Vibrotactile Stimuli Applied to Finger Pads as Biases for Perceived Inertial and Viscous Loads

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Abstract—The perception of the mass and viscosity of an object is based on the dynamic forces applied to our hands when we jiggle or lift the object [1], [2], [3]. This force is commonly assumed to be sensed by kinetic receptors [4] in our muscles or tendons. When jiggling objects, we also experience the cutaneous deformation of our finger pads. In this study, we show that the dynamic vibration on the finger pad influences our perception of mass and viscosity. We experimentally confirm that the vibration on the finger pad, that synchronizes with the hand's accelerations or velocities, enhances the perceived changes in the mass or viscosity when the vibrotactile stimuli and the changes in the mass and viscosity are in the same perceptual direction. For example, when the increased mass and an acceleration-synchronized tactile stimulus–which is a positive bias for the mass–are simultaneously presented to the experiment participants, they respond that the perceived increase in the mass is enhanced. In contrast, when the tactile and proprioceptive stimuli are in perceptually opposite directions, the vibrotactile stimuli cancel the perceived changes in the mass and viscosity. In particular, the effect of the velocity-synchronized vibration on perception is stronger than the effect of the actual viscosity.

Index Terms—Mass, Viscosity, Vibration, Skin stretch.

1 Introduction

We estimate the mass of an object from the forces applied to our hands [1], [2], [3] when we jiggle or lift the object. Such motions allow us to acquire the higher ability to discriminate the mass [5]. The forces exerted on our hands are assumed to be mediated by the proprioceptive mechanoreceptors in our muscles and tendons, which respond to stretching or tension in our muscles or tendons [4]. We also experience the cutaneous deformations of our finger pads when we jiggle or lift the objects. These cutaneous deformations activate the tactile mechanoreceptors in our finger pads. The tactile mechanoreceptors can also be innervated by vibrotactile stimulation. In this study, we show that vibrotactile stimuli, which are synchronized with the dynamic hand movements, serve as increasing- or decreasing biases for the perceived mass and viscosity of the object during the jiggling tasks.

Possible Applications

One of the clear advantages of the illusion of the mass and viscosity caused by vibrations is that this illusion enables the presentation of the mass and viscosity without force feedback displays. It is difficult to install force feedback displays, which need to be grounded to the environment or to parts of the body, on mobile information terminals or computer mice. To avoid this limitation, some studies have used alternatives to force feedback displays. For example, the sensory discrepancy between the visual and kinesthetic cues represented the virtual compliance of an object [6] or surface shapes such as bumps or holes [7], which are usually presented by the force feedback displays. A technique that delivers the sense of hard materials, such as metal or wood, using high-frequency vibration during contact with these materials has been proposed [8], [9]. Konyo et al. proposed a vibrotactile displaying method for the sense of friction of certain materials. They provided vibratory stimuli to finger pads, synchronizing the simulated frictional vibration between the finger pads and the explored materials [10]. Methods for presenting the mass or viscosity of an object through tactile vibrations have not yet been proposed. The vibrotactile biases presented in this study represent a new alternative method for the sense of mass and viscosity.

Since the haptic bias effects presented in this study use vibrotactile stimuli, it may be possible to combine them with other vibrotactile feedback methods to improve the haptic interaction of information terminals. For example, Fukumoto et al. presented a vibrotactile display method to present the sensations acquired by pressing a virtual button [11]. The symbolic vibratory stimuli, called haptic icons [12], and the vibrotactile texture displays for virtual clothes or roughness [13] were also realized through vibrotactile stimuli to the finger pads. These techniques and the illusory displaying method for the mass and viscosity shown in this study may be realized using the same vibrotactile actuator on the information terminals.

2 Experimental Paradigm

Here, we present the paradigm of the experiments. We will design the vibrotactile stimuli that will become the

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positive/increasing and negative/decreasing biases for the perception of the mass and viscosity. The positive tactile stimuli will increase the perceived mass and viscosity, and the negative stimuli will have the opposite effects. We will present the influences of the tactile stimuli on the perception of the mass and viscosity by demonstrating that these tactile stimuli bias the perception of the mass and viscosity. First, we will show that the tactile stimuli enhance the perceived changes in the mass and viscosity. For example, when the increase in the actual mass and the positive tactile stimuli are simultaneously presented to the participants, the perceived increase in the mass becomes stronger. Second, we will show that the tactile stimuli cancel or weaken the perceived changes in the mass and viscosity, given that these changes can be detected by the participants without the tactile biases. For example, when the increase in the actual mass and the negative tactile stimuli are simultaneously presented, the perceived increase in the mass is canceled or weakened.

3 Apparatus

To independently manipulate the vibrotactile and proprioceptive stimuli, which correspond to the mass and viscosity of an object, we prepared an actuated slider with a vibrotactile stimulator. The participants haptically explored the mass and viscosity of an impedance-controlled slider (Fig. 1a). The slider was driven horizontally, and its position ($x(t)$) was controlled by

$$F_x(t) = m\ddot{x}(t) + c\dot{x}(t). \quad (1)$$

The actuated slider behaved as if it was a frictionless object with mass (m) and viscosity (c). The participants exerted a force ($F_x(t)$) on the slider with the right index finger. They moved the slider as if they were jiggling the object to the right or left (Fig. 1b). A piezo stack actuator was installed on the slider as a vibrotactile stimulator. The actuator stimulated the finger pad of the participants by producing a vibratory displacement of 280 Hz and 7.2 μm peak-to-peak amplitude along the Z-axis (Fig. 1c; also, see discussion about the usage of this frequency in section 8.2). The amplitudes could change and details are described in section 4.3.

The product information for the actuated slider, force sensor and tactile stimulator is the following: MR12T, Yamaha, Hamamatsu, Japan; ThinNANO1.2/1, BL AUTOTEC, Kobe, Japan; and ASB510C801P0, NEC/TOKIN, Sendai, Japan, respectively. The slider was driven by a shaft motor that did not produce any noticeable vibrations while the slider was in motion. The 280 Hz vibrations of the stimulator did not influence the output of the force sensor because these vibrations were far above the cut-off frequency (100 Hz) of the force sensor. The sampling and control frequencies for the force sensor and the actuated slider were 1 kHz. The output rate of the tactile stimuli was 2 kHz. The contactor of the tactile stimulator was 11.6 mm in diameter. The output force of

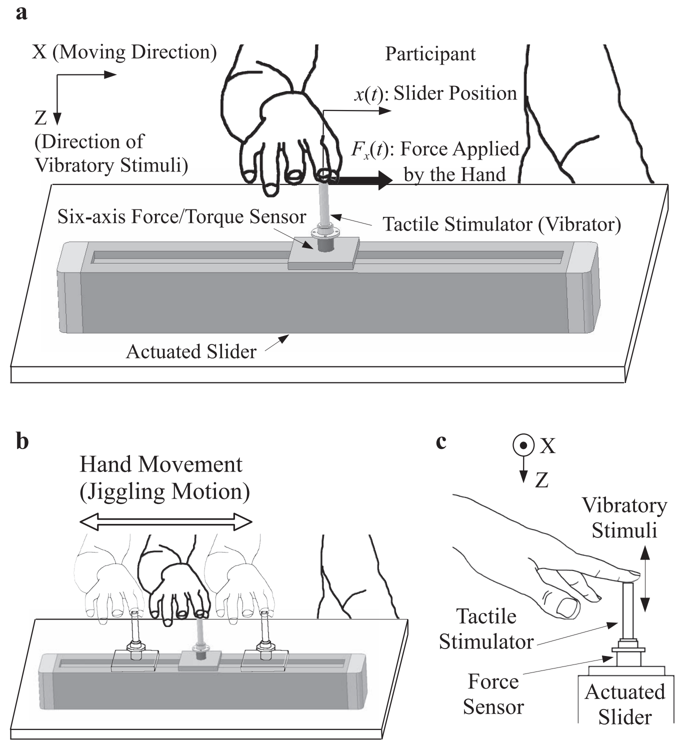

Fig. 1. a. Actuated slider, force sensor, and vibrator. b. The jiggling movement. c. The tactile vibration applied to the finger pad.

the stimulator was approximately 800 N, which is much larger than the force exerted by a human finger.

4 Vibrotactile Stimuli that Serve as Biases for Inertial and Viscous Loads

4.1 General Design

To design vibrotactile stimuli that could serve as biases for inertial and viscous loads, we analyzed the lateral deformation of the finger pad that occurs when the hand is jiggling an object. If the object mass increases and the hand movement is maintained, the lateral deformation of the finger pad increases as a result of the increased external force on the finger pad (see section 4.2). Such increases are significant when the hand acceleration is large. With the increase in the cutaneous deformation, the activities of the RA and SA receptors of the finger pad increase (see section 8.2). In order to mimic the increase of the RA receptors' activities, the amplitude of the vibrotactile stimuli is increased in synchronization with the acceleration of the hand. If the mass of the object decreases, the activity level of the mechanoreceptors will be lower than that in the case of a larger mass. In order to mimic the decrease in the RA receptors' activities, the amplitude of the vibrotactile stimuli is decreased in synchronization with the hand acceleration.

The change in lateral deformation on the finger pad due to the change in viscosity of the object is prominent when the hand velocity is large (see section 4.2). In order to mimic the change in the activities of the RA receptors

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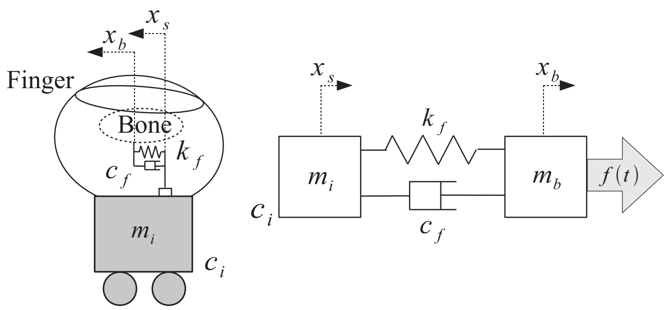

Fig. 2. Skin model for the numerical analysis of the lateral deformation of a finger pad in jiggling a frictionless 1-DOF object. Left. Schematic model of a finger and a virtual object with no friction. Right. Symbolic version of the the figure on the left.

that is caused by an increase or decrease of the viscosity, the amplitude of the vibrotactile stimuli is increased or decreased in synchronization with the hand velocity.

4.2 Numerical Simulation of Lateral Skin Stretch

We will consider the certain case in which a human finger moves a frictionless virtual object (Fig. 2). When the finger moves the object, a dynamic lateral deformation occurs on the finger pad. This deformation depends on the mechanical impedance of the object and the hand movement. In the model, the skin surface and the object are fixed and do not slide. The finger is expressed as a mass point (m_b) with a spring (k_f) and damper (c_f) connected. The force ($f(t)$) that the finger produces is applied to the mass of the finger. The object is represented by its mass (m_i) and viscosity (c_i). The equation of motion is given by

$$m_i\ddot{x_s} + (c_i + c_f)\dot{x_s} + k_f x_s = c_f\dot{x_b} + k_f x_b, \quad (2)$$

$$m_b\ddot{x_b} + c_f\dot{x_b} + k_f x_b = c_f\dot{x_s} + k_f x_s + f(t), \quad (3)$$

where $x_b(t)$ and $x_s(t)$ are the position of the finger's mass and the position of the object, respectively. The lateral skin stretch is expressed as $x_b(t) - x_s(t)$. The values of the parameters used for the computation are as follows. The mechanical impedance of the object was $m_i = 0.2$ kg, and $c_i = 0.5$ N·s/m; these values were also used in the experiments conducted in this study. The physical parameters of the skin were $k_f = 400$ N/m, and $c_f = 2.0$ N·s/m, based on the report of Nakazawa et al. [14], in which they estimated the spring coefficient and viscosity of the finger pad when lateral forces were applied to its surface. The model of the finger used in their study is very similar to our skin model. The mass of the finger was set to $m_b = 0.01$ kg. The finger force ($f(t)$) exerted to jiggle the object was approximated as a sinusoidal function: $f(t) = F\sin(\omega t)$, with $\omega = 2\pi$ rad/s. The magnitude of the force ($F = 0.5$ N) was determined from actual data observed using the same equipment that was used in the present study.

We now look at the effects of mass change on lateral skin stretches. For instance, Fig. 3 shows the difference in the skin stretches between the case of $m_i = 0.2$ kg and 0.3 kg. The phase difference between the change in skin stretch due to the change in mass and the finger velocity is approximately $\pi/2$ rad. This is close to the phase of the acceleration of the finger. The phase difference (θ) between the change in skin stretch and the finger velocity is $\theta = 1.79$ rad (102.6°). If we change the mechanical parameters of the skin, this relationship remains approximately the same. For example, when k_f and c_f change by a factor of 0.5 to 2 and m_b changes by a factor of 0.1 to 10, θ changes by 1.69 to 1.80 rad.

Fig. 4 shows the difference in skin stretches between the cases of $c_i = 0.5$ N·s/m and 0.6 N·s/m. The phase of the difference in skin stretches is close to that of the hand velocity ($\theta = 0.36$ rad, 20.9°). If we change the mechanical parameters of the skin, this relationship remains approximately the same. For example, when k_f and c_f change by a factor of 0.5 to 2 times and m_b changes by a factor of 0.1 to 10, θ changes by 0.23 to 0.38 rad.

From these analyses, it is predicted that the manipulation of the lateral skin stretch of the finger pad that is synchronized with the finger's acceleration will lead to the perception of mass change. Also, the manipulation of skin stretch in synchronization with the finger's velocity will influence the perception of viscosity change. In this study, instead of the skin stretches, we apply vibrotactile stimuli to the finger pad and investigate the effects of the stimuli on the perception of changes in the inertial and viscous loads.

4.3 Equations of Tactile Stimuli

The displacement of the tactile stimuli was given by $y(t) = A(t)\sin(2\pi f t)$. The vibratory frequency was $f = 280$ Hz for both the reference and test stimuli in the experiments. For the reference stimuli, the amplitude of the displacement was constant: $A(t) = 3.6$ μm. The amplitude of the tactile stimuli intended to affect the perception of the mass–these stimuli were used for Exp. 1–changed in synchronization with the hand acceleration. The amplitudes were determined by

$$\begin{cases} A(t) = \alpha_i & \text{if } |\ddot{x}(t)| < B_i, \\ A(t) = \alpha_i(1 \pm \dfrac{|\ddot{x}(t)| - B_i}{D_i}) & \text{if } |\ddot{x}(t)| \geq B_i, \end{cases} \quad (4)$$

where α_i, B_i and D_i are the amplitude of the stimuli when the hand is at rest, the width of the insensitive range of hand acceleration in which the amplitude did not change, and the rate of amplitude change, respectively: $\alpha_i = 3.6$ μm, $B_i = 0.4$ m/s^2, and $D_i = 1.0$ m/s^2. These values were determined by the researchers to represent one condition that was likely to be the bias for the perception of the inertial load. The insensitive range was introduced so that these amplitude changes were not driven by the small movement of the linear

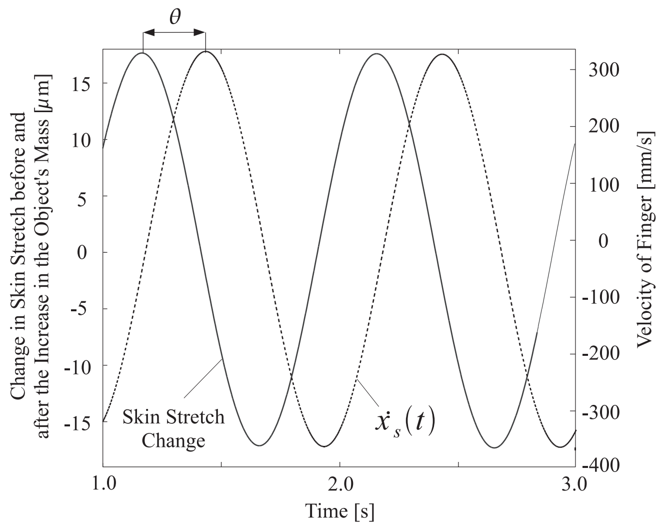

Fig. 3. Skin stretch change caused by an increase in the mass, $(x_b(t) - x_s(t)|_{m_i=0.2\ \mathbf{kg}}) - (x_b(t) - x_s(t)|_{m_i=0.3\ \mathbf{kg}})$. The solid line is the change in lateral skin stretches caused by an increase in object mass. The dashed line is the finger velocity. The phase of the skin-stretch change is approximately $\pi/2$ apart from that of finger velocity, and it is close to that of the finger acceleration.

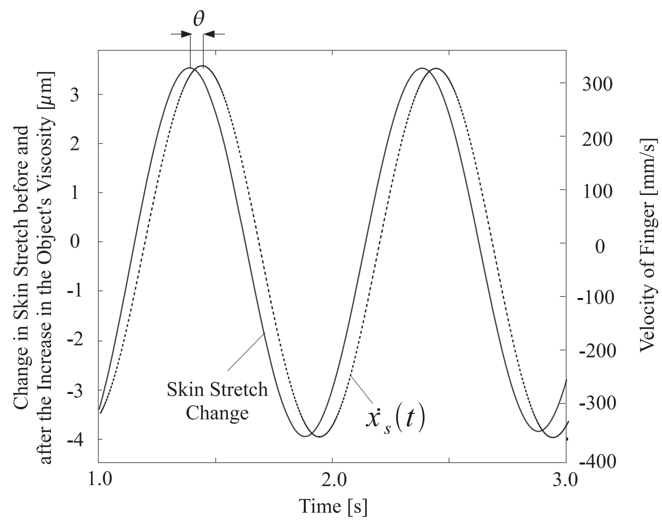

Fig. 4. Skin stretch change caused by an increase in the viscosity, $(x_b(t) - x_s(t)|_{c_i=0.5\ \mathbf{N \cdot s/m}}) - (x_b(t) - x_s(t)|_{c_i=0.6\ \mathbf{N \cdot s/m}})$. The solid line is the change in lateral skin stretches caused by an increase in the viscosity. The dashed line is the finger velocity. The phase of the skin-stretch change is close to that of finger velocity.

slider along the X-axis when the participant placed his or her finger on the tactile stimulator at the beginning of every experimental trial. In other words, this value was intended to ensure that the tactile biases were generated only by the jiggling movements of the hand. The "±" sign in (4) corresponds to "+" for increasing the perceived mass, and "−" for decreasing the perceived mass.

The amplitudes of the tactile stimuli intended to affect the perception of viscosity–these stimuli were used for Exp. 2–changed in synchronization with the hand velocity. The amplitudes were determined by

$$\begin{cases} A(t) = \alpha_v & \text{if } |\dot{x}(t)| < B_v, \\ A(t) = \alpha_v (1 \pm \dfrac{|\dot{x}(t)| - B_v}{D_v}) & \text{if } |\dot{x}(t)| \geq B_v, \end{cases} \tag{5}$$

where α_v, B_v and D_v are the amplitude of the stimuli when the hand is at rest, the width of the insensitive range of the hand velocity, and the rate of amplitude change, respectively: $\alpha_v = 3.6\ \mu$m, $B_v = 40 \times 10^{-3}$ m/s, and $D_v = 120 \times 10^{-3}$ m/s.

5 Experiments

Two types of experiments were conducted. In Exp. 1, the effects of the tactile stimuli given in (4) on the perception of the inertial load were investigated. In Exp. 2, the effects of the tactile stimuli given in (5) on the perception of viscous load were investigated.

5.1 Experiment 1 (Biases for Mass)

5.1.1 General

Exp. 1 was designed to investigate the effects of the acceleration-synchronized tactile stimuli on the perception of the virtual object's mass. Eight participants explored the mass by jiggling the slider with his or her finger following the sounds of a metronome at 1.42 Hz. They compared the reference and test stimuli and noted whether the mass of the test stimulus had increased or decreased compared with the reference mass. For the test stimuli, the mass was increased or decreased from the reference mass. The tactile stimulus was either the same as that of the reference stimulus or its amplitude was increased (served as a positive bias) or decreased (served as a negative bias) in synchronization with the finger's acceleration.

5.1.2 Groups of Test Stimuli

The test stimuli were divided into three groups with different combinations of inertial and tactile stimuli (Table 1). Group (i), in which only the mass was manipulated, was prepared in order to verify that the participants would be able to detect the change in mass (conditions 1 and 2). Group (ii), in which the mass and the tactile stimuli were manipulated so as to be perceived in the same direction, was prepared in order to verify that the tactile stimuli would enhance the perception of mass change (conditions 3 and 4). Group (iii), in which the mass and tactile stimuli were manipulated in opposite directions, was prepared in order to verify that the tactile stimuli would prevent the perception

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of mass change (conditions 5 and 6). The effects of the tactile stimuli were investigated by comparing the answer ratings in the above three stimuli groups.

In conditions 1 and 2, a constant vibration–identical to the one used in the reference stimulus–was used as a tactile stimulus. In condition 1, the mass was increased from that of the reference stimulus. In condition 2, the mass was decreased. In condition 3, the mass was increased and the amplitude of the tactile stimulus was increased in synchronization with the hand acceleration, so that both the inertial and tactile stimuli would be perceived as a mass increase. In condition 4, the mass and vibrotactile stimulus were decreased. In condition 5, the mass was increased but the vibrotactile stimulus was decreased, so that the proprioceptive and tactile stimuli affected the perception in opposite directions. In condition 6, the mass was decreased while the vibrotactile stimulus was increased.

5.1.3 Expected Results

Fig. 5 presents the comparison scheme for the results. It shows the average correct answer ratings for each stimulus group. Here, a correct answer indicates the case in which the participants' answer matched the change in the inertial stimulus. Before investigating the main point, we will look at the answer ratings for group (i). An average rate that is larger than the chance level of 0.5 implies that the participant correctly detected the changes in mass when the constant vibration was applied to his or her finger. We focus on the differences in ratings between the groups. If there is no difference observed in the ratings, we infer that the vibrotactile stimuli do not influence the perception of mass. If the ratings of group (ii) are higher than those of group (i), we conclude that the tactile stimuli enhance the perceived change in mass. If the ratings of group (iii) are smaller than those of group (i), we infer that the tactile stimuli prevent the perception of the mass change. We also focus on whether the ratings of group (iii) are lower than the chance level; if they are lower, we infer that the effect of the tactile stimuli dominates the actual mass change in the participants' perception of the mass change.

5.1.4 Vibrotactile and Inertial Stimuli

For the reference stimulus, the inertial and viscous stimuli were $m = 0.2$ kg and $c = 0.5$ N·s/m, respectively. The tactile stimulus was a sinusoidal displacement of 280 Hz with a peak-to-peak amplitude on the Z-axis of 7.2 μm. This stimulus was presented to the finger pads of the participants.

In the test stimuli, the changes in mass (Δm) presented to the participants were determined for each individual participant in the preliminary experiment so that the changes in mass were just noticeable to the participant. If the mass difference between the reference and test stimuli is much larger than the effect of the tactile stimuli, the above-mentioned experimental design cannot verify the effect of tactile stimuli on the perception of

TABLE 1
Test stimuli in Exp. 1 (Biases for Mass).

Stimuli Group	Condition #	Mass	Accel.-Synch. Tactile Stimuli
(i)	1	Increased	Constant
Mass Only	2	Decreased	Constant
(ii) Tactile & Mass,	3	Increased	Increased
Same Direction	4	Decreased	Decreased
(iii) Tactile & Mass,	5	Increased	Decreased
Opposite Direction	6	Decreased	Increased

TABLE 2
Test stimuli in Exp. 2 (Biases for Viscosity).

Stimuli Group	Condition #	Viscosity	Velocity-Synch. Tactile Stimulus
(iv)	7	Increased	Constant
Viscosity Only	8	Decreased	Constant
(v) Tactile & Visc.,	9	Increased	Increased
Same Direction	10	Decreased	Decreased
(vi) Tactile & Visc.,	11	Increased	Decreased
Opposite Direction	12	Decreased	Increased

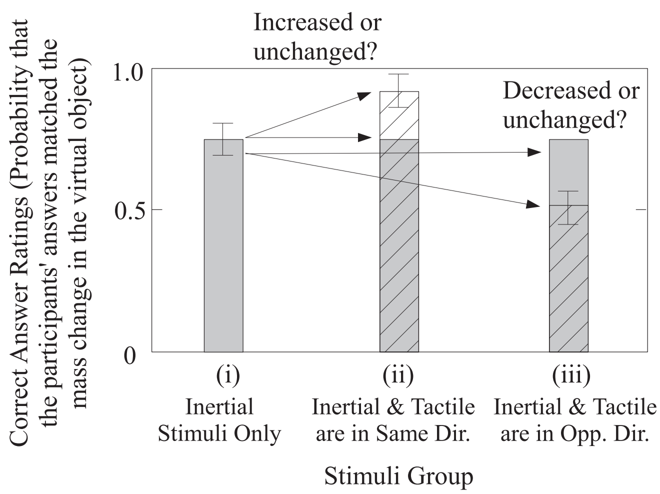

Fig. 5. Comparison of results. Correct answer ratings for each stimulus group. The stimuli in group (ii) are designed to enhance the perceived change of mass. Hence, the ratings for group (ii) are expected to be higher than those of group (i). The stimuli in group (iii) are designed to cancel the perceived change of mass. Hence, the ratings for group (iii) are expected to be smaller than those of group (i).

mass. Before the main experiments, the magnitudes of the mass changes or viscosity changes were determined for each participant. Such just noticeable changes were determined by the method of limits. In this method, ascending and descending series were presented to each participant twice for each series. The step sizes of the stimuli were 0.01 kg (Exp. 1) and 0.02 N·s/m (Exp. 2). The thresholds of the four series were averaged. Through these investigations with all the participants, the values

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of Δm used as test stimuli were determined to be 0.025 to 0.065 kg when an increased mass was presented (conditions 1, 3, and 5). When a decreased mass was presented (conditions 2, 4 and 6), Δm values were -0.015 to -0.04 kg.

5.1.5 Tasks and Participants

Before the experiments, the participants practiced moving the linear slider in accordance with the sounds of a metronome. In the main trial, after the reference stimulus, one of the six types of test stimuli was randomly presented to participants with an interval of 3 s. While these stimuli were presented, the participants tried to maintain the contact status between their fingers and the stimulator. After comparing the two stimuli, they released their fingers from the stimulator and orally responded regarding whether the mass of the test stimulus was larger or smaller than that of the reference stimulus. Each type of test stimuli was presented 20 times; thus, 120 trials were performed for each participant. The participants moved their hands with the beat of a metronome that had a rhythm of 1.42 Hz (85 beats per minute) in the manner of one beat for one stroke and two beats for one right-to-left reciprocation. The metronome was not used for strictly restricting the jiggling movements of the participants but for approximately determining their hand movements. As a result, the participants moved their hands at a maximum speed of approximately 220 mm/s with a stroke of approximately 50 mm. For most of the trials, the participants responded after two or three reciprocations.

Eight paid participants took part in Exp. 1. They were students of Tohoku University in their twenties. All had given their informed consent. In order to shut out the sounds produced by the tactile stimulator, they listened to pink noise through headphones during the experiments. The participants did not know the possible effects of the tactile stimuli before the experiments. The experiment lasted approximately 40 min.

5.2 Experiment 2 (Biases for Viscosity)

In Exp. 2, the combinations of test stimuli and tasks were the same as in Exp. 1. In the test stimuli, the viscosity of the object was manipulated, and the velocity-synchronized tactile stimuli were presented to eight new participants (Table 2). An increased viscosity was presented with Δc values of 0.10 to 0.26 N·s/m (condition 7, 9, and 11), and the decreased viscosity was presented with Δc values of -0.16 to -0.32 N·s/m (conditions 8, 10 and 12).

6 RESULTS

6.1 Results of Exp. 1 (Biases for Mass)

Regarding the experimental results, Fig. 6a and 6b show the answer ratios of the participants in Exp. 1 and Exp. 2, respectively. First, we looked at the results of group (i) in Exp. 1 (Fig. 6a). The ratios of group (i) were higher

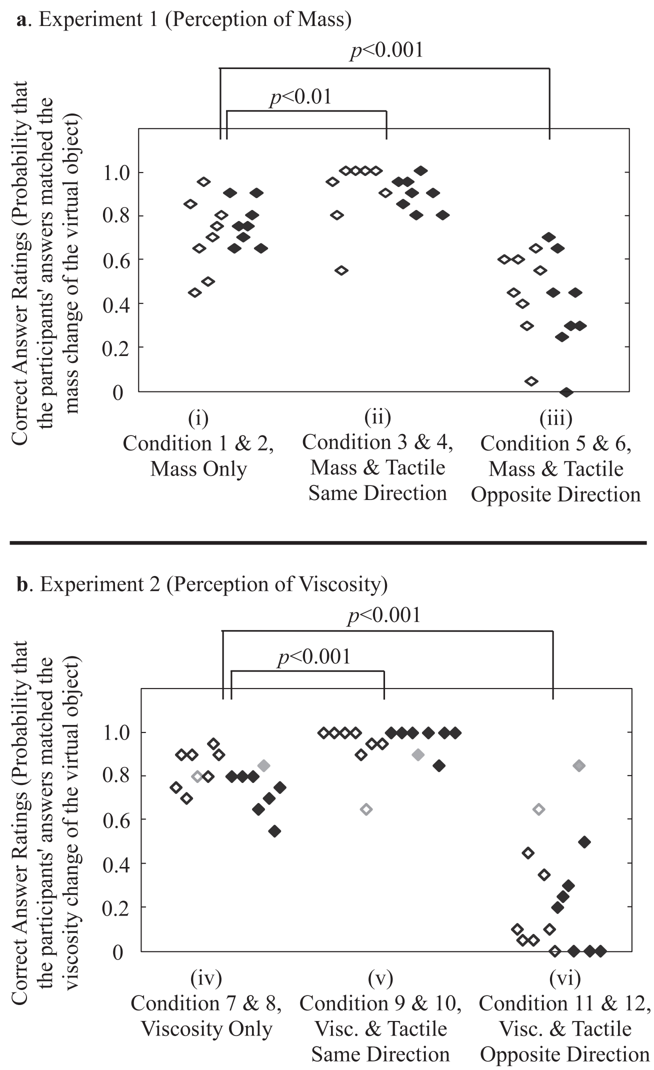

Fig. 6. Experimental Results. a. the answer ratios in Exp. 1 (mass). b. the answer ratios in Exp. 2 (viscosity). The answer ratios are shown for each stimuli group. The blank diamonds are the results of test stimuli with which mass or viscosity increased (conditions 1, 3, 5, 7, 9, and 11). The filled diamonds are the results of test stimuli with which mass or viscosity decreased (conditions 2, 4, 6, 8, 10, and 12). In Exp. 2 (Fig. 6b), one participant did not show the effects of tactile stimuli. The results of this participant are shown as gray diamonds.

than the chance level (t-test, $t_0(15) = 6.60$, $p = 8.4 \times 10^{-6}$, two-tailed). The participants responded correctly to the directions of mass changes when the constant vibrations existed. Second, we focused on the difference in the answer ratios between groups (i) and (ii). The ratios of group (ii) were higher than those of group (i) (Steel-Dwass test, $q_0(3, \infty) = 4.73$, $p = 2.4 \times 10^{-3}$). This result indicates that the acceleration-synchronized tactile stimuli enhanced the perceived change in mass. Finally, we focused on the difference between groups (i) and (iii). The ratios in group (iii) were smaller than those in group (i) (Steel-Dwass test, $q_0(3, \infty) = 5.75$,

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$p = 1.4 \times 10^{-4}$). Also, the ratios in group (iii) were as low as the chance level (average of 0.42, standard deviation of 0.21). These results indicate that the tactile stimuli canceled the perceived change in mass. From these analyses, we may conclude that the tactile stimuli increased and decreased the perceived changes in mass when tactile and inertial stimuli of the perceptually same directions were imposed. When tactile and inertial stimuli of perceptually opposite directions were used, the perceived changes were canceled. The acceleration-synchronized tactile stimuli were perceived as a positive and negative bias of the mass.

6.2 Results of Exp. 2 (Biases for Viscosity)

Fig. 6b shows the results of Exp. 2, in which the viscosity was manipulated. The answer ratios in group (iv) were higher than the chance level (t-test, $t_0(15) = 10.70$, $p = 2.0 \times 10^{-8}$, two-tailed). The participants correctly identified the directions of the viscosity changes when constant vibrations were applied. The ratios in group (v) were higher than those in group (iv) (Steel-Dwass test, $q_0(3, \infty) = 5.60$, $p = 2.2 \times 10^{-4}$). This indicates that the velocity-synchronized tactile stimuli enhanced the perceived change in viscosity. The ratios in group (vi) were smaller than those in group (iv) (Steel-Dwass test, $p_0(3, \infty) = 6.15$, $p = 4.1 \times 10^{-5}$). The tactile stimuli canceled the perceived change in viscosity. The ratios in group (vi) were lower than the chance level (t-test, $t_0(15) = 3.87$, $p = 1.5 \times 10^{-3}$). This shows that the effect of the tactile stimuli dominated the participants' perception of viscosity over the proprioceptive viscosity. From these analyses, we conclude that the velocity-synchronized tactile stimuli were perceived as a positive or negative bias of viscosity. Individual differences were observed in the results. The results of one of the eight participants did not exhibit the effect of the tactile stimuli (Fig. 6b, gray diamonds).

6.3 Summary of Results

In both Exp. 1 (mass) and Exp. 2 (viscosity), the vibrotactile stimuli on the finger pad enhanced the perceived change in the mass and viscosity when the changes in the mass and viscosity and the effects of the tactile stimuli were in the same perceptual direction. In contrast, the vibrotactile stimuli canceled the perceived changes in the mass and viscosity when the changes in mass and viscosity and the effects of the tactile stimuli were in opposite directions. The tactile stimuli worked as both positive and negative biases of the mass and viscosity. The tactile stimuli in which the amplitude changed in synchronization with the finger acceleration were perceived as a bias of the mass. The velocity-synchronized tactile stimuli were perceived as a bias of the viscosity. The velocity-synchronized tactile stimuli dominated the change in the actual viscosity. Although it is known that various information [15]–including visual cues [16]; static pressure on the skin [5], [17]; motor commands [18]; an object's geometrical shape [19]; surface textures [20], [21]; and sense of effort [22], [23], [24], [25]–affects the process of perceiving the mass of an object or a force, in this study, it was found that the vibrotactile stimuli to the finger pad also affect the perceived mass and viscosity of an object.

7 Follow-Up Experiment: Discrimination of Acceleration- and Velocity-Synchronized Vibration

Both the acceleration- and velocity-synchronized vibrotactile stimuli may become perceptual biases for both the mass and viscosity. For instance, the acceleration-synchronized stimuli may become not only the inertial, but also the viscous biases. Also, the velocity-synchronized stimuli may become both the inertial and viscous biases. Both types of vibrotactile stimuli may play the role of perceived heaviness in the same manner. To counteract this possibility, we experimentally confirmed that these two vibrotactile stimuli are recognized differently. As well as the experiments in the previous sections, the participants placed their fingers on the stimulator and moved their hands following the rhythm of a metronome in order to compare the reference and test stimuli. For the test stimuli, the amplitudes of the vibrotactile stimuli increased in synchronization with either the hand velocity or the hand acceleration. Eight new participants answered regarding whether the mass or the viscosity of the test stimuli increased compared with the reference stimulus; this occurred in the manner of a two-alternative forced choice.

7.1 Trainings regarding Impedance-Controlled Mass and Viscosity

Prior to the experiment, we confirmed that the participants discerned the increases in the mass and viscosity of the jiggled object. To this end, they compared two types of test stimuli in which either the mass or viscosity increased compared to the reference stimulus while the vibrotactile stimuli were constantly presented to the participants. The mechanical parameters of the virtual object were $(m, c) = (0.2\ \mathrm{kg}, 0.5\ \mathrm{N \cdot s/m})$ for the reference stimulus. For the test stimulus, its mass was increased to $m = 0.25$ kg or its viscosity was increased to $c = 0.7$ N·s/m. For three of the eight participants, larger mechanical parameters were used for the test stimuli because they claimed that the differences between the reference and test stimuli were too small to discern.

Five of the eight participants did not successfully discriminate the increases in the mass and viscosity. We taught them a helpful technique, as follows: In regards to the increase in the object's mass, we are especially able to perceive the resistance when the hand acceleration is large, or when the directions of hand movements change during the jiggling motions. In regard to the

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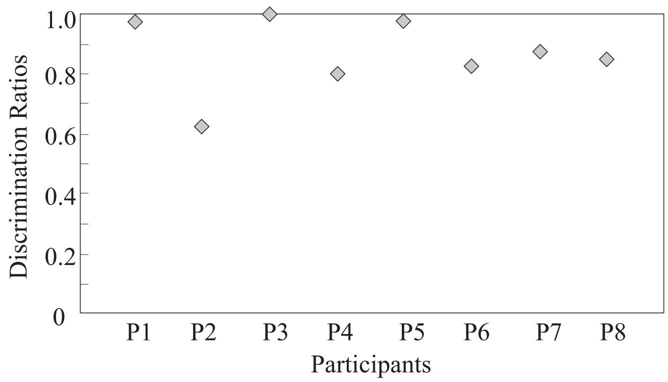

Fig. 7. Ratios at which participants discriminate the acceleration- and velocity-synchronized vibrotactile stimuli

increased viscosity, we perceive the resistance when the hand velocity is large. With these techniques the participants repeated practices until they correctly responded to the test stimuli five times in a row. Finally, all the participants discerned the increases in the mass and viscosity, and they took part in the main experiment described in the following subsection.

7.2 Tasks of Main Experiment

The participants jiggled the virtual object following the rhythm of a metronome as in the previous experiments. They compared the reference and test stimuli. It should be noted that for both stimuli, the mass and viscosity of the object were maintained: $(m, c) = (0.2\ \mathrm{kg}, 0.5\ \mathrm{N \cdot s/m})$. For the test stimuli, the amplitudes of the vibrotactile stimuli increased in synchronization with either the hand acceleration or the hand velocity; the amplitudes corresponded to (4) and (5), respectively. The participants answered regarding whether the mass or viscosity of the test stimuli was larger than that of the reference stimulus. Each participant conducted 40 trials; each of the mass and viscosity was increased 20 times, respectively.

7.3 Results

Fig. 7 shows the answer rates of the participants in the main experiments. The figure shows the ratios at which the participants answered that the mass and viscosity increased for the test stimuli in which the acceleration- and velocity-synchronized vibrotactile amplitudes, respectively, were presented. Because the answer ratios were significantly higher than the chance level (average of 0.866, standard deviation of 0.123, t-test, $t_0(7) = 8.40, p = 6.68 \times 10^{-5}$, two-tailed), the acceleration- and velocity-synchronized stimuli were recognized as different stimuli. From the above results, we speculate that the two types of vibrotactile stimuli affect the perception of loads differently: the acceleration-synchronized stimuli are the biases for the inertial load, and the velocity-synchronized stimuli are the biases for the viscous load.

8 Discussions

8.1 Finger pad as dynamic force sensor

This study suggests that, in addition to using the proprioceptive force sensors, we use our finger pads as dynamic force sensors when estimating the mass and viscosity of an object. In the present experimental setup, these cutaneous sensors functioned more dominantly than the proprioceptive sensors, especially in the sensing of small viscous forces. The finger pad may be able to play the role of a force/torque sensor when the central nervous system estimates the applied force from its cutaneous deformations. Birznieks et al. and Johansson et al. supported this possibility through neurophysiology by showing that the nervous activities of cutaneous mechanoreceptors code the direction of force applied to the finger pad [26], [27]. From a psychophysical point of view, enforced displacements of finger pads were shown to influence the perception of a virtual object's mass in lifting motions [28]. These studies and our experiments indicate that, in a dynamic way, our finger pads function as force sensors and help to estimate the kinetic characteristics of the mass and viscosity of an object.

8.2 Why do 280 Hz vibratory stimuli affect the perceived mass and viscosity?

The frequency of vibrotactile stimuli used in the present study was 280 Hz. We informally confirmed that other frequencies also cause the bias effects; however, on account of the frequency characteristics of the stimulator, we used frequencies higher than tens of hertz. In these frequency bands, FAII units preferentially respond to the vibrations.

SAI and SAII units respond to sustained pressure or indentation [4], [29]. Given that the weight indents the finger pads, these receptors mediate the perception of the lifted weight. Thus, SAI and SAII units are commonly supposed to be related to the perception of loads. In the case of dynamic cutaneous deformations, fast adaptors also respond to the stimuli. At the moment that dynamic deformations are applied to the finger pad–such as in prehension–FAII, FAI, and SAI units could be activated [30]. Birznieks and Johansson et al. reported that FAI units were innervated by the lateral deformation on the finger pad, though they did not mention FAII units [26], [27]. These reports imply that fast adaptors also respond to dynamic skin deformations, such as those that could have happened during the jiggling motions in the present study. One speculation from these neurophysiological studies is that in the case of dynamic conditions such as jiggling motions, fast adaptors may also contribute to the perception of applied forces.

8.3 Is directional information about skin stretches necessary for the perception of mass and viscosity?

The vibrotactile stimuli used in this study were considered to affect the activity level of FA units; however, the stimuli did not present information about the direction of the lateral deformation or the external force on the finger pad. One may doubt whether the directional information of forces applied to the finger pad influences the perception of the mass and viscosity, but their magnitudes certainly do so. Our experiments do not answer this question; however, we consider that both the direction and magnitude of the applied force influence the perception of the mass and viscosity. We make this conclusion because, during the experiments, the vibrotactile stimuli were applied to the participants' finger pads while their finger pads were laterally deformed. The participants must have been able to estimate the directions of the forces based on the directions of the lateral deformations of their finger pads. Hence, the results of this study do not imply that the directions of skin stretches do not contribute to the perception of inertial and viscous loads during jiggling motions.

9 Conclusions

We showed that the vibrotactile stimuli on our finger pads influence the perception of the mass and viscosity of the object when it is jiggled by the finger. From the numerical analyses of the skin stretches of the finger pad, it was predicted that the increase or decrease in the cutaneous mechanoreceptors' activity level in synchronization with the hand acceleration would affect the perception of the mass. Also, we predict that the changes in the mechanoreceptors' activity in synchronization with the hand velocity would affect the perception of the viscosity. The experiments were conducted using an apparatus that could manipulate the proprioceptive stimuli, which corresponded to the mass and viscosity of the virtual object, and the vibrotactile stimuli applied to the finger pad. As a result, the acceleration-synchronized and velocity-synchronized vibrotactile stimuli biased the perception of the mass and viscosity, respectively. The tactile stimuli increased and decreased the perceived changes in inertial and viscous loads when the loads and the tactile biases were imposed in the same perceptual direction. Through the paradoxical test stimuli–for example an increased actual viscosity and the tactile stimuli of a negative bias for the viscosity–that were simultaneously presented to the participants, it was found that the tactile stimuli canceled the perceived changes in the mass and viscosity. We expect that these vibrotactile biases will become alternative force displays and will expand the applications of vibrotactile displays in terms of haptic interactions.

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