direction. When an object held in the hand vibrates asymmetrically, it generates higher forces in the direction of a greater vibratory amplitude than in the opposite direction [21]. Moreover, the skin deforms more in that direction [22]. The nonlinearity between the physical stimuli, that is, the force and skin deformation, and their subjective magnitudes is a potential cause of the illusory force perception. An asymmetrically vibrating object feels heavier when the vibration is in the direction of gravity [20]. However, the vibration-weight illusion discussed in the present study uses a sinusoidal vibration, which is symmetric. Moreover, the vibration-weight illusion occurs even when the vibration is presented in a direction perpendicular to gravity.

Okamoto et al. and Nagano et al. proposed a method to increase the perceived inertia or mass by controlling the presentation timing of vibratory stimuli [23,24]. The inertial force generated by swaying an object causes finger skin deformations that activate mechanoreceptive units. They intended to additionally stimulate the mechanoreceptive units of the fingertips by vibration and cause an illusory sense of a magnified skin deformation. They thus made a swayed object feel heavier by presenting vibrations [23,24]. However, the vibration-weight illusion discussed in the present study is generated by a continuous vibration while the object is statically grasped. It thus differs from their findings.

The tonic vibration reflex is a muscle contraction evoked by the vibration applied to the muscle below the skin that stimulates muscle spindles, leading to a muscle contraction reflex [30,31]. The stimulation of agonist muscles makes an object feel lighter, and conversely, the stimulation of antagonist muscles makes the object feel heavier [26]. There are no reports of a tonic vibration at the fingers because fingers lack muscles; however, in the case of the forearm, a vibration with an amplitude of 0.2–0.3 mm at a frequency of 100–200 Hz was found to effectively generate a tonic vibration reflex [32]. If the tonic vibration reflex causes the vibration-weight illusion, the vibration delivered to the fingertips should be transferred to the antagonist muscles of the wrist or forearm. However, vibrations with amplitudes of less than 0.1 mm to the fingertips generated the vibration-weight illusion [25]. This stimulus is small when compared to that of a previous study [32]. Therefore, we speculated that the tonic vibration reflex does not cause the vibration-weight illusion.

We hypothesized that the vibration applied to an object will cause the grip force to increase as a result of the automatic grip force adjustment for stable grasping. Motions that generate more motor commands are perceived as higher intensity [26–29]. When the motor commands related to motions are larger, the object's weight is perceived as heavier [1–4]. Therefore, even if the weight of the object does not change, the increase in the grip force may make the grasped object feel heavier.

3. Experiment 1: Frequency Dependence of Vibration-Weight Illusion

Two different tasks were conducted in Experiment 1. The order of the two tasks was randomized for individual participants.

3.1. Participants

A total of 11 participants (10 males and 1 female) participated in the experiment. All participants were right-handed, healthy university students, aged 20 years and above.

3.2. Apparatus and Stimuli

A voice coil motor (Vp408, Acouve Laboratory, Inc., Tokyo, Japan, 85 g) shown in Figure 1A was used to present vibratory stimuli. A load cell (FS2050-0000-1500-G, TE Connectivity, Schaffhausen, Switzerland, 5 g) was attached to the center of the voice coil motor to measure the grip force.

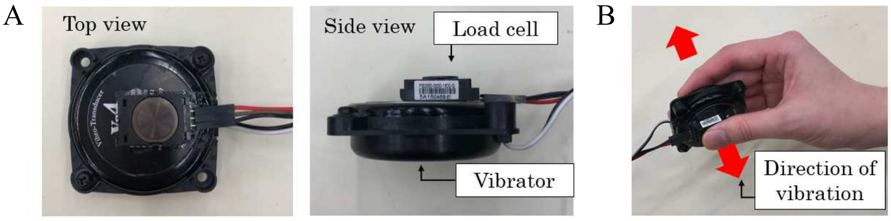

Figure 1. Apparatus. (**A**) Appearance of the apparatus. Load cell is attached to the center of the voice coil motor. (**B**) Direction of vibratory stimuli and how to grip it during the experiments.

Five sinusoidal vibratory stimuli with different frequencies and accelerations were prepared, as shown in Table 1. The accelerations of the vibratory stimuli were set to 3 dB higher than the thresholds of the vibration-weight illusion reported in a previous study [25], in which the minimum intensities of vibratory accelerations needed to cause the illusion were determined using the psychophysical method of limits. Acceleration was measured using an accelerometer (Model-2320B, Showasokki Co., Ltd., Japan) through an amplifier (Model-4035-50, Showasokki Co., Ltd., Japan). The accelerometer was attached to the center of the vibrator's surface, where the participant's thumbs contacted. Amplitudes were calculated from their frequencies and accelerations. During the experiment, the accelerometer was neither used nor fixed on the voice coil motor.

Here, we describe how the aforementioned stimuli were designed. This study aimed to investigate the relationship between the vibration-weight illusion and grip force adjustment. The types of mechanoreceptive units that mediate grip force adjustment have been discussed [33–35]. Different types of mechanoreceptive units exhibit different frequency responses [36]. Hence, we covered the frequency range of 30–300 Hz. The minimum amplitude (i.e., threshold) to evoke the illusion depends on the frequency [25]. Considering the properties of the actuator, it would be impossible to maintain equal amplitudes and induce the illusion over such a wide frequency range. Therefore, we determined the amplitudes of the vibrations based on the threshold for each frequency. Specifically, the amplitudes were 3 dB above the threshold so that the illusory weight was experienced by almost all participants.

Table 1. Acceleration, amplitude, and input voltage at each frequency of the vibratory stimuli used in Experiment 1. Accelerations and amplitudes of the stimuli were 3 dB higher than the thresholds at which the vibration-weight illusions were observed at individual frequencies. Voltage indicates the amplitude of the voltage applied to the voice coil motor (half to peak-to-peak).

Frequency	Acceleration	Amplitude	Voltage
30 Hz	$5.5\ \mathrm{m/s^2}$	156 µm	2.44 V
60 Hz	$11.9\ \mathrm{m/s^2}$	84 µm	0.86 V
100 Hz	$17.4\ \mathrm{m/s^2}$	44 µm	1.06 V
200 Hz	$75.3\ \mathrm{m/s^2}$	48 µm	4.06 V
300 Hz	$138.1\ \mathrm{m/s^2}$	39 µm	7.82 V

3.3. Task 1-1: Grip Force at Different Frequencies

3.3.1. Procedures

Participants were exposed to five different vibratory stimuli, as listed in Table 1. They gripped the voice coil motor with their dominant hands, as shown in Figure 1B, and placed their thumbs on the load cell while the other four fingers were on the opposite side. They were instructed to lift the voice coil motor using their entire arm but were not allowed to place their arms or wrists on the table. They were asked to grip the voice coil motor with a minimum grip force without letting it slip.

Participants lifted the voice coil motor that was not yet vibrating and continued holding it. Vibration stimuli were then initiated for 3 s after a random waiting time. The participants were unaware of the presentation timing. They then laid down the voice coil motor and lifted 100 g and 200 g weights in randomized orders to neutralize their sense of weight. The direction of the vibration was perpendicular to gravity. To prevent the influence of the sound made by the motor, pink noise was played through headphones.

The grip force of each participant was measured five times for each of the five different vibratory stimuli. In total, 25 (five frequencies × five repetitions) trials were tested in a randomized order for each participant. Between the trials, the participants were asked if they were fatigued and provided breaks, if necessary.

3.3.2. Analysis

The outputs from the load cell were submitted to a moving-average low-pass filter with a window size of 0.1 s. The grip forces before and after the presentation of the stimuli were compared to evaluate the increase in the grip force for each vibratory stimulus. The grip force before the presentation of the vibration was the mean of the 0.5 s immediately before the presentation of a stimulus (−0.5–0 s), as in Figure 2, where 0 s was the onset of the vibration. The grip force after the presentation of the stimulus was the mean during the 0.5 s, 1 s after the start of the presentation (1–1.5 s). The grip forces were transient for 0–1 s, and this period was not used for the analysis. The means and standard errors of the change in the grip force for each vibratory frequency were calculated, and two-tailed *t*-tests were conducted to confirm whether the stimuli changed the grip forces significantly.

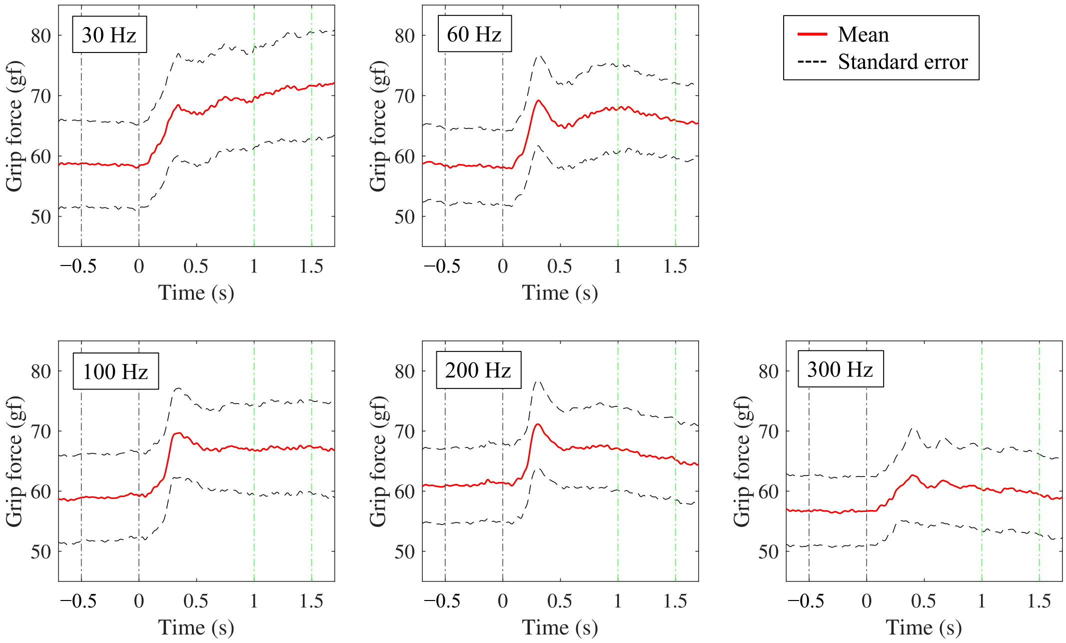

Figure 2. Grip force over time during Experiment 1. The red lines and dashed black lines indicate the means and range of standard errors, respectively. Stimuli started at 0 s and lasted 3 s. For the analysis of the change in grip force, means of 0.5 s before the stimulus (−0.5–0 s) and after the stimulus (1–1.5 s), which are surrounded by the black and green dashed lines, respectively, were used.

3.4. Task 1-2: Perceived Heaviness at Different Frequencies

3.4.1. Task

In addition to the five types of vibratory stimuli used in the previous task (Table 1), a condition of no vibratory stimulus was included in Task 1-2. Hence, a total of six stimuli (30 Hz, 60 Hz, 100 Hz, 200 Hz, 300 Hz, and no vibration) were presented in this task. The participants lifted the voice coil motor with their dominant hands in the same posture as in Task 1-1. During the task, participants continuously held the voice coil motor without releasing it. Similar to Task 1-1, each type of vibration lasted only 3 s to prevent perceptual adaptation. They could freely compare the six types of stimulus conditions and rank them in the order of perceived heaviness without tie ranks. They were allowed to experience the vibratory stimuli repeatedly until they made their decisions. The frequencies of the stimuli were not disclosed to them. Each participant performed the above tasks twice, with an interval of several minutes.

3.4.2. Analysis

For each participant, the mean ranks of the two ranking tasks were calculated. These mean ranks included ties. Ranks among the vibratory stimuli, including the control stimulus with no vibration, were compared using the Wilcoxon signed-rank test with a Bonferroni correction, with the correction factor being 15 ($_6C_2$). Furthermore, the relationship between the change in the grip force (Task 1-1) and perceived heaviness (Task 1-2) was examined using Spearman's rank correlation.

3.5. Results

3.5.1. Grip Force at Different Frequencies (Task 1-1)

Figure 2 indicates the means and standard errors of the time-series grip force among all the participants. For all types of vibratory stimuli, the grip force began to increase within 0.1 s after the onset of the vibration. After a rapid and large increase in the grip force, the excessive grip force was adjusted to potentially minimum levels to hold the activated voice coil motor during 0–0.5 s. Similar changes in the grip force have also been observed in other studies investigating its adjustment [34,37,38].

The means and standard errors of the increase in the grip force for each vibratory stimulus are shown in Figure 3A. The lower the frequency, the greater the increase in the grip force. There was a negative correlation between the frequency and increase in the grip force ($\rho = -0.30$, $p = 0.027$). The presentation of the 30 Hz ($t(10) = 4.03, p = 0.002$, two-tailed t-test) and 100 Hz ($t(10) = 2.31, p = 0.043$) vibrations significantly increased the grip force. For the 60 Hz vibratory stimuli, the grip force tended to increase but not significantly ($t(10) = 2.21, p = 0.051$). The mean grip force before the presentation of the stimuli was 58.7 g, and the 30–100 Hz vibratory stimulus increased the grip force by 9.8 g (17%) on average.

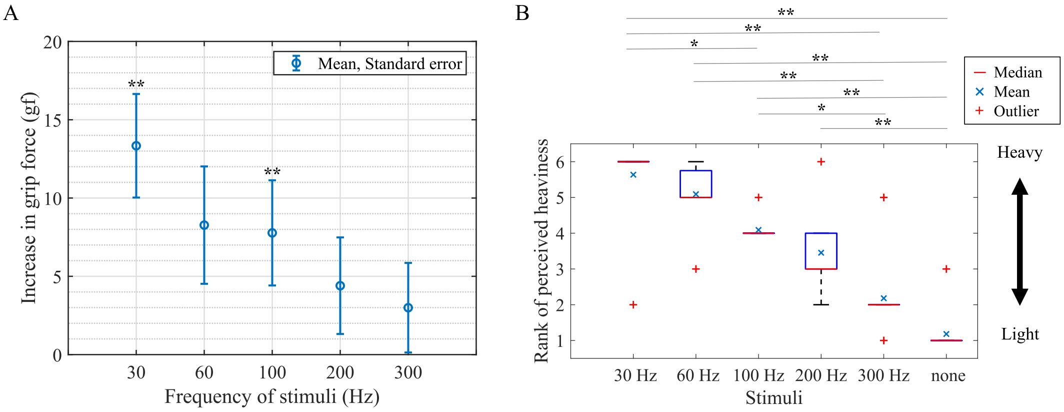

Figure 3. Results of Experiment 1. Stimuli with five different frequencies were used and their amplitudes were 3 dB higher than the thresholds for the weight illusion at each frequency. (**A**) Increase in grip force for five vibratory frequencies. (**B**) Ranks of perceived heaviness. A higher rank number indicates a perception of greater heaviness. * and ** indicate significant differences at the 5% and 1% levels, respectively. There was a positive correlation between the increase in grip force and perceived heaviness ($\rho = 0.66$, $p = 1.24 \times 10^{-9}$).

3.5.2. Perceived Heaviness at Different Frequencies (Task 1-2)

The ranks of the perceived heaviness for different vibration conditions are shown in Figure 3B. A higher rank indicates that the participants perceived the stimulus as heavier. The lower the frequency of the vibratory stimulus, the heavier its perception. For instance, the participants perceived the 30 Hz vibration as the heaviest. As shown in Table 2, the vibratory stimuli except for 300 Hz were judged as being significantly heavier than the condition with no vibratory stimulus.

Table 2. Comparison of heaviness ranks. p-values and (t-values) between vibration conditions in Task 1-2 (Wilcoxon signed-rank test with Bonferroni correction).

***p*-Value (*t*-Value)**	**60 Hz**	**100 Hz**	**200 Hz**	**300 Hz**	**None**
30 Hz	0.582 (161.0)	0.020 (176.0)	0.086 (171.5)	0.004 (181.5)	0.001 (186.0)
60 Hz	-	0.069 (172.5)	0.134 (171.5)	0.006 (182.5)	0.002 (186.5)
100 Hz	-	-	0.616 (161.0)	0.021 (176.5)	0.001 (187.0)
200 Hz	-	-	-	0.082 (172.5)	0.005 (183.0)
300 Hz	-	-	-	-	0.057 (172.0)

3.5.3. Correlation between Grip Force and Perceived Heaviness at Different Frequencies

The changes in the grip force (Figure 3A) and perceived heaviness (Figure 3B) exhibited a positive rank correlation coefficient of 0.66 ($p = 1.24 \times 10^{-9}$). This correlation indicates that the stimulus conditions with the larger increase in the grip force were perceived to be heavier.

To investigate the influence of the time intervals to the average grip force on the results, we calculated a rank correlation coefficient with different time interval conditions, namely when the time intervals before and after the stimulus onset were −1 s to 0 s and 1 s to 2 s. The correlation coefficient was 0.65 ($p = 3.73 \times 10^{-9}$), which is close to the result ($\rho = 0.66$) with intervals of −0.5 s to 0 s and 1 s to 1.5 s.

4. Experiment 2: Amplitude Dependence of Vibration-Weight Illusion

4.1. Participants

A total of 11 participants (6 males and 5 females) participated in the experiment. All participants were university students, aged over 20 years. Two participants also participated in Experiment 1, but Experiments 1 and 2 were conducted on different days.

4.2. Apparatus

The same apparatus as in Experiment 1 (Figure 1) was used in Experiment 2. The main components included a voice coil motor (Vp408, Acouve Laboratory, Inc., Japan, 85 g) and a load cell (FS2050-0000-1500-G, TE Connectivity, Switzerland, 5 g) to present the vibration stimuli and measure the grip force, respectively.

4.3. Stimuli

Three stimuli with the same frequency but different amplitudes as listed in Table 3 were used. The frequencies of the stimuli were set to 30 Hz, which increased the grip force and perceived heaviness the most in Experiment 1. The stimulus with the lowest amplitude among them was identical to the 30 Hz stimulus used in Experiment 1.

Table 3. Accelerations, amplitudes, and input voltages of the vibratory stimuli used in Experiment 2.

Amplitude	Acceleration	Frequency	Voltage
156 μm	5.5 m/s^2	30 Hz	2.44 V
177 μm	6.4 m/s^2	30 Hz	2.85 V
203 μm	7.2 m/s^2	30 Hz	3.25 V

4.4. Task 2: Grip Force and Perceived Heaviness at Different Amplitudes

In Experiment 2, the changes in grip force and perceived heaviness were investigated, similar to Experiment 1. Unlike Experiment 1, the number of stimuli was small, which allowed us to simultaneously investigate the rank of perceived heaviness and grip forces.

Participants gripped and lifted the voice coil motor in the same manner as in Experiment 1 (Figure 1B). After a random waiting time, a vibration stimulus, which was randomly selected among the three stimuli, was presented for 3 s, and the grip force was recorded continuously before and after the vibration period. They then laid down the voice coil motor and lifted 100 g and 200 g weights in randomized orders to neutralize their sense of weight. Each stimulus was presented only once, and after all the stimuli had been presented, participants ranked the perceived heaviness of the stimuli. The above task took approximately 2 min for each participant.

4.5. Analysis

The data were analyzed in the same manner as in Experiment 1. The grip forces measured by the load cell were submitted to a moving-average low-pass filter with a window size of 0.1 s to remove the effect of the vibration stimulus. The means of the grip forces before and after the vibration were calculated from the grip forces during the 0.5 s before the vibration and during 0.5 s from 1 s after the commencement of the vibration, respectively. For each stimulus, the mean and standard error of the change in the grip force among the participants were calculated, and two-tailed *t*-tests were conducted to confirm whether the changes were significantly different from zero. The ranks of the perceived heaviness were compared using the Wilcoxon signed-rank test with a Bonferroni correction, with the correction factor being 3 (${}_3C_2$). In the last step, the relationship between the change in the grip force and perceived heaviness was examined using Spearman's rank correlation.

4.6. Results

4.6.1. Grip Force at Different Amplitudes

Figure 4 shows the means and standard errors of the time-series grip force among all the participants for Experiment 2. The means and standard errors of the increases in the grip force for the three stimuli with different amplitudes are shown in Figure 5A. The grip force increased more for the stimuli with higher amplitudes. The grip force increased significantly for all three stimuli (156 µm: $t(10) = 5.32$, $p = 3.38 \times 10^{-4}$, 177 µm: $t(10) = 9.15$, $p = 3.56 \times 10^{-6}$, 203 µm: $t(10) = 16.50$, $p = 1.39 \times 10^{-8}$, two-tailed t-test). The average grip force before the stimuli was 58.8 g, and even the stimulus with the smallest increase in the grip force, that is, 156 µm, increased the grip force by 8.7 g (15%) on average.

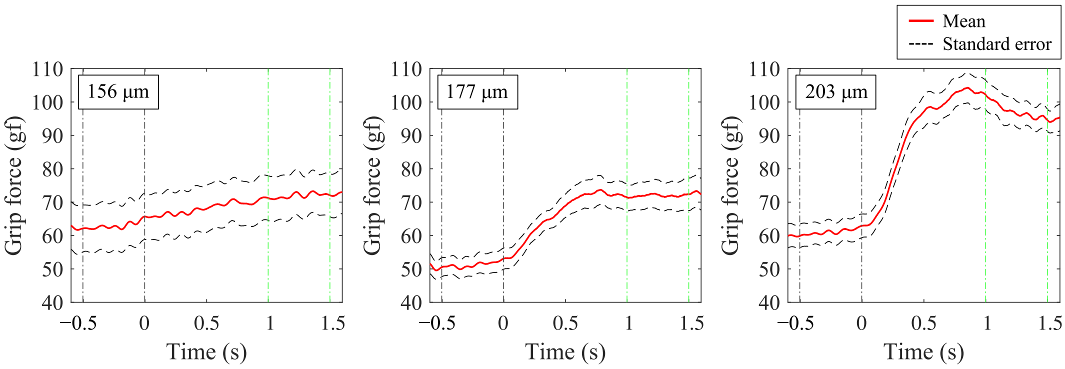

Figure 4. Grip force over time during Experiment 2. The red lines and dashed black lines indicate the means and range of standard errors, respectively. Stimuli started at 0 s and lasted 3 s. For the analysis of the change in grip force, means of 0.5 s before the stimulus (−0.5–0 s) and after the stimulus (1–1.5 s), which are surrounded by the black and green dashed lines, respectively, were used.

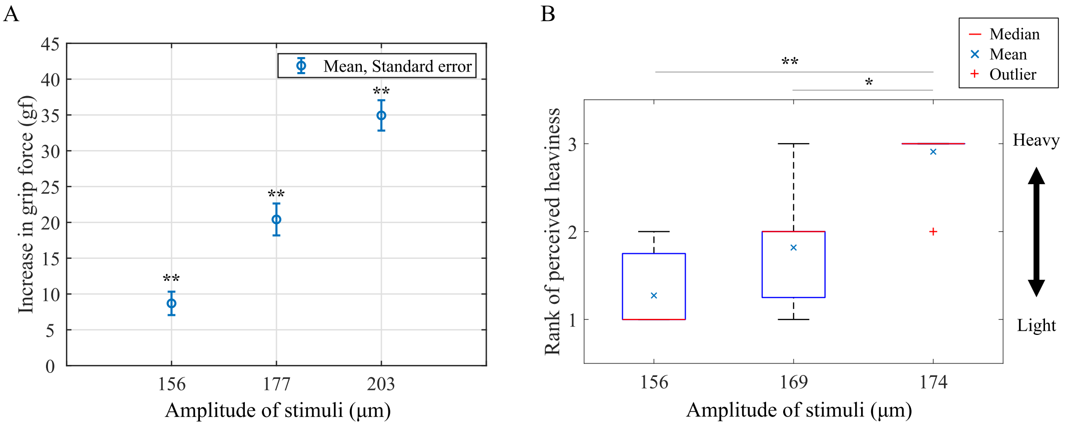

Figure 5. Results of Experiment 2. Three different stimuli with different amplitudes but the same frequency (30 Hz) were used. (**A**) Increase in grip force for three different amplitudes. (**B**) Ranks of perceived heaviness. A higher rank number indicates a perception of greater heaviness. * and ** indicate significant differences at the 5% and 1% levels, respectively. There was a positive correlation between the increase in grip force and perceived heaviness ($\rho = 0.77$, $p = 1.37 \times 10^{-7}$).

4.6.2. Perceived Heaviness at Different Amplitudes

The ranking of the perceived heaviness against the three stimuli with different amplitudes is shown in Figure 3B. The stimuli with higher amplitudes were perceived as heavier. The stimuli with the amplitude of 203 µm were perceived as significantly heavier than the other stimuli (203 µm vs. 156 µm: $t(10) = 67.5$, $p = 0.0018$, 203 µm vs. 177 µm: $t(10) = 75.5$, $p = 0.0145$, Wilcoxon signed-rank test with Bonferroni correction), but there was no significant difference between the amplitudes of 156 µm and 177 µm.

4.6.3. Correlation between Grip Force and Perceived Heaviness at Different Amplitudes

The increase in the grip force and perceived heaviness were positively correlated ($\rho = 0.77$, $p = 1.37 \times 10^{-7}$, Spearman's rank correlation). The grip forces and perceived heaviness increased with the amplitude of the vibration when the frequency was constant.

5. Discussion

The experimental results revealed a positive correlation between the increase in the grip force and perceived heaviness at different vibratory frequencies in Experiment 1 ($\rho = 0.66$, $p = 1.24 \times 10^{-9}$) and at different amplitudes in Experiment 2 ($\rho = 0.77$, $p = 1.37 \times 10^{-7}$). Specifically, the vibratory stimuli felt to be heavier introduced significant increases in the grip force. The results are consistent with our hypothesis, which posited that the grip force adjustment is the main factor underlying the vibration-weight illusion. The grip force adjustment might have functioned autonomously to retain the vibrating object. The increase in the grip forces indicates an increase in the motor commands, also known as the sense of effort, which in turn leads to an increase in the perceived weight [26–28].

In Experiment 1, though we did not fully equalize the vibratory amplitudes at different frequencies, those at 100 Hz (44 μm), 200 Hz (48 μm), and 300 Hz (39 μm) were similar. Among these three frequencies, the lowest frequency, that is, 100 Hz, led to the greatest and most significant increase in the grip force, whereas the other two frequencies exhibited smaller increases in the grip force. This suggests that the vibration-weight illusion depends on the frequency such that low vibration frequencies are effective. In Experiment 2, the greater the amplitude, the greater the increase in the grip force and perceived weight when the frequency was 30 Hz. This result suggests that the weight illusion also depends on the amplitude.

One might query whether the differences in the outputs of the load cell were caused by the vibratory amplitudes and resultant finger pad restoration forces and not by the grip force. However, this factor did not have a major impact on the results. In Experiment 1, although the amplitudes of the 100, 200, and 300 Hz stimuli were nearly equal, 44, 48, and 39 μm, respectively, as listed in Table 1, only the 100 Hz vibration significantly increased the grip force. Furthermore, the increases in the grip force were nearly identical for the 60 Hz and 100 Hz stimuli, despite their amplitudes differing by a factor of almost two. Therefore, the amplitudes of the stimuli did not notably affect the outputs of the load cell.

Experiment 1 showed that the 30 Hz vibratory stimulus increased the grip force the most. Additionally, the lower the frequency of the vibratory stimuli, the greater the increase in the grip force. This may be due to the characteristics of the fast-adapting type 1 (FAI) mechanoreceptive units that affect the grip force adjustment [33,39]. The FAI units play an important role in the grip force adjustment by detecting fast and subtle skin deformations, such as slippage, with a peak of activation between 30 Hz and 40 Hz [36,40], whereas the mediation of other types of receptive units are not negated [39]. The presentation of the 30 Hz local vibrations to the fingertips, which is expected to effectively stimulate the FAI units, was reported to increase the grip force, even without actual slippage [34]. It is possible that the stimuli with lower frequencies in the present study also effectively activated the FAI units. This might have resulted in an increase in the grip force, even when there was no actual slippage between the fingertips and surfaces of the voice coil motor.

Here, one question arises, namely whether the vibratory stimuli at frequencies below 30 Hz effectively cause the weight illusion. To investigate this, as a post hoc experiment, we compared the intensities of the illusion between the 15 Hz and 30 Hz stimuli. The same voice coil motor as in Experiments 1 and 2 was used, and the accelerations of the stimuli were 3 dB higher than the thresholds of the illusion (15 Hz: $1.39\ \mathrm{m/s^2}$, 30 Hz: $5.5\ \mathrm{m/s^2}$). The threshold of the 15 Hz stimulus was determined by the psychophysical method of the limits with five participants, following a previous experiment [25]. Ten out of twelve participants (eight males and four females) reported that the 30 Hz stimulus was heavier than the 15 Hz stimulus. The intensity of the illusion may peak at 30 Hz, at which frequency FAI units are sensitive [36,40].

Nonetheless, it is possible that the vibratory stimuli caused actual slippage. During the experiment, a participant accidentally dropped the voice coil motor from his hand at the onset of the vibratory stimuli. Such an accidental case was observed only once throughout the experiment. Further, we did not observe any other evident full slippages; however, it is known that incipient slippage occurs in the finger pad's contact area [41,42] and the tactile system permits the detection of this partial slippage [39,43]. The vibration reduces the sliding friction, and the effect of the vibration on the friction reduction is prominent with a greater vibratory amplitude and at a greater frequency [44]. As shown in Table 1, the vibrations at lower frequencies exhibited greater amplitudes in our setup. It is possible that the vibration had reduced the friction between the finger pad and voice coil motor, and the grip force adjustment might have occurred to readjust to the surface with a lowered coefficient of friction. From this perspective, the vibration-weight illusion can be compared with the material-weight illusion, wherein an object with a smooth surface feels heavier than an object with a rough surface [10]. The material-weight illusion was explained as a large grip force required to hold an object with a slippery smooth surface that magnified the perceived weight of the object [45,46].

The following are some limitations of the present study. In Experiment 1, to produce the weight illusion clearly, we presented vibration stimuli with accelerations of 3 dB above the threshold [25], at which amplitude the illusion barely occurred at each vibration frequency. These settings limit the generalizability of the results. Because the present study investigated the effect of the amplitude only for 30 Hz stimuli, it is not possible to conclude how the amplitude dependence of the weight illusion changes with other frequencies. In Experiment 1, there were six different stimuli, so the participants had to experience the stimuli multiple times and take time to make a decision. Therefore, the changes in the grip force (Figure 3A) and perceived heaviness (Figure 3B) were measured in different experiments, and the conditions of these two Experiments were not perfectly the same. This difference in the experimental conditions might have affected the experimental results. In Experiment 1, however, the grip force measurement was repeated several times and the participants spent time ranking the perceived heaviness. Thus, the reliability of Experiment 1 is not particularly questionable. Further, in Experiments 1 and 2, the intensities of the perceived heaviness were ranked, and the rank correlations were calculated to investigate whether the frequency or amplitudes affect the perceived heaviness. Therefore, we cannot discuss whether the effects of the frequency and amplitude on the illusion are linear or not. Finally, this study suggests a relationship between the grip force adjustment and the vibration-weight illusion. However, it does not negate other factors. It is also inconclusive as to why the vibratory stimuli increase the grip force, that is, whether the grip force is adjusted due to actual partial slippage.

Some points remain to be studied in the future. In the experiments, the participants gripped the voice coil motor with their finger pads. However, the vibration-weight illusion also occurs when other holding methods are adopted. The relationship between the holding methods and the intensity of the illusion is one of the interesting topics to be studied. Furthermore, interestingly, the temporal profiles of the grip forces differed among the frequency conditions. Nonetheless, we cannot explain the reasons behind this difference at this point.

6. Conclusions

This study is based on the vibration-weight illusion [25] wherein a vibrating object feels heavier than a still object. The continuous and sinusoidal vibration adequately causes the illusion, and understanding this perceptual phenomenon might help with the design of haptic displays that virtually and effectively present the sense of heaviness. This study investigated whether the grip force adjustment affects the vibration-weight illusion and how the grip force is changed by a sinusoidal vibration. Five types of vibratory stimuli at different frequencies and three types of stimuli at different amplitudes were presented, and the changes in the grip force and perceived heaviness were measured. The results showed positive correlations between the increase in the grip force and perceived heaviness at both different frequencies ($\rho = 0.66$, $p = 1.24 \times 10^{-9}$) and amplitudes ($\rho = 0.77$, $p = 1.37 \times 10^{-7}$). The increases in the grip force and the intensities of the weight illusion were greater for the low-frequency and large-amplitude vibratory stimuli. The results of this study suggest that sinusoidal vibrations change the grip force and weight perception, and the increase in the grip force makes the object feel heavy. Further studies are needed to clarify the reasons as to why the grip force is increased by the vibratory stimuli. Practically, the vibration-weight illusion could be implemented in game controllers or virtual reality, for which vibrotactile stimuli are commonly used [47], to present virtual loadings on avatars' hands. In immersive virtual environments, other illusory techniques called pseudo-haptics [48] can be applied with the vibration-weight illusion to influence the perceived heaviness. It is difficult to eliminate the perception of vibration during the illusion; hence, suitable applications may include fishing games and scenes that involve hugging moving objects or living creatures, during which vibratory motions and loadings naturally co-occur.

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