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Effect of Haptic Feedback on the Perceived Size of a Virtual Object

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ABSTRACT We investigate how different types of haptic feedback to hand affect the perceived size of a virtual object. Multiple haptic interfaces are designed to deliver different types of haptic feedback to hand. In the preliminary experiment, we investigated the effect of cutaneous feedback on the perceived size of the virtual object. The experimental results indicate that the availability of cutaneous feedback resulted in an insignificant effect on the perceived size of the virtual object. On the other hand, the availability of cutaneous feedback led the participants to exert significantly smaller grip force than when there is only force feedback. In the main experiment, we provided haptic feedback to the dorsum of the hand to modulate the hand kinesthesia at the moment of contact with the virtual object. For the reference stimuli, skin-stretch or vibrotactile feedback was provided to a participant's hand along with cutaneous and force feedback to the fingertips. Reference stimuli were rendered only with cutaneous and force feedback to the fingers. The experimental results indicate a significant effect of the type of haptic feedback to the dorsum of a hand. The skin-stretch feedback led the participants to feel virtual objects with a size of 40 mm, larger than without the feedback. The vibrotactile feedback resulted in the perceived size of virtual objects with a size of 20 or 40 mm, smaller than without the vibrotactile feedback.

INDEX TERMS Haptic interface, pinch grip, virtual reality, size perception, feedback control.

I. INTRODUCTION

Recent popularization of virtual reality (VR) technology is creating new demands for a mean that can let a user interact with a virtual environment more directly and intuitively. Accordingly, haptic feedback technology is attracting new public attention since it enables a user to feel and manipulate a virtual object with hands. Among various tactile information rendered with the haptic feedback, the size of an object plays an important role in the recognition and manipulation of a virtual object [1]. Previous studies show that the perceived size of an object grasped with fingers affects the grasp force and the perceived weight of the object, both of which are essential cues for an object manipulation [2]–[5]. Despite the significance of tactile perception of object size, little studies have been conducted to investigate the effect of haptic feedback on the perception of virtual object size.

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Previous studies show that tactile perception of an object's size is a process handling an ensemble of cutaneous and kinesthetic information on the hand. Burke identified the role of proprioceptive information regarding hand posture in the perception of object size [6]. Later, Berryman et al. showed that both cutaneous and kinesthetic information affects the perception of an object's size [7]. The results of their study indicate that the cutaneous information on the surface property including compliance affects the perception of the perceived size of an object. On the other hand, if there was only kinesthetic information available without cutaneous information, the subjects' perception of object size was impaired. Overall, the perception of object size is a process of capturing hand spread distance estimated with kinesthetic information at the event of the contact at the fingertip sensed with RA and SA1 mechanoreceptors. Berryman et al. additionally explains that the central nervous system (CNS) compensates for the effect of surface compliance given the cutaneous information at the fingertip [7]. The results of the previous studies can

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justify providing force and cutaneous feedback to the fingertip for an object size perception.

However, the effect of haptic feedback to a location other than the fingertip, e.g., the dorsum of a hand, on the size perception is not yet clear.

There is evidence that the stimulation of cutaneous afferents or muscle spindle can modulate the sensation of fingers/limb movement and thus possibly the tactile perception of object size. The analysis of neural response indicates that not only muscle afferent but also cutaneous responses of type 2 cutaneous afferent contribute to human limb kinesthesia [8], [9]. Edin and Johansson showed that the skin-stretch around finger joints created an illusory finger motion [10]. Similarly, Collins et al. verified that the stimulation of SA2 type cutaneous mechanoreceptors by skin-stretch created a kinesthetic illusion around the finger, elbow, and knee [11]–[13]. Another way to create the kinesthetic illusion is by providing vibratory stimulation of muscle spindles. Previous literatures provide evidences that vibrating muscle can cause an extension or flexion movement [14], [15]–[18]. Moreover, de Vignemont et al.'s research suggests that one can feel his/her finger elongated or shrinking with tendon vibration [19]. A study by Collins et al. provides a reference regarding the effect of vibrotactile and skin stretch cues on the hand pose perception [11]. They report that simultaneous stimulation of skin stretch and vibration elicited illusory movement of hands. Overall, we can expect that the modulation of hand kinesthesia with haptic feedback will alter the perceived hand pose.

The availability of a specific type of tactile information is known to affect grasp force as well as kinesthesia during object manipulation. Multiple studies report that grasp force changes being proportional to the weight or tangential force applied to the fingers during object manipulation task [20]–[22]. According to the studies, there is a linear relation between tangential force/torque and normal grip force, for a secure grasp of the object. It means that the availability of cutaneous information at the finger can affect the grip force. In a study by Nowak et al., the subjects whose cutaneous sensation was anesthetized grasped objects with a larger normal force than when they were not [23]. Then, we can expect that providing cutaneous feedback to a user's fingertip will increase the force to grasp a virtual object. However, it is not clear how haptic feedback applied to a location other than fingertip affect the grasp force of an object, as well as the perception of object size.

In the present study, we investigate the effect of providing haptic feedback on the perception of virtual object size grasped with a pinch grip. The results of previous studies on object size perception can be summarized as estimating an object size from finger spread length at the event of contact at the fingertip. In other words, the cutaneous information on finger skin signals the event of contact and the object size is estimated from the kinesthetic information of fingers. Then, modulating hand kinesthesia at the moment of contact may affect the object size perception grasped with a hand. Therefore, our first hypothesis is that *providing haptic feedback affecting hand kinesthesia can modulate the perception of an object grasped with fingers*. Specifically, we apply skin-stretch and vibrotactile feedback to the dorsum of the hand, which is known to affect hand kinesthesia [13]. In addition to the perception of virtual object size, we also study the effect of different type of cutaneous cues around hand on the grip force. According to the well-known size-weight illusion, a smaller object is felt heavier than a larger one even though their physical weight is equal [24]. Then if additional haptic feedback modulates the perception of object size, grip force will change, too. Thus, our second hypothesis is that *the type of cutaneous feedback to the hand can affect the grip force during object size perception*. To prove our hypotheses, we designed and conducted an experiment that measured the perceived object size providing subjects tactile stimuli to fingertips and the dorsum of a hand.

The rest of the paper is organized as follows. First, we explain general experimental methods, including the description of the haptic interface, haptic rendering, and overall experimental procedure. Next, we present the experimental results of preliminary and main tests. Finally, we discuss the implications of the experimental results and conclude the paper by summarizing the contribution of the present work and briefly mentioning the future work.

II. GENERAL METHODS

A. APPARATUS

Figure 1 shows the experimental apparatus which can provide both cutaneous and force feedback simultaneously by combining two commercially available Touch force feedback haptic interfaces (3D Systems Inc., SC, USA) and cutaneous feedback interfaces. We originally built the device for our previous study that investigated the perceived hardness given force and cutaneous feedback [25]. Touch is a 6-DOF force feedback interface with the nominal position resolution of 0.055 mm. It can provide 3-DOF force feedback to a user with the maximal force of 3.3 N. The cutaneous haptic feedback interface can create the cutaneous sensation of touching a surface at the fingertip by moving a contact plate, with the nominal position resolution of 0.05 mm. It can exert a nominal maximum force of 7.8 N, and its weight is 28 g. The weight of the cutaneous feedback interface is gravity-compensated. A force-sensing resistor attached to the contact plate can detect the contact with a fingertip and measure contact force. More details on the haptic interface can be found in [25].

B. HAPTIC RENDERING OF CONTACT WITH A VIRTUAL OBJECT

This subsection describes how we calculate haptic feedback based on the contact information between a finger avatar and a virtual object. For the haptic rendering, we use the minimum-distance finding scheme proposed by Johnson and Cohen [26], which keeps track of the minimum distance points on the surface of adjacent virtual objects, geometrically. The contact force is calculated by using the following

FIGURE 1. The experimental apparatus that can provide cutaneous and force feedback to a user, formed by combining two Touch force interfaces with cutaneous interfaces at the end effectors.

spring model:

$$\boldsymbol{F} = \begin{cases} K\left(\boldsymbol{x}_o - \boldsymbol{x}_f\right) & (with\ contact) \\ \boldsymbol{0} & (no\ contact), \end{cases} \tag{1}$$

where K, $\boldsymbol{x}_o$ and $\boldsymbol{x}_f$ represent virtual surface stiffness, the minimum distance point on the virtual object, and the minimum distance point in the finger avatar, respectively.

Cutaneous feedback at the fingertip is rendered by moving contact plate of the cutaneous feedback module. At the beginning of the experiment, the position of contact plate when it barely touches the fingertip is measured and defined as d_c. The point of contact is detected by an FSR sensor. Then, the reference position of the contact plate d_{ref} is targeted as:

$$d_{ref} = \begin{cases} d_c + \left|\boldsymbol{x}_p - \boldsymbol{x}_f\right| & (with\ contact) \\ d_c - 2mm & (no\ contact)\ , \end{cases} \tag{2}$$

which means that the contact plate is located away from the fingertip by 2mm when there is no contact between a finger avatar and virtual surface. We used a PID controller to move the contact plate to the reference position ($\tau_{out} = \left(K_p + \frac{K_i}{s}\right)\left(d_{ref} - d\right) - K_d sl$, where τ_{out}, l and s are output torque, the current contacting plate displacement, and the Laplacian operator, respectively).

C. PROCEDURES

We used a one-up one-down adaptive procedure to compare the perceived virtual object size rendered with different haptic feedback methods [27]. The experimental method estimates the point of subjective equality (PSE) of varying the size of a comparison object's size for a reference object size. The estimated PSE value is a measure showing how the size of a comparison virtual object rendered with different haptic modality is equivalent to that of a reference virtual object. The participant compared the size of a pair of virtual objects-reference and comparison virtual objects- rendered with different haptic feedback methods on each trial.

FIGURE 2. The experimental setup. A participant wears headphones where white noise is played. S/he inserted thumb and index finger in the experimental apparatus and the arm is placed on an armrest to minimize the fatigue. During the experiment, white cloth covered the hand to block any possible visual cue from the haptic interface.

Figure 2 shows the experimental setup. Before each experimental run, a participant was seated in front of a computer. Then, the experimenter placed the participant's arm on an X-Ar anti-gravity exoskeletal arm support, (Equipos, Manchester, NH, USA) to minimize possible fatigue at the shoulder. The participant's hand was covered with a white cloth to block visual cue on the object size from hand posture and s/he wore a pair of noise-canceling headphones (MDR10RNC, Sony, Tokyo, Japan). A training session was available before the main experiment. The participant could visually see a virtual object and the fingertip avatars. Also, s/he could feel a virtual object rendered with cutaneous and force feedback by varying its width. When the participant felt was ready for the main experiment, s/he could terminate the training by pressing an 'e' button.

Once switched to the main experiment, white noise was played on the headphone to block possible audio cues from the haptic interface. Initially, finger avatars were visible to the participant. Before touching a stimulus, the participant was asked to spread his/her finger outside of two red borders that were separated by 65 mm. We decided the border width by considering participants' maximum finger spread in pilot tests. As the participant squeezes the fingers to feel the virtual object size and the finger spread is less than or equal to 61 mm, the finger avatars disappeared. We made this routine to prevent the participant from acquiring possible cue on the virtual object size from the avatar position. Thus, the participant had to rely on his/her sense of touch to estimate the size of the virtual object. On each trial, a reference object and a comparison object were displayed in random order.

After, s/he felt the size of the virtual object, the participant judged which object felt larger than the other by typing 1 or 2 (1: the first object felt larger; 2: the second object felt larger). If the participant answered that s/he felt the comparison object was larger than the reference object, the size of the comparison object in the next trial was decreased. Otherwise, the size of the comparison object was increased while the size of the reference object was constant for each experimental run. The step size of object size increase/decrease changed to a smaller value after three reversal of answers, which is to enhance the precision of the estimated PSE value. The experiment was terminated after twelve reversals of the answers at the smaller step size. The size of the comparison object and the participant's response were recorded for each trial. Also, the fingertip avatar penetration depth in (1) and (2) was sampled at a rate of 40 Hz and mean and max penetration depth values were recorded for each trial.

The experimenter repeated another run if s/he judged the data failed to converge. After each experimental run, the participant took a 4-min break to prevent his/her fingers from numbness due to the exposure to haptic feedback. The experimental protocol was approved by the IRB at the Korea Institute of Science and Technology.

D. DATA ANALYSIS

We estimated the PSE estimate for a reference virtual object by taking the average of peak/valley values at the smaller step size, for each participant and the experimental condition. The PSE estimate was compared to the size of the reference virtual object by using t-tests.

III. PRELIMILARY EXPERIMENT: EFFECT OF HAPTIC FEEDBAK TO THE FINGERTIP ON THE PERCEIVED SIZE OF A VIRTUAL OBJECT

Before the main experiment, we evaluated the role of cutaneous feedback to the fingertip in the perception of virtual object size. If the availability of cutaneous feedback affects haptic size perception of a virtual object, we need to take into account whether to include or exclude the cutaneous feedback. This prompted us to compare the human haptic perception of virtual object size rendered with force feedback to the one rendered both with force and cutaneous feedback.

A. METHODS

Twelve healthy participants (4 females, 24 to 35 years old) who participated in the preliminary experiment completed this experiment with informed consent. None of them had any known problem with their sense of touch, and all were right-handed by self-report. The experiment compared the perceived size of comparison virtual objects rendered with force feedback to that of a reference virtual object rendered both with cutaneous and force feedback. The test was conducted for two reference stimuli, virtual objects with a thickness of 20 and 40 mm. Thus, there were two experimental runs for the preliminary experiment. The initial size of the comparison object was 60 mm, and the step size was 20 mm. After three reversals of the answers, the step size was decreased to 2.5 mm. It took approximately 12 minutes for each participant to complete two runs of the experiment, including a 4-min break between the experimental runs.

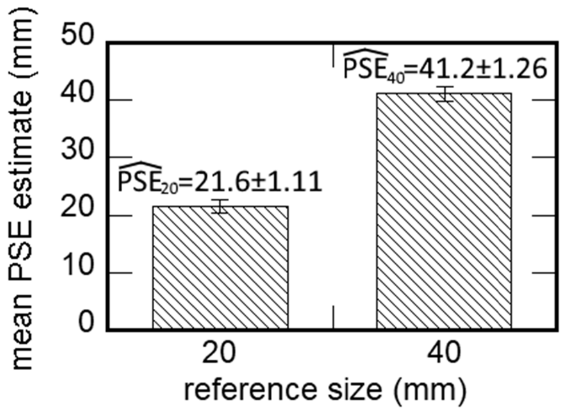

FIGURE 3. Mean estimated PSE of perceived virtual object size by reference size in the preliminary experiment. Error bars indicate standard errors.

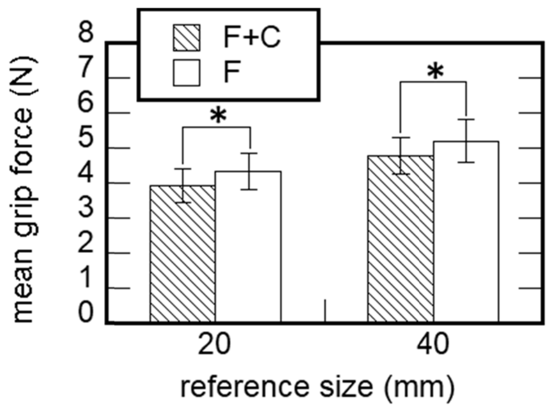

FIGURE 4. Mean grip force by reference size in the preliminary experiment. Error bars indicate standard errors.

B. RESULTS

Figure 3 shows the mean PSE estimates of the virtual object by reference object size. We conducted a one sampled t-test on the PSE estimate with the null hypothesis $\mu_{PSE} = R_{ref}$ where R_{ref} indicates the reference object size. The results indicate that there was no significance difference between the PSE estimate and the reference object size [$t(11) = 2.07$, $p = 0.18$ for $R_{ref} = 20$mm; $t(11) = 2.2$, $p = 0.36$ for $R_{ref} = 40$mm]. In Fig. 4, the mean grip force is plotted against the reference object size. We computed the contact force from the penetration depth by using (1). When we conducted paired t-tests, the grip force was significantly larger for the comparison stimuli [$t(11) = 1.8$, $p = 0.011$ for $R_{ref} = 20$ mm; $t(11) = 1.79$, $p = 0.011$ for $R_{ref} = 40$ mm]. This means that the participants applied a larger force to feel an object rendered with force feedback than when both force cutaneous feedback was available.

C. DISCUSSIONS

The results of the preliminary experiment can be summarized that the availability of the cutaneous information does not affect the haptic perception of virtual object size. On the other hand, grip force significantly increased when the cutaneous feedback was not available. The object size perception model in [7], the experimental results suggest that the participants applied more force with the absence of cutaneous feedback to acknowledge the contact with a virtual object. Larger grip force without cutaneous feedback can be translated as higher absolute thresholds for the contact, considering the lower tactile threshold of cutaneous feedback than that of force feedback [28].

The PSE estimates of object size were not affected by the availability of cutaneous feedback, which implies that CNS compensates for the larger penetration due to larger grip force. A similar effect was found in Berryman et al.'s study where the authors found that CNS compensates for the deformation of fingertip skin during object size perception task [7]. From the result of the current experiment and Berryman et al.'s study, the estimate of object size grasped with fingers can be modeled as follows:

$$\hat{R} = \hat{R}_{kinesthesia} + \hat{d}_{cutaneous} + \hat{d}_{kinesthesia}, \quad (3)$$

where $\hat{R}_{kinesthesia}$, $\hat{d}_{cutaneous}$ and $\hat{d}_{kinesthesia}$ indicate the estimate of finger when making sure contact $t_{contact,perceived}$, estimated fingertip skin deformation and the estimate of excessive finger flexion from the instant of physical contact $t_{contact}$ till $t_{contact,perceived}$. Considering that humans can scale the indentation of fingerpad [29], we expect that CNS can estimate $\hat{d}_{cutaneous}$ accurately, and thus $\hat{R}$. Our experimental results imply that human CNS can also compensate for the error of $\hat{R}_{kinesthesia}$ due to surface compliance or lack of cutaneous information by estimating $\hat{d}_{kinesthesia}$.

In the next section, we further investigated the effect of haptic feedback that can possibly affect the perception hand kinesthesia, $\hat{R}_{kinesthesia}$ on the size of a virtual object.

IV. MAIN EXPERIMENT: EFFECT OF HAPTIC FEEDBACK TO THE DORSUM OF A HAND ON THE PERCEIVED SIZE OF A VIRTUAL OBJECT

The goal of this experiment is to study the effect of haptic feedback to the dorsum of a hand on the human haptic perception of virtual object size. According to previous studies in neurophysiology, the stimulation of type 2 mechanoreceptors around the joint can affect the perception of the joint pose [13], [30]. Then, stimulating SA2 or FA2 type mechanoreceptors at the instant of contact during object grasp task will affect hand kinesthesia. Then, the perception of the object size may be modulated. We verify our assumption by conducting an experiment which evaluated the human haptic perception of virtual object size rendered with cutaneous and force feedback at the fingertip and haptic feedback to the dorsum of the hand.

A. METHODS

1) PARTICIPANTS

The twelve participants (4 females, 24 to 35 years old) who same participants took part in the experiment. None of them had any known problem with their sense of touch, and all were right-handed by self-report.

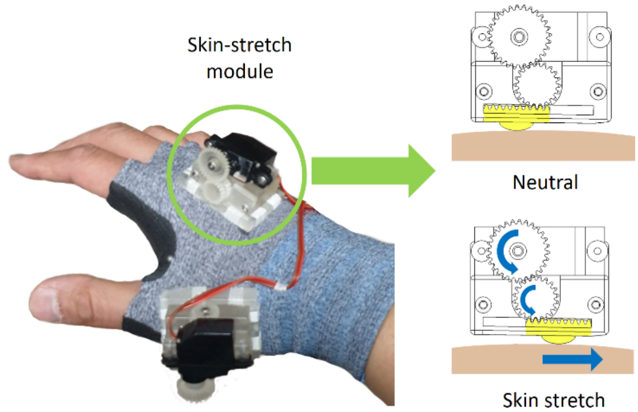

FIGURE 5. An open finger glove type haptic interface with a pair of skin-stretch modules (Left). When actuated, a servo-motor moves a contact element (colored in yellow) to stimulate the skin on the dorsum of the hand (Right).

2) APPARATUS

We built two types of haptic gloves to provide two types of haptic feedback to the dorsum of a hand. The haptic gloves were in the form of open-finger gloves to be compatible with the cutaneous interface described in Sec. II. A. For the stimulation of SA2 type mechanoreceptors at the dorsum of a hand, we built a skin-stretch type haptic interface (Fig. 5), an improved version of the one designed for virtual interaction [31]. The haptic interface has two skin-stretch modules each of which is located right behind the metacarpophalangeal joints of the thumb and the middle fingers. We designed the skin-stretch module to stretch the skin on the dorsum of a hand by linearly moving a contact element module, covered with silicon rubber to prevent the slip with the skin. Two gears convert the rotation of a servo motor (DES281BB MG, Graupner, Germany) to the linear motion of the contact element. The size of the skin-stretch module is 33 × 28 × 26 mm and the nominal moving range of the contact element is 11 mm. When a fingertip avatar contacts a virtual object, the contact element is moved backward to create skin-stretch, and the skin is moved toward the wrist. The skin-stretch is rendered separately for each fingertip.

For the stimulation of FA2 type mechanoreceptors, we installed two eccentric motors (MB1632-1245V, MotorBank, Korea) on the back of an open-finger glove (Fig. 6). We covered the motor with a plastic case to prevent a possible injury of a participant due to the contact with an asymmetrical mass during the vibration. The case was attachable/detachable to the glove with Velcro tape to be fitted to the participant's hand size. The vibration frequency was set to be 70 Hz, which was found to be effective in creating an involuntary motion of fingers in [11]. The motor is activated when a finger touches a virtual object. As with the skin-stretch feedback, the vibrotactile feedback is rendered separately for each fingertip.

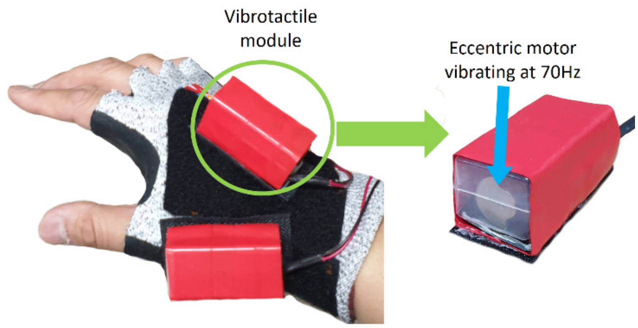

FIGURE 6. An open finger glove type haptic interface with a pair of vibrotactile modules (Left). Inside the vibrotactile module is located an eccentric motor vibrating at 70Hz (Right).

3) PROCEDURE

The experiment consisted of two sessions by the types of reference haptic stimuli applied to the dorsum of a hand. For each session, a reference stimulus was rendered with cutaneous and force feedback at the fingertip and haptic feedback to the dorsum of a hand. Thus, there were two types of reference stimuli; skin-stretch plus fingertip-cutaneous-feedback plus fingertip-force-feedback (F+C+S) and vibrotactile plus fingertip-cutaneous-feedback plus fingertip-force-feedback (F+C+V). A comparison stimulus was rendered with cutaneous and force feedback at the fingertip.

Each session consisted of two experimental runs by the size of the reference object, 20 and 40 mm. The order of the experimental runs was randomized for each participant. The rest of the experimental procedure was the same as the preliminary experiment.

B. RESULTS

In Fig. 7, the average PSE estimate is plotted as a function of reference object size by the haptic feedback to the dorsum of a hand. To see the effect of haptic feedback to the dorsum of a hand on the perceived object size, we compared the PSE estimates to the size of the reference stimuli. For the case that skin-stretch feedback were provided to the participants for the reference stimuli (F+C+S), the results of one-sample t-test (H_0: $\mu_{PSE} > R_{ref}$) indicated that the PSE estimates were significantly larger than the reference size of R_{ref} = 40 mm [t(11) = 2.51, p = 0.015] while no significant difference was observed for R_{ref} = 20 mm [t(11) = 0.2, p = 0.86]. When vibrotactile stimuli were provided to the participants for the reference stimuli (F+C+V), the results of one-sample t-test (H_0: $\mu_{PSE} < R_{ref}$) indicated that the PSE estimates were significantly smaller than the reference object size for both R_{ref} values [t(11) = 6.68, p <0.0001 for R_{ref} = 20mm; t(11) = 3.73, p = 0.002 for R_{ref} = 40mm]. Thus, additional haptic feedback to the dorsum of the hand affected the haptic perception of object size. When we conducted a two-way repeated measure ANOVA on the PSE estimates with the factors of object size and the type of haptic feedback, both of the factors had significant effect on the PSE estimates [F(1,11) = 493.95, p <0.0001 for object size; F(1,11) = 14.57, p = 0.003 for the type of haptic feedback].

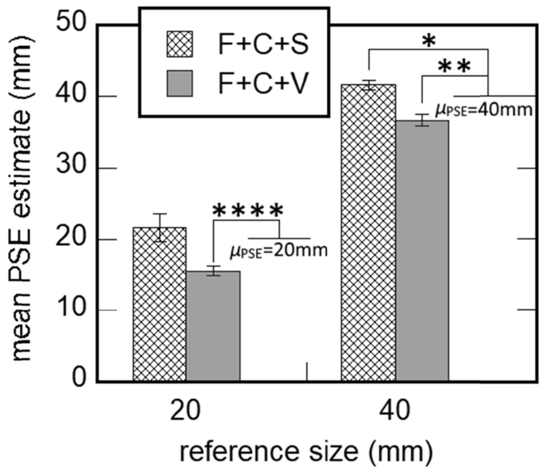

FIGURE 7. Mean estimated PSE of perceived virtual object size by reference type and size in the main experiment. Error bars indicate standard errors.

There was no interaction between the two factors [F(1,11) = 0.247, p = 0.63].

In a subsequent Bonferroni test, the mean PSE estimates were not grouped either by the reference object size or by the type of haptic feedback. Therefore, the kind of haptic feedback to the dorsum of the hand also affected the haptic perception of virtual object size.

In Fig. 8, the average contact force is plotted as a function of reference object size by the haptic feedback to the dorsum of a hand. We evaluated the effect of haptic feedback to the dorsum of a hand on the grip force by comparing the mean contact force of grasping reference objects (F+C+S or F+C+S) to that of comparison objects (F+C). A two-way repeated measure ANOVA with the factors of object size and the type of haptic feedback indicate that both of the factors had significant effects on the grip force [F(1,11) = 6.07, p = 0.031 for object size; F(1,11) = 8.72, p = 0.013 for the type of haptic feedback]. No interaction between the two factors was observed [F(1,11) = 0.66, p = 0.53]. The result of the Bonferroni test indicated that the contact force was not grouped by either object size or by haptic feedback type. We also compared the contact force for the reference stimuli (F+C+S, F+C+V) to that of comparison stimuli (F+C). The results of paired t-test for the reference stimuli F+C+S indicate no significant difference in contact force for R_{ref} = 20mm [t(11)= −0.57, p = 0.29] and significantly smaller contact force for R_{ref} = 40mm [t(11)= −2.02, p = 0.034]. For the reference stimuli F+C+V, the grip force for the reference stimuli was significant larger than that of the comparison stimuli for both R_{ref} = 20mm [t(11) = 3.84, p = 0.001] and R_{ref} = 40mm [t(11) = 2.06, p = 0.032]. Therefore, the type of haptic feedback to the dorsum of hand significantly affected the grip force, as with the PSE estimates.

C. DISCUSSIONS

The results of the main experiment show that the haptic feedback to the dorsum of the hand can modulate the

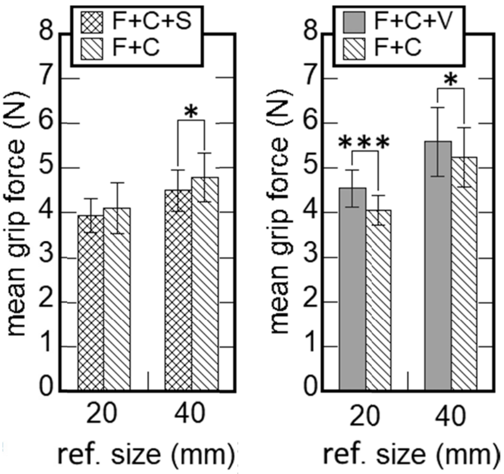

FIGURE 8. Mean grip force by haptic feedback type and reference size in the main experiment. The graph on the left is the mean grip force of reference (F+C+S) and comparison (F+C) when skin-stretch feedback was provided for the reference stimuli. The graph on the right is the mean grip force of reference (F+C+V) and comparison (F+C) when vibrotactile feedback was available for the reference stimuli. Error bars indicate standard errors.

perceived size of a virtual object. We modeled the perception of object size with (1) and the experimental results indicate that the estimated finger spread $\hat{R}_{kinesthesia}$ was modulated when haptic feedback was applied to the dorsum of the hand, which confirmed our first hypothesis. The effect of the haptic feedback on the size perception varied by the type of haptic feedback. Skin-stretch feedback resulted in the perception of a virtual object feel larger than without the feedback for $R_{ref} = 40$ mm. On the other hand, vibrotactile feedback led the participants to perceive the virtual object size smaller than without the feedback. A similar effect of the haptic feedback to the dorsum of hand was found for the grip force. Average grip force with skin-stretch feedback was smaller than without the feedback for $R_{ref} = 40$ mm. Vibrotactile feedback to the dorsum of a hand resulted in smaller average grip force than without the feedback. Therefore, the variation of the grip force by the type of haptic feedback to the dorsum of hand confirmed our second hypothesis.

A possible explanation for the modulation of the perceived size of a virtual object is the illusory movement of hand due to haptic feedback to the dorsum of the hand. Collins et al. showed that cutaneous stimulation around the joints can evoke an illusory movement of limbs [11]–[13]. Especially, their study on the illusory movement of fingers verified that skin-stretch and vibration around finger joints created the illusory finger motions of extension and flexion, respectively [11]. The results correspond with our main experiment since extension and flexion of fingers cause the finger-spread larger and smaller, and thus $\hat{R}_{kinesthesia}$ in (3). A similar explanation for the modulated perception of virtual object size can be found in the illusory hand size modulation due to haptic feedback around the finger joint. Bruno and Bertamini showed that the illusion of a change in hand size resulted in the modulated haptic perception of metal disk [32]. A study by de Vignemont showed that a finger could feel longer by applying vibrotactile feedback to a joint. Thus, an illusory change of finger size due to haptic feedback could have affected haptic object size perception and thus $\hat{R}_{kinesthesia}$.

When skin-stretch feedback was applied to the dorsum of a hand, the PSE estimate was larger than the reference stimuli only when R_{ref} was 40 mm. A possible explanation for this asymmetric effect of skin-stretch feedback is the change of friction coefficient by the flexion of fingers. As fingers bend when grasping a larger object, the skin on the dorsum shrinks, and surface roughness decreases. References show that sliding friction increases as the surface roughness increases [33], [34]. Thus, a larger friction force between the contact element and the dorsum skin can be evoked when a hand grasps a larger object. Then, the larger friction force can cause enough force for an additive extension motion when grasping a large object. This explanation is supported by analyzing the results of the experimental runs for the reference stimuli of F+C+S. There was a linear trend between the PSE estimate and the grip force ($R^2 = 0.864$). Also, the skin-stretch feedback significantly affected the grip force and the PSE estimates only for $R_{ref} = 40$ mm while it had an insignificant effect for $R_{ref} = 20$ mm. Therefore, the varied effect of skin-stretch feedback on object size perception and grip force can be explained with the variation of friction due to the change of finger pose by virtual object size.

V. CONCLUSIONS AND FUTURE WORK

The present study investigated the effect of haptic feedback on the perceived size of a virtual object grasped with two fingers. In the preliminary experiment, we found that the availability of cutaneous feedback has an insignificant effect on the size of object size perception while grip force was significantly affected. From this result, we built a haptic object size perception model in (1), where CNS compensates for error due to fingertip deformation and pose excessive finger flexion. In the main experiment, we applied skin-stretch and vibrotactile feedback to the dorsum of hand in order to modulate the perceived size of a virtual object. The participants felt the virtual object smaller with the vibrotactile feedback and larger with the skin-stretch feedback when the virtual object size was 40 mm wide. The grip force was significantly affected by haptic feedback to the dorsum of the hand. The skin-stretch feedback resulted in less grip force when $R_{ref} =$ 40 mm while the participant exerted a larger grip force with the vibrotactile feedback was provided.

The contribution of the present study can be evaluated in terms of providing a reference on haptic size perception and haptic rendering as well as haptic interface design for VR interaction. Most of the previous studies on haptic size perception focused on human size perception with cutaneous or force feedback [35], [36]. On the other hand, the results of the present study provide an extensive reference on the effect of different types of haptic feedback on haptic object size perception. Meanwhile, the haptic feedback methods proposed in the present study can be viewed in the haptic rendering of a virtual object. Equation (3) derived in our study suggests that the haptic size can be effectively rendered with a conventional glove type haptic interface design – a combination of cutaneous and force feedback. However, the results of the present study suggest that haptic object size can be rendered with an alternative method, e.g., cutaneous feedback to the fingertip plus skin-stretch/vibrotactile feedback to the dorsum of a hand. Such a design will reduce the size and complexity of a force feedback interface, which will provide an engineer with more degree of freedom in haptic interface design.

In our future work, we plan to investigate the effect of haptic feedback on size perception in different aspects. The present study mainly focused on verifying the effect of different types of haptic feedback on object size by comparing PSE estimates. Additionally, we plan to measure the JND values to derive the relative contribution of haptic feedback on the object size perception [37]. Furthermore, we will study how the combination of different types of haptic feedback affect the object size perception. Previous studies on haptics and HCI indicate that the delay of a haptic stimulus often leads to significant modulation of an object's haptic perception [38], [39]. We expect that the delay of haptic feedback will affect the haptic size perception so that we are going to investigate the effect of relative delays. We plan to further evaluate the effect found in this paper is also valid for other joints of the limbs.

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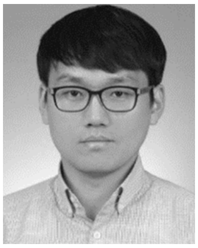

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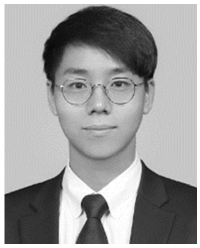

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