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Psychophysical Effects of Grasping Conditions of a Handheld Device on Vibrotactile Perceptions

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Abstract—Tactile perception varies between individuals and the state of the grasp. To investigate the psychophysical effects on vibrotactile perceptions influenced by grasp type and strength of a handheld device, perceived intensities were tested against various grasp strengths and stimulus levels using 40 and 250 Hz vibrations under power grasp and precision grasp conditions. Grasp strength was measured with a pressure distribution sensor on the cylindrical device capable of presenting vibrations up to approximately 2.0 m/s^2 . The analysis using a physical model supported the measured acceleration characteristics, indicating greater attenuation of low-frequency vibrations due to grasping. The psychophysical experiments indicated that the perceived intensity decreases with grasp strength at 40 Hz vibrations under power grasp, whereas the perceived intensity slightly increases with grasp strength at 250 Hz vibrations under precision grasp. On the other hand, small differences were observed for 40 Hz vibrations during precision grasp and 250 Hz vibrations during power grasp. This highlights the need for compensatory measures in low-frequency vibrations or the use of high-frequency vibrations to achieve consistent vibrotactile feedback in handheld devices across different grasping conditions.

Index Terms—Vibrotactile perception, Grasp condition, Handheld device, Frequency.

I. INTRODUCTION

IN virtual reality (VR) technologies, haptic feedback is attracting attention as a means to bridge the perceptual gap between virtual environments and the real world. Various tactile displays have been studied in recent years to further enhance VR immersion. Handheld devices are emerging as key user interfaces for commercial VR systems. They offer advantages such as supporting large-scale body movements, being relatively unaffected by individual physical differences, and being user-friendly because they do not require finger restraints [1], [2], [3]. Handheld devices must incorporate tactile stimulus functions that are compact enough to fit comfortably in the hand. Therefore, vibrotactile feedback has gained widespread adoption owing to its ease of control using small transducers [4], [5], [6]. Understanding the perceptual characteristics of vibration is expected to advance VR development, as demonstrated by studies exploring the simulating of viscosity [7] and traction [8], [9] through vibrotactile stimuli.

Tactile sensation exhibits greater differences compared to visual and auditory senses, posing challenges in delivering

uniform sensations to multiple users or enabling shared experiences [10], [11]. Intrinsic factors influencing perception include age-related declines in touch sensitivity owing to changes in vibrational transmission through skin friction [12] and variations in skin elasticity affecting tactile sensitivity [13]. On the other hand, various extrinsic factors such as contact pressure [14], skin temperature [15], and motion state [16] have been identified as potential sources of errors in sensory presentation. If these conditions can be consistently quantified to account for individual differences in perception, it could enhance immersion and improve the reproducibility of interactions with the device. Therefore, there is a critical need to elucidate the factors influencing perceptual characteristics and understand their relationships and effects.

The perceptual characteristics of vibration have been studied for many years, with numerous previous investigations into the influence of extrinsic factors. Studies have demonstrated, for instance, that the vibration detection threshold increases, and vibration perception becomes more challenging with reduced static pressure or contact area [17], [18], [19], shorter stimulus durations [20], or lower skin surface temperatures [15]. Furthermore, distinctions have been noted between passive and active contact [21], indicating that active motion can dampen sensation [22] while grounding the device has been shown to enhance perceived intensity [23]. The relationship between contact pressure and perception thresholds has been investigated across various conditions. Research has shown that the vibration detection threshold in the normal direction decreases with increasing pressure, up to 4.9 N at 250 Hz [24], while remaining unchanged in the tangential direction [25]. Another study reported that under pressures up to 10.8 N , the threshold at 40 Hz increased slightly at 2.0 N , whereas the threshold at 250 Hz decreased progressively with increasing pressure [14]. Conversely, the specific relationship between grasp types unique to handheld devices and perceived intensity has not been extensively studied and thus warrants further detailed exploration.

The aim of this study is to elucidate how different grasping techniques of a handheld device affect the perceived intensity of vibrotactile stimuli. We used vibrations at 40 and 250 Hz , corresponding to the sensitivity peaks of FA I and FA II mechanoreceptors [26], and compared them at various intensities. These frequencies have been widely used in previous studies on vibrotactile perception [14], [24], [25] and provide a valuable reference for comparison. Furthermore, we analyzed grasp strength as a parameter in power grasp and precision grasp, as proposed by Napier [27], to understand its impact on device handling. Power grasp, chosen for tasks requiring strong force, stability, and safety, involves a large contact

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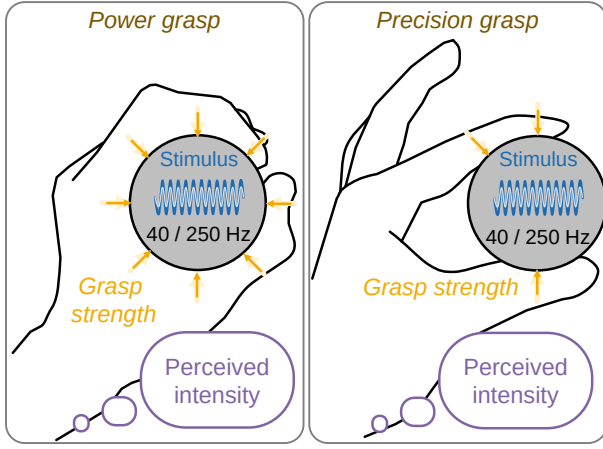


Fig. 1. A schematic diagram of the experiment illustrating the relationship between grasp strength, vibration intensity, and perceived intensity across four conditions: power grasp and precision grasp at 40 and 250 Hz.

area between the object and the palm/fingers, minimal finger motion, and relies on the thumb exerting pressure against the palm. In contrast, the precision grasp, selected for tasks requiring sensitivity and dexterity, involves gripping the object between the thumb and fingertips, allowing for intrinsic object manipulation without moving the arm [28].

This paper begins with an overview and description of the experimental apparatus used. Next, it describes measurements and numerical analysis used to understand the physical stimuli. Then, psychophysical experiments are presented. Finally, we discuss how the grasp state influences vibrotactile perception based on physical observations and subjective feedback. Our findings aim to facilitate comparisons of tactile experiences and contribute to the development of design guidelines for achieving more stable and consistent sensory displays.

II. SYSTEM DESIGN AND ANALYSIS

An experimental system was developed to examine how grasp conditions affect vibration perception characteristics. We used a handheld device equipped with a vibrotactile display and grasp strength measurement capabilities. During the experiment, participants were instructed to grasp the handheld device at specified strengths and report their perceived intensities of the presented vibrations. As depicted in Fig. 1, the relationship between these variables was explored by recording responses of perceived intensity alongside grasp strength and vibration intensity. Additional parameters, including grasp type and vibration frequency, were predetermined and incorporated into the experiment. In this experiment, grasp strength was defined as the pressure exerted across the entire surface of the device, measured as the average of the pressure distribution. In the subsequent sections, we elaborate on the details of the experimental apparatus, followed by measurement experiments conducted using the actual apparatus to analyze the physical stimuli and a numerical analysis of the vibration propagation using a modified three-degree-of-freedom (3-DOF) model.

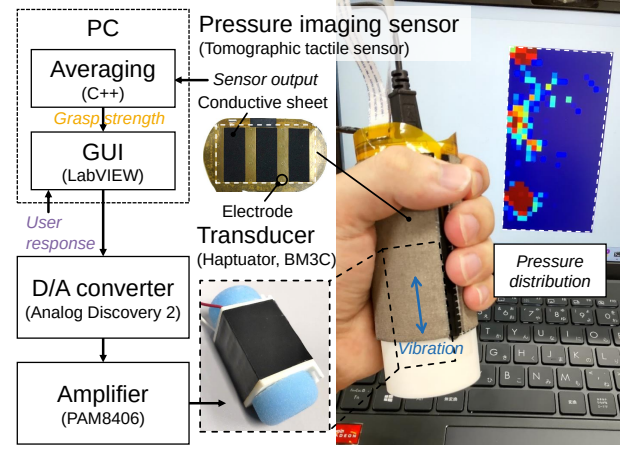


Fig. 2. The practical implementation of the pressure distribution sensor in the experimental device and the internally housed transducer.

A. Apparatus

As shown in Fig. 2, a handheld device that simultaneously measures grasp strength and present vibration was developed. The cylindrical device has a diameter of 136 mm and is fabricated using PLA material with a 3D printer. Grasp strength was defined as the pressure applied across the device's entire surface, measured using a tomographic tactile sensor based on electrical contact resistance and electrical impedance tomography (EIT) [29]. Grasp strength during 1.5 s of vibration was determined by averaging the pressure distribution data obtained over time and space.

We designed the sensor in our previous work [29] and confirmed that it had sufficient accuracy, with a normalized root mean square error of less than 5 %. The pressure distribution sensor measured 136 mm $\times$ 85 mm in size and consisted of an electrode film with 16 electrodes, a 1-mm thick conductive porous material, insulating mesh tape, and conductive fabric. A transducer (Haptuator BM3C, Tactile Labs) capable of delivering accelerations up to 10 G at a frequency of 40 Hz was employed for vibration stimuli. The transducer was mounted inside the device to vibrate along the axial direction of the cylindrical structure. Experimental control was facilitated using a program written in a graphical programming language (LabVIEW, National Instruments), with a D/A converter (Analog Discovery 2, Digilent) and a power amplifier (PAM8406) used to drive the transducer.

B. Measurement of stimuli

Understanding the mechanical relationship between the intensity of presented stimuli and grasp strength is crucial. Thus, a measurement experiment was conducted to explore how grasp strength influences the physical vibration of the device when grasped and vibrated under conditions replicating those used in the actual experiment. Many studies address stimulus level in relation to displacement, but under the three grasping conditions, measuring displacement accurately can be challenging. Therefore, this study measures the device's acceleration characteristics under multiple grasp strengths and

analyzes vibration propagation to understand the observed effects.

An accelerometer (KXR94-2050, Kionix) was securely mounted on the bottom of the device using a 3D-printed socket and masking tape to measure the vibration amplitude along the axial direction. An input and output module (Analog Discovery2, Digilent) and WaveForms software (Digilent) were used to capture the frequency response. The measurement conditions included five conditions: free state and two different grasp strengths (weakly or strongly) and two grasp states (power grasp or precision grasp). In the free state, the device was suspended by using a thin metal wire in order to eliminate the mechanical constraint. This configuration creates a low-stiffness gravity spring that allows for relatively free motion along the actuator's axis [30]. The obtained gain can be used as an input/output characteristics of vibrator, i.e., reference. Gain measurements were taken during three 20–500 Hz sweep vibrations generated by the D/A converter for each of the five conditions. Vibration transmissibility (dB) at different frequencies was calculated by subtracting the gain of the free state $20 \log |G_{\text{act}}(\omega)|$ from the measured gains of the other conditions $20 \log |G_{\text{meas},s}(\omega)|$ ($s = 1, \dots, 4$) as the frequency response of the vibration stimulus. This calculation assumes that the system is linear and that the transmission characteristics of the grip are connected in series.

Figure 3 shows that vibration attenuation at 40 Hz was greater in the strong power grasp condition than in the weak power grasp condition. In contrast, no remarkable differences were observed between the weak and strong grasp strengths in the precision grasp condition or in the power grasp condition at 250 Hz. These results indicate that in the designed experimental system, grasp strength significantly attenuates vibration at 40 Hz when the device is gripped firmly, but has a minimal effect under other conditions. This attenuation is likely attributed to the mechanical constraint caused by gripping. One reason for the non-significant effect of grasp strength in the precision grasp condition is the small contact area between the device and the skin.

C. Numerical analysis of stimulus propagation

As a supportive conceptual framework to understand the measured transmissibility for various grasp conditions, numerical analysis was performed using an analytical model of the vibrotactile system. Several mechanical models have been proposed to analyze hand-arm vibration, including the Kelvin-Voigt model and the ISO 10068 standard model (multi-degree of freedom: DOF model) [31]. Wiertelowski and Hayward performed parameter identification using the Kelvin-Voigt model to analyze tangential vibrations at the fingertip [32]. Dong et al. proposed several improved ISO models and identified parameters for analyzing multidirectional vibrations using a handheld device [33], [34]. This paper adopts a 4-DOF model [34] which is well applicable to the hand grip vibration in the axial direction of the cylindrical device [35]. Although the input acceleration in the previous work is greater than that of our device, the scalability of the model allows for the investigation of the influence of grasp strength. Because

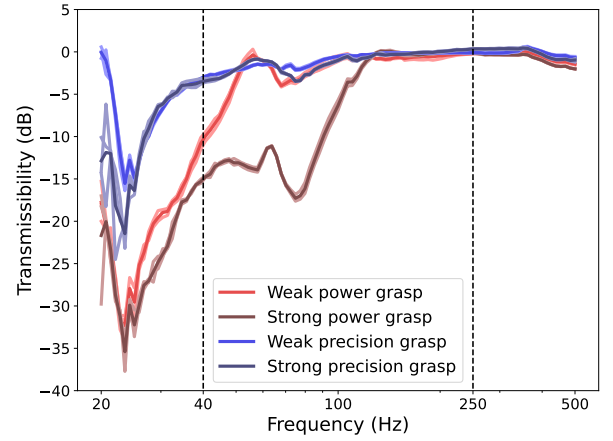


Fig. 3. The vibration transmissibility at various frequencies determined through actual measurements under weak and strong power grasp and precision grasp conditions. To eliminate device-specific characteristics, the results were derived by subtracting those of the device in a free state versus when suspended with a thin metal wire. Light colors indicate individual trials; dark colors indicate average values.

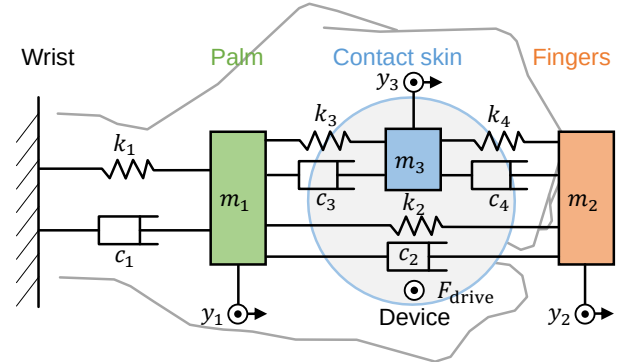


Fig. 4. The model depicting a hand grasping the vibration device as a 3-DOF spring-mass-damper system, along with the parameters employed for analysis.

our interest is to explore the relationship between the force input and the displacement of the body, we use a modified 3-DoF model where the skin and device vibrate together as a single mass.

By solving simultaneous equation of motion for a mechanical system, depicted in Fig. 4, this approach adequately simulates the deformation responses of the skin and hand-to-device vibrations during grasping up to a certain frequency. The simultaneous equations of motion for this system are expressed as follows.

$$M\ddot{\mathbf{y}} + C\dot{\mathbf{y}} + K\mathbf{y} = \mathbf{f}, \quad (1)$$

The displacement vector $\mathbf{y}$ and force vector $\mathbf{f}$ are expressed as $\mathbf{y} = [y_1, y_2, y_3]^T$, $\mathbf{f} = [0, 0, f_{\text{drive}}]^T$, where y_i is the displacement of mass in axial direction of the device, and f_{drive} is the driving force related to measured acceleration. The mass matrix M , damper matrix C , and stiffness matrix K are expressed as following equations:

TABLE I
PARAMETERS USED IN THE CALCULATION OF THE 3-DOF MODEL WITH
EQUATIONS OF MOTION [33]

Model	i	m_i (kg)	k_i (N/m)	c_i (Ns/m)
Palm	1	0.388	—	—
Fingers	2	0.079	—	—
Contact skin & device	3	0.118	—	—
Wrist-palm	1	—	1000	18.8
Palm-fingers	2	—	10	16.7
Palm-contact skin	3	—	170.64 – 17064	22.3
Fingers-contact skin	4	—	341 – 34113	27.8

$$M = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix},$$

$$C = \begin{bmatrix} c_1 + c_2 + c_3 & -c_2 & -c_3 \\ -c_2 & c_2 + c_4 & -c_4 \\ -c_3 & -c_4 & c_3 + c_4 \end{bmatrix}, \quad (2)$$

$$K = \begin{bmatrix} k_1 + k_2 + k_3 & -k_2 & -k_3 \\ -k_2 & k_2 + k_4 & -k_4 \\ -k_3 & -k_4 & k_3 + k_4 \end{bmatrix},$$

where m_i is the mass of the hand part and the device, k_i is the spring constant, and c_i is the damping constant. For k_i and c_i , $i = 1$ refers to the wrist-palm, $i = 2$ refers to the palm-fingers, $i = 3$ refers to the palm-contact skin, and $i = 4$ refers to the fingers-contact skin. For m_i and x_i , $i = 1$ refers to the palm, $i = 2$ refers to the fingers, and $i = 3$ refers to the contact skin and the device.

By applying the Fourier transform, the equations of motion are expressed in complex numbers and matrices. The transmissibility of relative displacement between masses, $G_1(\omega) = 20 \log |Y_1(\omega)/Y_3(0)|$, $G_{12}(\omega) = 20 \log |Y_{12}(\omega)/Y_3(0)|$ and $G_{23}(\omega) = 20 \log |Y_{23}(\omega)/Y_3(0)|$ were then calculated using the inverse matrix of the stiffness matrix. $Y_1(\omega)$, $Y_{12}(\omega)$, and $Y_{23}(\omega)$ are relative displacements of palm, palm-fingers, and fingers-contact skin, respectively. This was numerically calculated based on the parameters shown in Table I, presented in the previous study [34], and the device's weight. Additionally, grasp strength increases the apparent stiffness of the skin due to the nonlinearity [36]. Although viscosity depends on the strain rate [37], we assume that the effect of a static grasping force is negligible. In our model, the grasp strength is associated with the interaction between the palm and the contact surface, as well as between the fingers and the contact surface. To account for the effect of grasp strength, the analysis was also performed under the condition that the values of k_3 and k_4 were varied to simulate changes in the skin surface condition in response to different grasp strengths. Because the stiffness values of k_3 and k_4 reported in [34] are large due to the large grasp strength (30 N), we apply various scale factors from 0.01 to 1 in order to represent conditions of weaker grasp strength. Consequently, the stiffness of the finger-contact skin under weak grasp strength is 341 N/m, which is of the same order of magnitude as reported in the previous study using small contact force (0.5 N) [32].

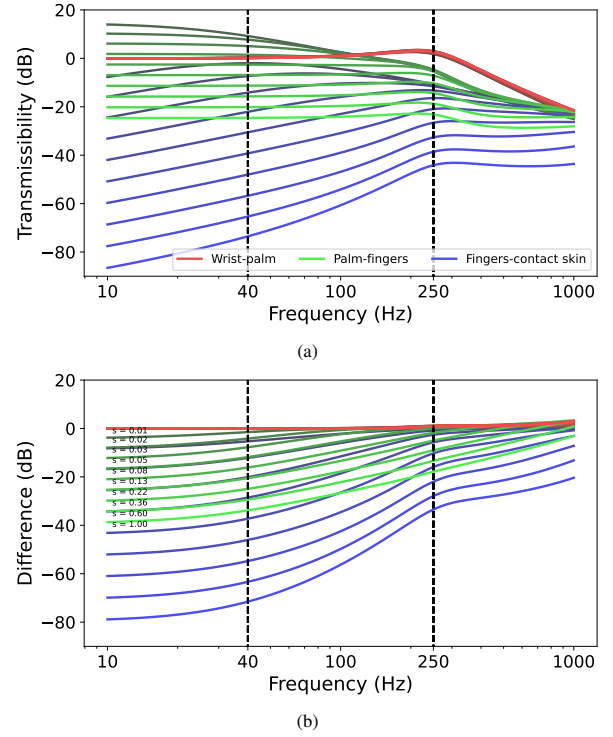


Fig. 5. Results of the analysis. (a) Frequency-dependent transmissibility of relative displacement obtained by numerical analysis under various grasp strength conditions and (b) difference between various grasp strength and lowest grasp strength conditions by varying k_3 and k_4 . The scaling factor s was varied from 0.01 to 1 in 10 logarithmically spaced steps. Brighter colors represent larger scaling factors, corresponding to greater grasp strengths (see the text labels next to the green lines).

The transmissibility of relative displacement under conditions of strong grasp strength and the difference in transmissibility between various grasp strength and lowest grasp strength conditions for each frequency are depicted in Fig. 5. Figure 5(a) shows similar characteristics to those observed in a previous study [34]. Figure 5(b) illustrates that increasing grasp strength attenuates the relative displacements between the fingers and contacting skin and between palm and fingers. This effect becomes smaller related to the frequency. Conversely, the relative displacement between the wrist and palm slightly increases at higher frequencies. Vibration appears to be primarily perceived through the skin in contact and the palm. In particular, Figure 5(a) shows that the displacement of the palm is relatively larger than that of other body parts.

Based on the acceleration characteristics obtained from measurements and the vibration propagation characteristics obtained from the analysis, the following conclusions were made regarding the impact of grasp strength on the physical stimuli of vibration;

- In a power grasp condition, the output of 40 Hz vibrations is attenuated by grasp strength.
- Grasp strength attenuates the relative displacements of palm-fingers and fingers-contact skin. This effect becomes smaller at higher frequencies.
- The relative displacement between the wrist and palm shows a slight increase in relation to grasp strength at frequencies above several hundred hertz.

III. EXPERIMENTS

Psychophysical experiments were conducted to explore how grasp states influence perceived vibration characteristics. We examined the relationship between perceived intensity and the amplitude of presented vibrations across different grasp strengths and postures using a custom device equipped with a pressure distribution sensor and vibrator. A free magnitude estimation is a possible method [38], however, normalization of the responses is challenging due to the variability in grasp conditions among participants. To efficiently obtain responses for multiple parameters, this study employed the rating scale method, which has been used in previous studies to assess the subjective intensity of tactile stimuli [39].

A. Participants

Eleven healthy adult volunteers (6 males and 5 females, aged 22–32) participated in the experiments. This experiment was conducted with the approval of the Ethics Review Committee of the University of Tokyo (23–268). Participants were fully informed about the experiment and provided consent before participating.

B. Conditions

The experiment employed two types of grasp states, power grasp and precision grasp, with five levels of grasp strength. As described in the apparatus section, the average value of the pressure distribution determined the grasp strength. Based on the observed changes in output voltage with varying grasp strength, the values were categorized into five ranges and displayed on the digital gauge. In this paper, the grasp strength is represented by pressure unit.

As for the vibrotactile stimuli, two frequencies, 40 and 250 Hz, were used. The stimulus level ranged from 1 to 20 divided into 20 levels. The maximum stimulus level was subjectively set in a range that would not cause discomfort. In magnitude estimation, to facilitate answering, it is important to consider that the perceived intensity of vibration follows logarithmic characteristics according to the Weber–Fechner law. To enhance the linearity between stimulus and perceived intensities, the acceleration amplitude of the vibrotactile stimulus was determined using the following exponential function;

$$Acc = a \exp\left(\frac{S}{b} - c\right), \quad (3)$$

where Acc is the acceleration amplitude (m/s^2), S is the stimulus level, and $a = 0.169$, $b = 8$, and $c = 0.809$ are experimentally determined constants. Consequently, the acceleration amplitude ranges from approximately 0.14 m/s^2 to 2.0 m/s^2 . These parameters were carefully selected in order to prevent the saturation of the perceived intensity.

C. Procedure

The experimental procedure followed by the participants is illustrated in Fig. 6. First, the participants adjusted their grasp strength according to a gauge indicating five random levels. Participants grasped the device with their left hand, regardless

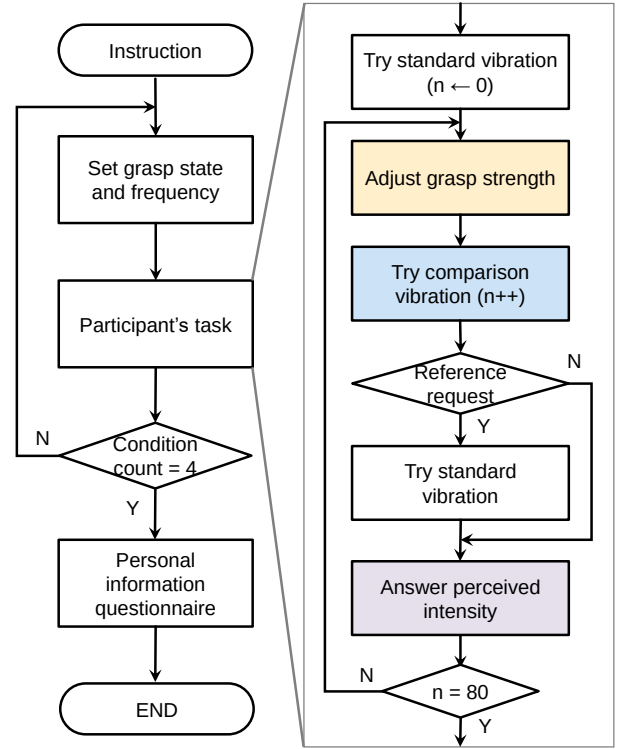


Fig. 6. Protocol of the experiment. n is the total number of data points for each condition, defined by grasp type (power grasp and precision grasp) and vibration frequency (40 Hz and 250 Hz). At each step, stimulus level was randomly selected from 20 levels with possible repetition, while grasp strength was randomly chosen from 5 levels without repetition.

of their dominant hand. In the power grasp condition, all participants could consistently reach the maximum grasp strength category. However, in the precision grasp condition, some participants had difficulty achieving the maximum strength and were instructed to use the greatest force possible.

Next, participants clicked a button to play the 1.5 s vibration. Then, participants are required to answer perceived intensity using a digital slider bar. They could optionally check the vibration as a criterion for their response before responding to the perceived intensity of the vibration. This procedure was repeated until the specified number of times was completed. Total experiment time was less than 30 min and breaks between trials were allowed to be taken upon participants.

For grasp strength, each of the five conditions was tested 16 times randomly. For the stimulus level, 80 trials were conducted, with stimulus levels randomly selected from 20 possible levels, allowing for repetition.

D. Measurement and analysis

It is important to shorten the measurement time because maintaining a consistent grasp strength over long periods is difficult. Additionally, it is difficult to normalize the psychometric curve for each participant because the grasp strength is different between the participants. Therefore, we integrated rating scale method into free magnitude estimation. Different from general free magnitude estimation method, perceived

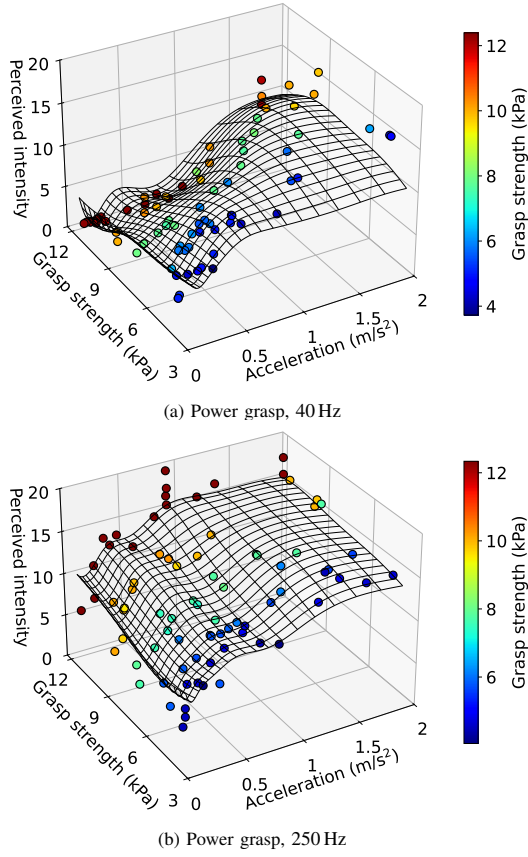


Fig. 7. Examples of the perceptual characteristics with surfaces fitted by using support vector regression with RBF kernels. The sensor output voltage value and stimulus level were converted into pressure value and acceleration, respectively.

intensity was evaluated via a questionnaire using a 21-point absolute rating scale, including 0, i.e., no perception. This approach is similar to the rating scale method commonly used for subjective evaluation of tactile stimuli, such as in [39]. In order to facilitate answering and prevent response saturation, i.e. ceiling effect, the vibration at the middle (10th) stimulus level (0.53 m/s^2) with the lowest grasp strength in each condition was used as the reference for the perceived intensity 10.

To investigate the effect of grasp strength, we first analyzed the relationship between perceived intensity and grasp strength using the collected data. Next, we performed a linear regression to model the perceptual relationship between perceived intensity and acceleration. Considering both the number of points and accuracy of the grasp control, each participant's data were evenly divided into three groups based on grasp strength, resulting in participant-specific thresholds. The value of the regression curve at each stimulus level within each condition served as the participant's response, and data from all participants were subsequently analyzed statistically.

IV. RESULTS

Figure 7 shows examples of perceptual characteristics from a participant in the power grasp condition using 40 and 250 Hz stimuli. The plot shows a surface fitted to the experimental

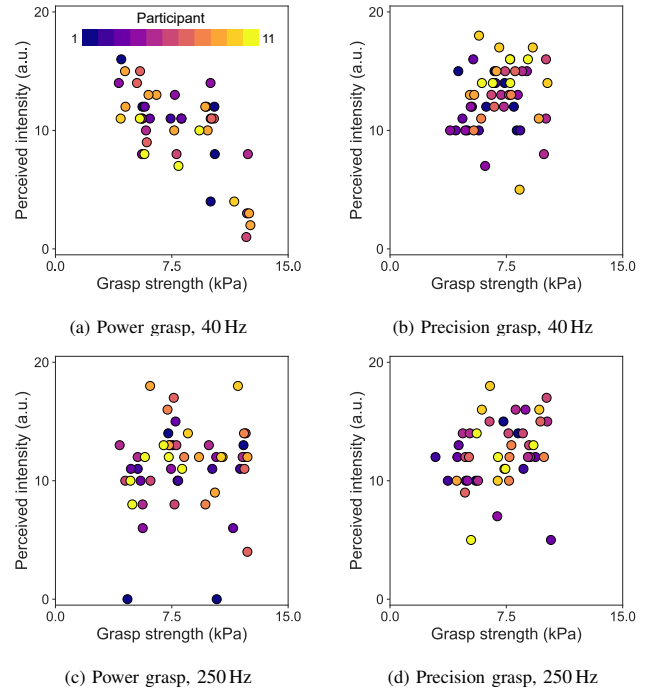


Fig. 8. Relationship between perceived intensity and grasp strength at the 13th stimulus level (0.8 m/s^2). Data points represent measurements from all participants.

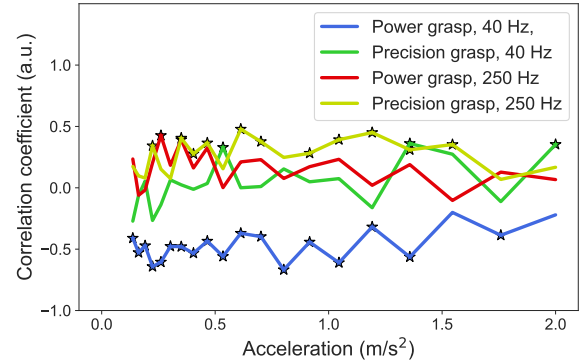


Fig. 9. Correlation coefficients between perceived intensity and grasp strength are shown for each acceleration. Asterisks indicate statistically significant correlations ($p < 0.05$).

data using the support vector regression with the radial basis functions (RBF) for surface interpolation. This surface helps visualize the trend. Figure 7 shows that in the power grasp condition at 40 Hz, higher grasp strength led to lower perceived intensity when stimulus level was low. In other conditions, perceived intensity varied with stimulus level, and the influence of grasp strength was minimal. Figure 8 illustrates the relationship between perceived intensity and grasp strength at the 13th stimulus level (0.8 m/s^2). In the power grasp condition at 40 Hz, a significant negative correlation was observed (-0.67 , $p < 0.05$) between grasp strength and perceived intensity. Figure 9 presents the correlation coefficients between perceived intensity and grasp strength across all stimulus levels (accelerations), which are summarized in Table II. In the

TABLE II

CORRELATION COEFFICIENT BETWEEN PERCEIVED INTENSITY AND GRASP STRENGTH (PI-GS CORRELATION), ALONG WITH THE CORRESPONDING p -VALUES, ARE SHOWN FOR EACH GRIP TYPE (GT), FREQUENCY TYPE (FT), AND STIMULUS LEVEL (SL).

GT	FQ (Hz)	SL (a.u.)	Acceleration (m/s ²)	PI-GS Correlation
Power	40	10	0.53	-0.559 ($p < 0.001$)
Power	40	20	2.0	-0.220 ($p < 0.05$)
Precision	40	10	0.53	0.329 ($p = 0.99$)
Precision	40	20	2.0	0.353 ($p = 0.31$)
Power	250	10	0.53	0.002 ($p = 0.10$)
Power	250	20	2.0	0.067 ($p < 0.05$)
Precision	250	10	0.53	0.155 ($p = 0.68$)
Precision	250	20	2.0	0.168 ($p = 0.33$)

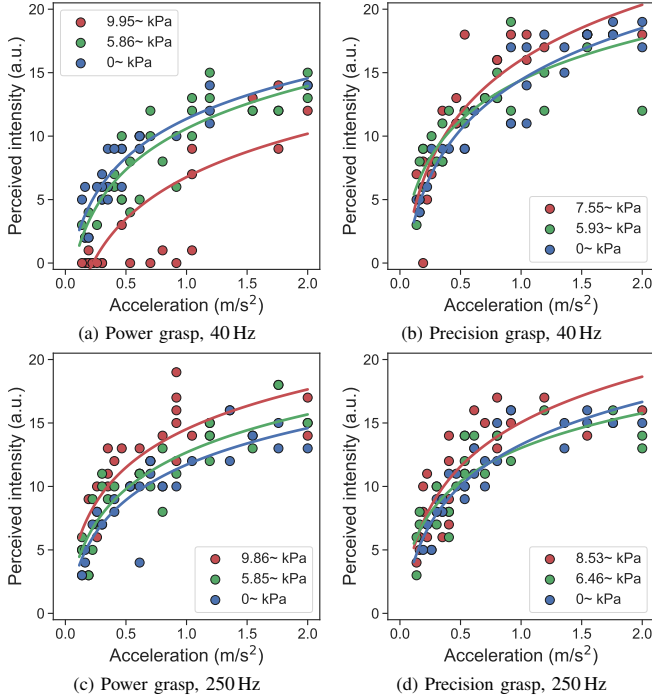


Fig. 10. Results of stimulus-perception characteristics from a participant in power grasp and precision grasp conditions using 40 and 250 Hz stimuli. Each plot shows the experimental data labeled using the three levels of grasp strength and curves fitted to the data.

power grasp condition at 40 Hz, most stimulus levels showed a negative correlation, whereas in the other conditions, positive correlations were observed at certain stimulus levels.

To validate the results of the correlation analysis, we estimated perceived intensity using fitted curves for each grasp strength and conducted statistical tests. Figure 10 presents the stimulus-perception characteristics from a single participant across four different conditions. Each plot shows the experimental data labeled using the three levels of grasp strength and curves fitted to the data. Each curve was obtained by performing a linear fit to the experimental data as a function of stimulus level, and subsequently transformed into acceleration space using equation (3). The coefficient of determination (R^2) exceeded 0.99 under all conditions. Furthermore, the root mean square errors (RMSEs) indicate that the fitting was performed with appropriate accuracy, as shown in Table III. This curve was used to estimate the

TABLE III

SLOPES, INTERCEPTS AND ROOT MEAN SQUARE ERRORS (RMSEs) OF THE MODEL FITTING WERE CALCULATED FOR EACH CONDITION. THE MEAN AND STANDARD DEVIATION ARE SHOWN.

Metrics	Strength	40 Hz		250 Hz	
		Power	Precision	Power	Precision
Slope	Low	0.67 (0.13)	0.78 (0.14)	0.71 (0.18)	0.68 (0.16)
	Middle	0.72 (0.14)	0.71 (0.14)	0.65 (0.19)	0.68 (0.18)
	High	0.72 (0.14)	0.87 (0.12)	0.69 (0.14)	0.74 (0.15)
Intercept	Low	2.58 (1.67)	1.38 (1.58)	1.61 (2.66)	2.43 (2.02)
	Middle	1.24 (1.70)	2.35 (1.67)	2.85 (2.68)	2.71 (2.30)
	High	-1.41 (1.83)	0.62 (1.75)	2.77 (2.20)	2.87 (2.26)
RMSE	Low	2.91 (0.43)	2.14 (0.43)	2.51 (1.07)	2.12 (0.55)
	Middle	2.21 (0.61)	2.46 (0.51)	2.51 (1.05)	2.12 (0.34)
	High	2.29 (0.93)	2.08 (0.68)	2.32 (0.93)	2.10 (0.51)

TABLE IV
RESULTS OF THREE-WAY MANOVA

Effect	Pillai's trace	$F(df_1, df_2)$	p
GT	0.041	$F(2, 109) = 2.35$	0.100
FT	0.017	$F(2, 109) = 0.92$	0.401
GS	0.317	$F(4, 220) = 10.35$	1.06×10^{-7}
GT $\times$ FT	0.039	$F(2, 109) = 2.23$	0.113
GT $\times$ GS	0.225	$F(4, 220) = 6.96$	2.70×10^{-5}
FT $\times$ GS	0.278	$F(4, 220) = 8.89$	1.14×10^{-6}
GT $\times$ FT $\times$ GS	0.127	$F(4, 220) = 3.74$	0.0057

perceived intensity at the required acceleration due to the sparsity of data. The graph indicates that perceived intensity of the 40 Hz vibration decreased with higher grasp strength. It is considered that examining the effect on perceived intensity at specific stimulation levels, rather than focusing on the slope or intercept of the psychophysical function, leads to a more direct understanding of the underlying characteristics. Figure 11 presents the estimated perceived intensities at acceleration amplitudes 0.53 and 2.0 m/s², i.e., 10th stimulus level (middle) and 20th stimulus level (maximum), using linear models for three levels of grasp strength. Box plots display the median and quartile points for each of the 11 participants, with lines connecting grasp strengths for each participant.

A multivariate analysis of variance (MANOVA) was conducted with grasp types (GT), frequency types (FT), and grasp strength (GS) as within-subject factors and two dependent variables, i.e., perceived intensities at 10th and 20th stimulus levels. Results of the three-way MANOVA are shown in Table IV. As we expected, the analysis revealed a significant multivariate effect of grasp strength. Following a significant GT $\times$ FT $\times$ GS interaction in the MANOVA, simple effects of GS were examined at each level of GT and FQ. Pairwise comparisons were conducted using paired t-tests with Bonferroni correction for multiple comparisons. Resulting significant differences are annotated in the boxplot shown in Fig. 11. In 40 Hz vibrations during power grasp conditions, the perceived intensities significantly decrease with grasp force. Other hand, the perceived intensities significantly increase with grasp force in 250 Hz vibrations during precision grasp conditions. The results are consistent with the results of the correlation analysis presented in Table II.

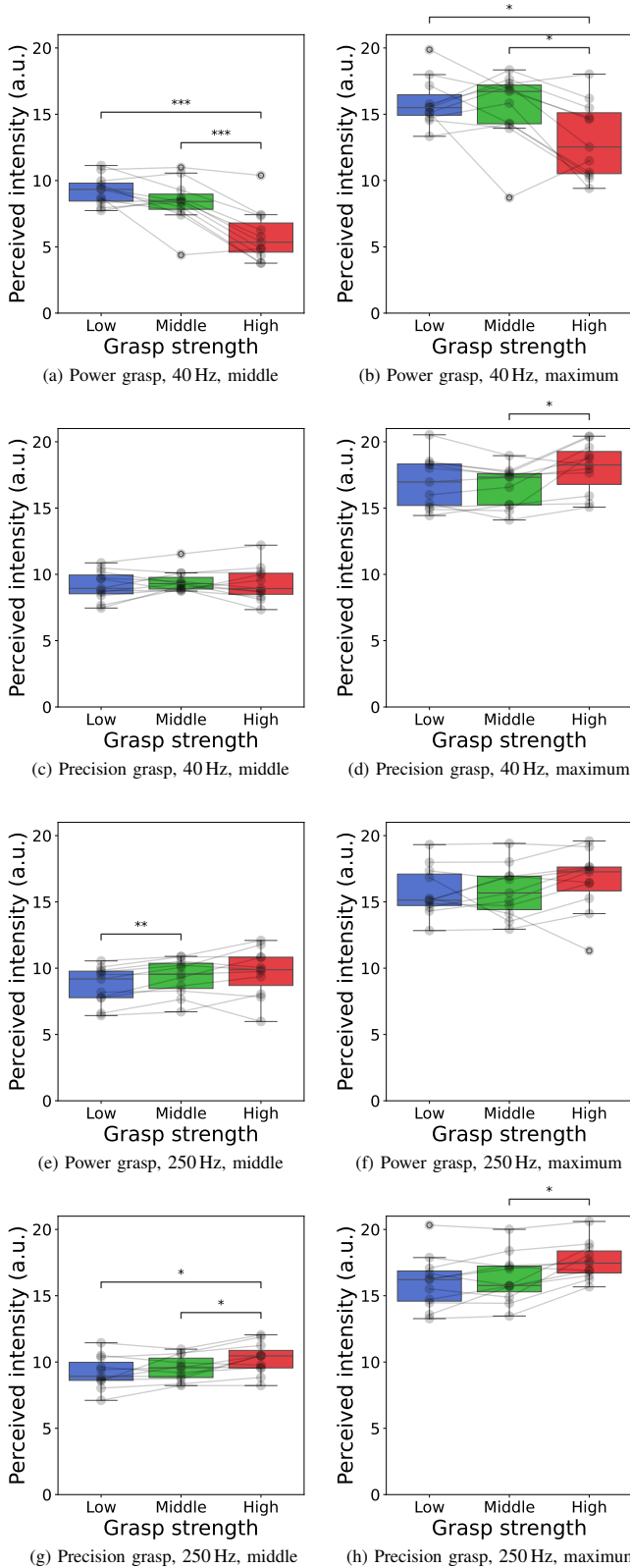


Fig. 11. The estimated perceived intensity for the three levels of grasp strength under each combination of grasp types (power grasp and precision grasp), frequencies of 40 and 250 Hz, and stimulus levels of middle and maximum are displayed. The box represents the interquartile range, the median is indicated by the center line, whiskers extend to 1.5 times the interquartile range, and diamond-shaped points denote outliers.

V. DISCUSSION

The physical measurement results (Fig. 3) showed that grasp strength reduces 40 Hz vibrations during a power grasp. In comparison, it does not affect 250 Hz vibrations regardless of the grasp condition. The analysis of vibration propagation using the modified 3-DOF model (Fig. 5) revealed that relative displacement between the fingers and contact skin decreases with grasp strength at 40 and 250 Hz. Specifically, the attenuation at 40 Hz is greater than that at 250 Hz. The results of the psychophysical experiments (Fig. 11) indicated that perceived intensity decreased with grasp strength when a 40 Hz vibration was presented in the power grasp condition. This finding aligns with the results of physical stimulus measurement and analysis, suggesting that perceived intensity is reduced owing to physical stimulus attenuation. Moreover, these results are consistent with those reported in the previous study by Mann and Griffin [24]. On the other hand, perceived intensity increased with grasp strength when a 250 Hz vibration was presented under the precision grasp condition. Specifically, Figs. 11(g) and 11(h) show that perceived intensity slightly increased with grasp strength at 250 Hz. The tendency is consistent with the weak but statistically significant positive correlation between perceived intensity and grasp strength observed in Fig. 9. The findings contract with the measurement and analysis results, which indicated that the physical stimulus decreases with grasp strength. Figure 12(a) summarized the results of the physical and perceptual measurements.

Here, we discuss potential reasons for the contradiction observed in the 40 Hz vibration under precision grasp condition based on the systematic understanding of vibrotactile perception as depicted in Fig. 12(b). Low-frequency vibrations (40 Hz) are primarily detected by Meissner corpuscles (FAI) and, to some extent, by Merkel cells (SAI) and Ruffini corpuscles (SAII), while stimuli by grasping are detected by Merkel cell (SAI) and Ruffini corpuscle (SAII). The following possibilities are considered reasons for perceiving low-frequency vibrotactile stimuli.

- The attenuation effect due to the grasp strength is smaller than that under the power grasp conditions. The result shown in Fig. 3 supports this reason.
- The sensitivity increases with contact force, as reported in previous studies [17], [18], [19]. This is because contact area increases with grasp strength.

It is suggested that there are small cross modal effects between the static force and vibrotactile sensations because the perception mechanism is the same as power grasp condition. Therefore, under precision grasp, it is possible that the change in sensitivity and the vibration attenuation balanced each other out, canceling their effects.

On the other hand, high-frequency vibration (250 Hz) is detected primarily by Pacinian corpuscles (FAII), whereas stimuli from grasping are detected by Merkel cells (SAI) and Ruffini corpuscles (SAII). The following possibilities are considered reasons for the slight increase in perceived strength in response to grasp strength at 250 Hz, which is consistent with the previous study [14].

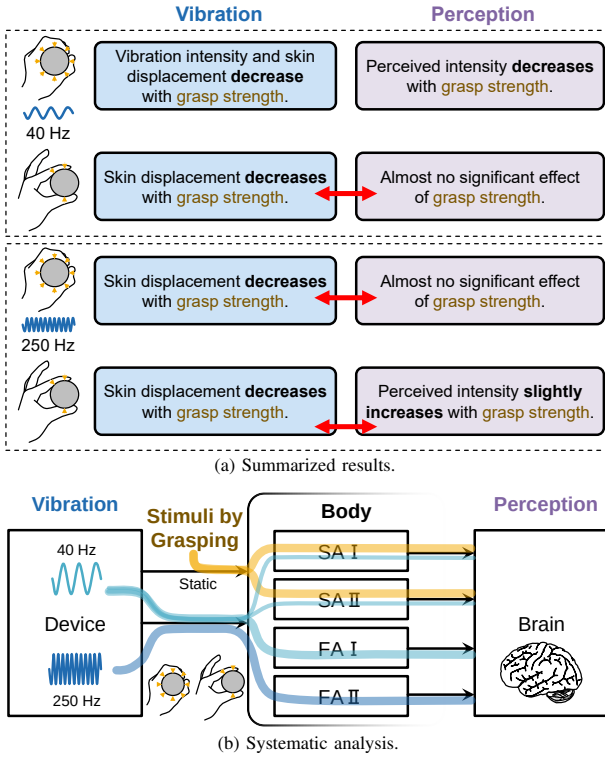


Fig. 12. (a) Summarized results of the physical observations and psychophysical experiments. Significant effects of grasp strength were observed under 40 Hz vibrations during power grasp conditions and 250 Hz vibrations during precision grasp conditions, which contrast with the observed decrease in vibration stimulus with grasp strength. (b) A systematic diagram of vibrotactile perception using a handheld device. The colored lines above the arrows illustrate the transmission paths of each stimulus.

- High-frequency vibration is detected by mechanoreceptors in the hand and arm rather than solely at the contact skin. The analysis results shown in Fig. 5(a) support this reason.
- FAII units are less sensitive to grasping force but still respond to changes in vibration stimuli due to static contact conditions. Slight sensitivity increase is attributed to static contact force and increased contact area [19]. The change rate in contact area under a precision grasp is larger than that under a power grasp.
- Grasp force and vibration stimuli are detected by different mechanoreceptors. However, vibration perception is slightly influenced by grasp strength and, to a greater extent, by neural integration in the brain [40].

The abovementioned findings suggest the following strategy for practical applications of handheld vibrotactile feedback devices. Low to medium-intensity low-frequency vibrations may be perceived as weaker than intended when the device is firmly grasped. In such cases, enhancing the sensory experience could involve compensating for the stimulus, or using higher frequencies. While there are individual differences in the perceived intensity of high-frequency vibration, the effect of grasp strength is small, suggesting that adjusting for grasp conditions during vibration presentation may not be necessary if sensitivity is corrected for specific conditions.

Although we carefully designed the perceptual experimental

method, some potential factors of bias and error remain. First, perceived intensities at high stimulus levels may be affected by bias due to the limited range of the rating scale. The results indicated that the grasp strength effect decreases with increasing acceleration. However, it remains unclear whether this is a true psychophysical effect or an artifact of the experimental method. The standard free magnitude estimation paradigm is a possible approach for further investigating the saturation problem. Second, the number of participants and individual differences in physical strength may have influenced the results. Nevertheless, the large effect sizes (Pillai's traces) observed in the power grasp conditions at 40 Hz and precision grasp conditions at 250 Hz support the validity of our findings. Finally, there are also issues related to the accuracy of the measurements and the analysis. Although the analysis yielded results consistent with the measurements, the model was effective only for qualitative understanding, as the model parameters were not independently identified. In addition, measuring skin displacement is important for further understanding the physical effects of grasp strength.

VI. CONCLUSION

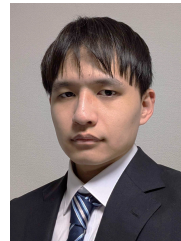
We developed an experimental system to efficiently measure the perceived intensity of vibrations at 40 and 250 Hz under power grasp and precision grasp conditions with varying grasp strengths. Each of the four conditions yielded 80 data points in the psychophysical experiment. The results indicated that the perceived intensity of 40 Hz vibrations during power grasp conditions was negatively correlated with grasp strength, whereas the perceived intensity of 250 Hz vibrations during precision grasp conditions was positively correlated with grasp strength. On the other hand, the effects of grasp strength were small for 40 Hz vibrations during precision grasp or 250 Hz vibrations during power grasp. These findings partially contradict the physical observations, which indicated that the relative displacement between the skin and hand decreased as grasp strength increased.

This finding suggests the need for compensation in low-frequency vibrations or the use of high-frequency vibrations to achieve consistent vibrotactile feedback under various grasping conditions. Further investigation through neuroscience is essential to elucidate the underlying causes of the perceptual phenomena identified in this study. Nevertheless, we believe that our sensory measurement and modeling approach contributes significantly to designing high-quality haptic experiences using handheld devices.

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