# Effect of Cutaneous Feedback on the Perceived Hardness of a Virtual Object

Jaeyoung Park, *Member, IEEE*, Yonghwan Oh, *Member, IEEE*, and Hong Z. Tan, *Fellow, IEEE*

**Abstract**—We investigate the effect of adding cutaneous cues to kinesthetic feedback on the perception of a virtual object's hardness. A cutaneous haptic interface is designed to deliver hardness information to a user's fingertip along with a force-feedback interface, and the corresponding rendering strategy is implemented. Two sets of experiments are conducted to evaluate the proposed approach for hardness perception using one-finger touch and two-finger grasp. Experimental results indicate that the addition of cutaneous feedback can make the virtual surface feel significantly harder than the nominal stiffness delivered by force-feedback alone. In addition, the perceived hardness is significantly affected by the rate of hardness rendered with a cutaneous interface for the nominal stiffness $K = 0.3$ and 0.5 N/mm. For two-finger grip, the effect of a virtual object's thickness has a significant effect on the perceived hardness measured in stiffness. When the perceived hardness is converted to Young's modulus, the effect of thickness is insignificant.

**Index Terms**—Hardness perception, psychophysics, tactile display, haptic rendering, stiffness

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## 1 INTRODUCTION

HARDNESS/SOFTNESS is an important physical feature of an object that can be obtained by haptic interaction. In this regard, the range of achievable stiffness is often used as a measure to evaluate a haptic interface's performance. To deliver a wide range of stiffness/compliance with a force-feedback system, a large range of torque is required, which can increase the system's weight and complicate stability control. We are currently working on a research program developing a wearable haptic system. Part of the system is a glove-type haptic interface that is aimed to have a large workspace and lightweight to maximize the interactivity with a virtual environment. However, the lightweight requirement significantly reduces the range of a virtual object's stiffness that can be rendered and its realism. We addressed the problem by providing cutaneous feedback along with kinesthetic feedback [1].

Previous studies indicated that the stiffness/compliance of a virtual object can be effectively represented when both kinesthetic and cutaneous information are available. As shown by Tan et al., humans can discriminate an object's compliance with a two-finger grip in the absence of any cutaneous information on surface deformation [2]. Lawrence et al. demonstrated that perceived hardness can be effectively represented by the ratio of initial contact force over initial velocity when a virtual surface is rendered with a force-feedback interface [3]. Higashi et al. showed the correlation between the perceived hardness of different materials with their dynamic stiffness defined by frequency components [3]. This implies that a human can use cutaneous cues for hardness perception considering that the SA II mechanoreceptors responsible for kinesthetic sensation are less sensitive to higher frequency components [4]. Bergmann Tiest and Kappers also showed that the surface deformation of an object provides crucial information for the haptic perception of compliance [5]. However, as Srinivasan and LaMotte demonstrated, neither kinesthetic nor cutaneous information alone is sufficient for haptic softness discrimination for objects with deformable surfaces [6]. Therefore, both kinesthetic and cutaneous information may be necessary for realistic and effective rendering of a virtual object's hardness.

Findings from the previous studies on multisensory integration imply that the addition of properly rendered cutaneous feedback can lead to a shift in the perceived hardness of a virtual object. Van Beer et al. demonstrated that simultaneously presented visual and proprioceptive information affects the perception of position [7]. Ernst and Banks proposed the optimal multimodal sensory integration model to explain the perception of an object's property from different sensory modalities [8]. The result of their study demonstrated that visual and haptic cues contributed to the perception of an object's size by following the maximum likelihood estimation (MLE) rule. In a recent study by Bianchi et al., an additional tactile cue resulted in an illusory sensation of hand orientation, which can be ascribed to the sensory integration of cutaneous and proprioceptive cues [9]. If the perception of hardness also follows the optimal integration law, the addition of properly rendered cutaneous feedback will cause a virtual surface to feel harder than with kinesthetic feedback only.

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There have been many attempts to develop haptic interfaces that can effectively deliver cutaneous information to a user. A variety of haptic interfaces have been proposed to present diverse tactile cues on the skin including contact location [10], slip [11], skin-stretch [12], [13] and multi-DOF force and torque [14], [15], [16]. Cutaneous feedback has also been provided to a user to improve the immersiveness of the virtual environment [17], [18]. Pacchierotti and Prattichizzo reported a series of studies demonstrating that additional cutaneous feedback can enhance teleoperation ([1], [19], [20], [21]). They showed that the stability of a tele-operated system can be improved with cutaneous feedback with the sensory subtraction technique. Regarding the perception of compliance/stiffness, previous studies have confirmed that cutaneous feedback alone or the combination with another type of feedback can enhance or modulate the perceived stiffness of object surfaces. Bicchi et al. proposed a haptic interface that can render the surface compliance of a virtual surface. They found that the addition of cutaneous compliance information can enhance softness discrimination when used in combination with kinesthetic feedback [22]. Bianchi et al. designed a fabric-based cutaneous haptic interface and demonstrated that it can effectively render softness based on the rate of increase in contact area [23], [24]. Chinello's recent study reported the effect of 3-DOF cutaneous feedback and vibrotactile feedback on the perception of a virtual object's stiffness ([25]). Quek and Okamura investigated the effect of additional cutaneous feedback on the perceived properties of virtual object felt via a tool ([26], [27], [28], [29]). Their studies provided abundant evidence that lateral skin stretch feedback can augment the sensation of stiffness when a virtual surface is felt with a stylus-like tool. De Tinguy et al. demonstrated that cutaneous feedback can make a real tangible object's surface feel stiffer, even when the feedback is not applied to the point of contact [30]. Overall, the results of previous studies show that cutaneous feedback can modulate the perceived stiffness of a virtual or real surface. However, there are fewer studies on the analysis of cutaneous feedback on the perceived hardness/softness of virtual objects felt directly at the fingertips, as compared to through kinesthetic feedback. Pacchierotti et al. applied cutaneous feedback to compensate for the loss of contact force to avoid instability in a teleoperated system [21]. The participants judged a virtual stiff constraint with cutaneous feedback to be stiffer than that with kinesthetic feedback only, when a passivity controller was applied. When we consider the results of the previous studies, a more general question arises about whether and how the additional cutaneous feedback affects human perception of a virtual object's surface regardless of the system controller used.

The present study investigates the effect of adding cutaneous information to kinesthetic feedback for the perception of a virtual object's stiffness. Previous studies showed that the availability of cutaneous cues significantly affects the perception of an object's surface stiffness [5], [31]. However, we are not aware of any study that examined the effect of cutaneous feedback on the shift in the perceived hardness of a virtual object. Our first objective of the present study is, therefore, to investigate how the perceived hardness rendered with both cutaneous and kinesthetic feedback is matched to that with kinesthetic feedback only. As verified by Bergmann Tiest and Kappers, cutaneous cues play a crucial role in perceiving an object's compliance [5]. Thus, we hypothesize that a virtual object will feel significantly harder when cutaneous feedback is properly rendered than when only force-feedback is available. The second objective is to evaluate our strategy for rendering hardness with cutaneous feedback. Considering that a human is less sensitive to force changes in the normal direction than in the tangential direction at the skin, the perception of surface hardness is presumably processed with the contact area change given normal displacement [32]. Then if we can effectively change the rate of increase in contact area, a user may perceive an object's surface as being harder [31]. Thus, for the second objective, we hypothesize that the perceived hardness of virtual objects can be modulated by changing the rate of increase in contact area. Two experiments were conducted, the first for one-finger touch and the second for two-finger grip. The results of the present study can provide knowledge on how the addition of cutaneous information to kinesthetic feedback affects the perception of hardness. In addition, the hardware and rendering strategy proposed in this paper are expected to provide a means to create the sensation of touching a harder surface with less torque from a kinesthetic feedback interface.

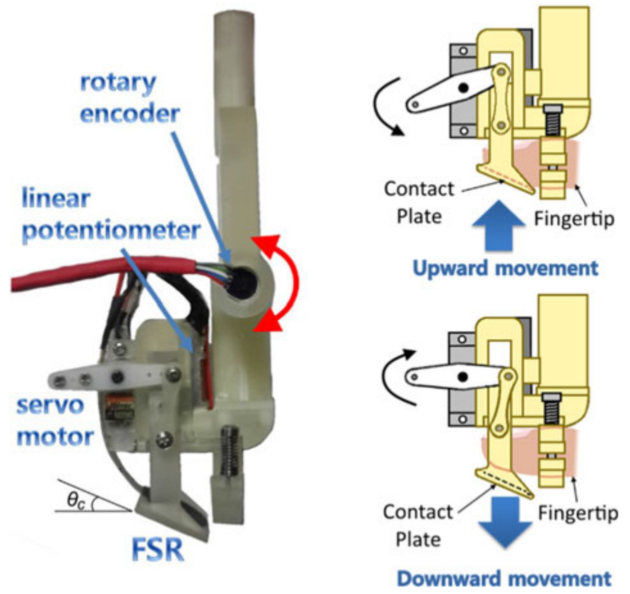
The rest of the paper is organized as follows. In the next section, we present the hardware and rendering strategy for delivering contact and hardness information on the fingertip with cutaneous and kinesthetic feedback. Next, the effect of cutaneous hardness information for one finger touch is evaluated in three experiments. We then investigate the effect of additional cutaneous feedback for two-finger grip with two experiments. In the last section, we summarize our findings along with future work.

## 2 PRESENTING HARDNESS AT THE FINGERTIP WITH CUTANEOUS AND KINESTHETIC FEEDBACK

### 2.1 Hardware Setup

Fig. 1a shows our cutaneous interface for rendering the change of contact surface/contact force at the fingertip. A servo-motor drives the movement of a contacting plate which is connected to a linear potentiometer to read the displacement of the plate. Nominal position resolution of the potentiometer is 0.05 mm after applying a lowpass filter. Fig. 1b describes the upward and downward movements of the plate with the rotation of the motor to increase or decrease the contact area at the fingertip. The motor (model HS-5035HD, Hitec RCD Korea Inc., Korea) has a nominal maximum force of 7.8 N (stall torque: 0.8 kg·cm and center-rotation axis distance: 1 cm), and the weight of the cutaneous interface is 28 g. A force sensing resistor is attached to the contact plate to read the force between the plate and the user's fingertip. The cutaneous interface was fabricated in three different sizes and easily replaceable for different fingertip sizes. A pair of springs tightly fixes the haptic interface to a user's fingertip at the distal interphalangeal (DIP) joint. Note that the cutaneous contact information due to such fixation is a necessary part of any wearable haptic devices, and it does not contribute to stiffness perception because the contact area remains fixed during the experiment.

The cutaneous interface is designed to be installed on a commercially available PHANToM Premium and Touch (3D



(a) (b)

Fig. 1. (a) Profile of the cutaneous contact hardness interface ($\theta_c$: contact plate tilting angle) and (b) the description of the control scheme to increase/decrease contact area. An upward movement of the contact plate increases the contact area (top) and a downward movement of the contact plate decreases the contact area (bottom).

Systems Inc., SC, USA). This allows a user to feel a virtual object's surface hardness through both cutaneous and kinesthetic feedback. For installation on the PHANToM Premium, the cutaneous interface is attached to a link with a 1-DOF rotation (Fig. 1a), which is read by a miniature magnetic rotary encoder with an accuracy of ±0.3° (RM08, RLS, Slovenia). The weight of the cutaneous interface with the link is 46 g.

## 2.2 Rendering of Surface Hardness

In this section, we describe the haptic stiffness rendering algorithm with cutaneous and kinesthetic feedback. A user's fingertip is modeled as a NURBS (Non-Uniform Rational B-Spline) surface to ensure smooth contact at a virtual fingertip. The virtual fingertip has the size of 28 mm × 17.5 mm × 15 mm for an index finger and 34 mm × 22 mm × 20 mm for a thumb based on the measurement of five male participants who were recruited for this measurement only. We did not use a polygonal model because discontinuities in the contact vector could occur as the finger moves over edges or vertices. As Doxon et al. demonstrated, a participant can be more sensitive to the discontinuities of haptic feedback when cutaneous feedback is available [33]. We used a minimum-distance finding scheme proposed by Johnson and Cohen [34] to track the contact point between the fingertip avatar and a virtual plane. For the present study, we consider only the contact between a curved fingertip surface and a virtual plane. Then, the minimum-distance point relation between two surfaces [35] reduces to the following form:

$$\boldsymbol{F}(u,v) = \begin{bmatrix} A(u,v)_z \left(\frac{\partial A(u,v)}{\partial u}\right)_z \\ A(u,v)_z \left(\frac{\partial A(u,v)}{\partial v}\right)_z \end{bmatrix}, \tag{1}$$

where an $x$-$y$ plane is assumed for the virtual plane and $z$ denotes the $z$-axis component. The parameters $u$ and $v\,(0 \leq u, v \leq 1)$ determine a point's position on the fingertip surface. For example, changing $u$ and $v$ mov a point on the surface in the transverse and longitudinal directions, respectively. The minimum distance point on the fingertip $\boldsymbol{x}_f$ is tracked with Newton's method,

$$\Delta\boldsymbol{p} = -\boldsymbol{J}^{-1}(u,v)\boldsymbol{F}(u,v), \tag{2}$$

where $\boldsymbol{J}(u,v)$ is the Jacobian of $\boldsymbol{F}(u,v)$ and $\Delta\boldsymbol{p} = [\,\Delta u \quad \Delta v]^T$ [36]. Then $\boldsymbol{x}_f = A(u_i + \Delta u,\ v_i + \Delta v)$ and the minimum distance point on the virtual plane $\boldsymbol{x}_p$ is calculated as the projection of $\boldsymbol{x}_f$ onto the virtual plane.

Once the minimum distance points are decided, the contact status between the two surfaces can be readily tracked. Then, the contact force by a force-feedback interface is calculated using a typical spring model:

$$\boldsymbol{F} = \begin{cases} K(\boldsymbol{x}_p - \boldsymbol{x}_f) & \text{if } (\boldsymbol{A}_u(u,v) \times \boldsymbol{A}_v(u,v)) \cdot (\boldsymbol{x}_p - \boldsymbol{x}_f) \leq 0 \\ 0 & \textit{otherwise}. \end{cases} \tag{3}$$

where $K$,$\boldsymbol{A}_u(u,v)$ and $\boldsymbol{A}_v(u,v)$ denote the stiffness of the virtual plane and the partial derivatives of the fingertip surface with respect to $u$ and $v$, respectively.

For the rendering of contact hardness with the cutaneous interface, we define $d_c$ as the position of the contact plate when it barely touches the fingertip. This first contact is detected by an FSR sensor. The reference position of the contact plate $d_{ref}$ is then determined as:

$$d_{ref} = \begin{cases} d_c + K_C|\boldsymbol{x}_p - \boldsymbol{x}_f| & (\textit{with contact}) \\ d_c - 2\ mm & (\textit{no contact}), \end{cases} \tag{4}$$

where $K_C$ (unit-less) defines the virtual hardness by the cutaneous interface. We call this parameter the "rate of cutaneous hardness." It represents the rate at which the contact plate compresses the fingertip as a virtual fingertip presses on the virtual surface. Equation (4) also means that the contact between the real fingertip and the contact plate is synchronized with the contact rendered with kinesthetic feedback in Eqn. (3). The contact plated is moved to the reference position by a PID controller ($\tau_{out} = (K_p + \frac{K_i}{s})(d_{ref} - d) - K_d s l$,. where $l$ and $s$ are the current contacting plate displacement and the Laplacian operator, respectively). The controller minimized the instability of the plate motion.

The haptic interface in this paper can render the hardness of a virtual object separately for kinesthetic and cutaneous information. Noting that the kinesthetic information is sensed mainly by the sensory receptors within muscles, tendons, and joints [37], the kinesthetic perception of hardness can be rendered with a force-feedback interface. Then the hardness of a virtual surface for kinesthetic perception can be controlled by adjusting the virtual stiffness $K$ of (3).

The hardness perceived through cutaneous information can be controlled by the rate of contact area increase, which is defined by $K_C$ of (4). Chang et al. suggested a contact model for the Hertzian contact between a sphere and a flat plate, where contact force ($F_c$), area (A) and contact interference ($\omega$) follow the following relation:

$$A = \pi\left(\frac{3F_cR}{4E^*}\right)^{2/3} = \pi R\omega, \tag{5}$$

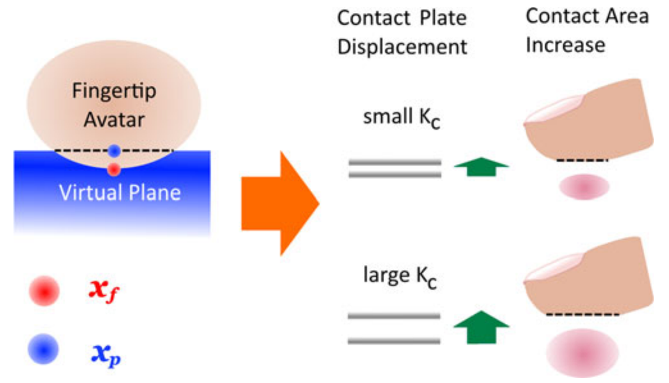


Fig. 2. The effect of changing $K_C$ on the contact area of a fingertip. Given the same penetration depth, a larger $K_C$ results in a larger displacement of the contact plate that is proportional to the penetration depth (Eq. (4)) and a larger increase of the contact area.

where $E^*$ and R denote the Hertz elastic modulus and the sphere radius, respectively [38]. By combining (4) and (5), when there is a contact between a virtual fingertip and the plane, contact area becomes

$$A = \pi R\omega = \pi R\big(\cos\theta_c K_C \left|\boldsymbol{x}_p - \boldsymbol{x}_f\right|\big), \tag{6}$$

where $\theta_c$ is the tilting angle of the contact plate (see Fig. 1a). Then the contact area is linearly proportional to $K_C$ and the penetration depth $|\boldsymbol{x}_p - \boldsymbol{x}_f|$. As shown in Fig. 2, given the same penetration depth, a larger $K_C$ will result in a larger displacement of the contact plate, which in return leads to a larger increase of the contact area. Accordingly, the hardness of the virtual surface can be controlled separately for kinesthetic and cutaneous sensation by adjusting $K$ and $K_C$, respectively.

The rendering strategy proposed for cutaneous feedback assumes that the contact area increases linearly with displacement, which is proportional to $K_C|\boldsymbol{x}_p - \boldsymbol{x}_f|$ (Eq. (4)) and thus to A (Eq. (5)). For verification, we measured the fingertip contact area as a function of contact plate displacement with five male participants. As shown in Fig. 3, a transparent plate compressed the participant's index fingerpad downward by a displacement of 0.5, 1.0, 1.5, 2.0 and 2.5 mm. The maximum displacement of 2.5 mm was chosen to be the minimum value among the participants' maximum compressible displacement at the fingertip. On the surface of the transparent plate were marked four dots forming the corners of a rectangle. The images of the contact plate at the penetration depths were captured with a digital microscope. They were then normalized in size with a 2D projective transformation of the four dots' position to the corner position of the four dots' positions in a rectangle for the contact plate's flat image [39]. The contact area was calculated by counting the number of pixels within the contact area and converting it to a value in $\mathrm{mm}^2$.

The increase in fingertip contact area as a function of the penetration depth for the five participants is plotted in Fig. 4. The goodness-of-fit for each participant as measured in $R^2$ values for a linear model are 0.9896, 0.9928, 0.996, 0.9972 and 0.9898, respectively. The data confirm a linear relation between the contact area and displacement, thereby supporting the use of a linear model for rendering cutaneous hardness.

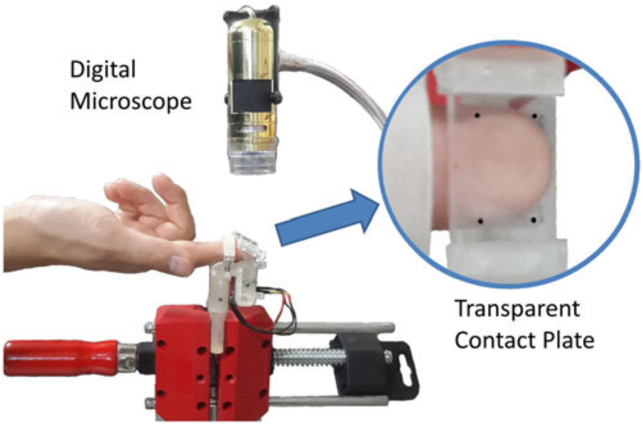


Fig. 3. Measurement setup for the increase in fingertip contact area as a function of penetration depth. The images of a finger pad compressed by a transparent contact plate were captured with a digital microscope. Four dots were marked on the plate as references for the 2D projective transformations performed later.

## 3 EXPERIMENT 1: EFFECT OF CUTANEOUS FEEDBACK ON HARDNESS PERCEPTION FOR ONE-FINGER TOUCH

We divided our evaluation in three experiments. In Section 3.1, we studied hardness perception of soft virtual surfaces when providing cutaneous feedback, while in Section 3.2, we studied hardness perception of hard virtual surfaces when providing cutaneous feedback. In Section 3.3, we investigated hardness perception when the rate of compressing the fingertip was low. The experimental protocol was approved by the IRB at Korea Institute of Science and Technology.

### 3.1 Experiment 1a: Hardness Perception of Virtual Surfaces with Low Stiffness Values ($K \leq 0.3$ N/mm)

The purpose of this experiment was to test if cutaneous feedback can enhance the perception of hardness for force-feedback interfaces that cannot exert a large torque. The virtual stiffness K values were chosen to be less than 0.3 N/mm to represent virtual surfaces rendered with low-torque actuators.

#### *3.1.1 Participants*

Twelve participants (2 females; 22-37 years old, average 28.3 years) were recruited for Exp. 1a. All participants gave their informed consent. All participants had fully functional sensory systems. All but one participant were right-handed by self-report.

#### *3.1.2 Stimuli*

The stimuli for the experiment were virtual surfaces that could be explored with the finger. The surface hardness was defined by $K_C$ and $K$ for cutaneous and kinesthetic feedback, respectively. There were six reference stimuli whose hardness values were decided as the combination of two $K_C$ values (1 and 3) and three K values (0, 0.15 and 0.3 N/mm). $K_C = 1$ means that the contact plate presses a fingertip as deep as the penetration depth of a virtual fingertip. When $K_C = 3$, the plate presses the fingertip by three times that of the penetration depth. $K_C = 3$ was selected

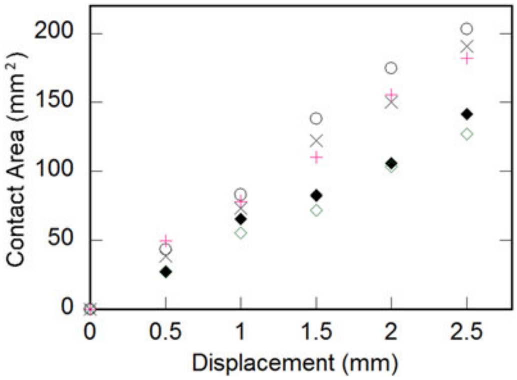


Fig. 4. Fingerpad contact area versus displacement. Each symbol corresponds to one participant's data.

from a pilot test where the participants could adjust $K_C$ and K value was fixed at 0.3 N/mm. The minimum $K_C$ value for a virtual plane to feel distinctly different from the one rendered with $K_C = 1$ was 3. The comparison stimulus contained only kinesthetic (force feedback) cues.

### 3.1.3 *Procedure*

A one-up one-down adaptive procedure [40] was employed to match the perceived hardness of a virtual plane rendered with both cutaneous and kinesthetic feedback to that rendered with kinesthetic feedback only. For each reference stimulus, the point of subjective equality (PSE) for perceived hardness was estimated by varying the stiffness of the comparison stimuli using the adaptive procedure. The estimated PSE was based on the average of the reversals in the adaptive procedure. The estimated PSE then provided a measure for the perceived stiffness of a virtual plane rendered with force-feedback that felt equivalent to that of a virtual plane rendered with each combination of $K$ and $K_C$.

Each participant conducted six experimental runs defined by the reference stimuli (2 $K_C \times 3K$). The order of the reference stimuli was randomized for each participant. On each trial, the participant was presented with two virtual planes: a reference plane rendered with both cutaneous and kinesthetic feedback and a comparison plane rendered with kinesthetic feedback only. If the participant responded that the reference plane felt harder than the comparison plane, the stiffness of the comparison plane was increased. Otherwise, the stiffness of the comparison plane was decreased. The initial stiffness was 1.3 N/mm and the step size of increasing/decreasing K was changed from 0.2 N/mm to 0.025 N/mm after the first three reversals of the responses. Each experimental run was terminated after 12 reversals of the responses at the smaller step size. The total number of trials for one experimental run typically ranged between 25 and 45. It took approximately 1 hour and 20 minutes for each participant to complete the six runs of the experiment.

Fig. 5 shows the setup for Exp. 1. At the beginning of each experimental run, the participant was seated in front of a computer and asked to put his/her lower arm on an *X*-Ar anti-gravity exoskeletal arm support (Equipos, Manchester, NH, USA) that reduced the weight of the arm to minimize possible fatigue. The participant worea pair of noise-canceling headphones (MDR10RNC, Sony, Tokyo, Japan) to block possible audio cues during the experiment. Then, the participant was asked to insert the index finger of the dominant hand into the haptic interface. The participant's hand was covered with a cloth to block possible visual cues.

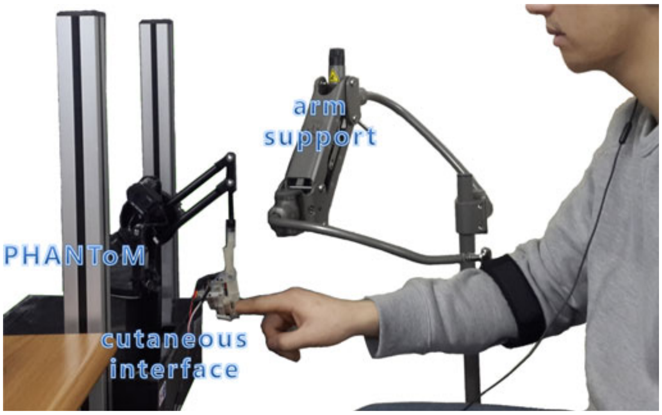


Fig. 5. An index finger is inserted inside the haptic interface, and the arm is attached to an anti-gravity arm support. The participant wears noise-canceling headphones to minimize audio cues.

Before the experiment, the participant pushed his/her finger down to feel the hardness of virtual planes rendered with cutaneous and kinesthetic feedback or with kinesthetic feedback only during a training session. S/he could adjust the virtual plane's stiffness by selecting a number between 1 and 4, which corresponded to 0.25 to 1.0 N/mm. Virtual fingertips were visually displayed along with the virtual plane. When the participant felt ready, the training was terminated.

During the experiment, the order of the reference and comparison planes was randomly determined on each trial. In the beginning, a virtual fingertip was displayed on the screen along with a horizontal line indicating the location of the virtual plane. The participant was asked to lower his/her fingertip to feel the hardness of the virtual plane. When the distance between the virtual finger and the virtual plane was less than 5 mm, visual cues indicating the finger and the plane disappeared, and white noise was played through the headphone to block possible audio cues from the haptic interface. Once the stimulus was activated, the participant could feel it for as many times as possible by tapping the index finger on the virtual plane, and no visual cues were available before the next phase. By hitting the enter key, the participant moved to the next phase to feel the other stimulus. Then, the participant answered the question "Which stimulus felt harder?" by pressing "1" if the first stimulus felt harder or "2" if otherwise. The participant's response, collision depth during each tapping and trial duration were recorded for each trial. The PSE estimate was calculated at the end of each experimental run, and the participant took a 5-min break.

After the completion of all the experimental runs, the participant was prompted to feel three additional virtual surfaces for the three $(K_C, K)$ value pairs of (3, 0), (0, 0.3) and (3, 0.3), which included cutaneous feedback only, force-feedback only and cutaneous plus force-feedback, respectively.

### 3.1.4 *Data Analysis*

For each experimental run, the PSE for each $(K_C, K)$ pair was calculated from the mean of the six peak and valley values of $K$ over the 12 reversals at the smaller step size.

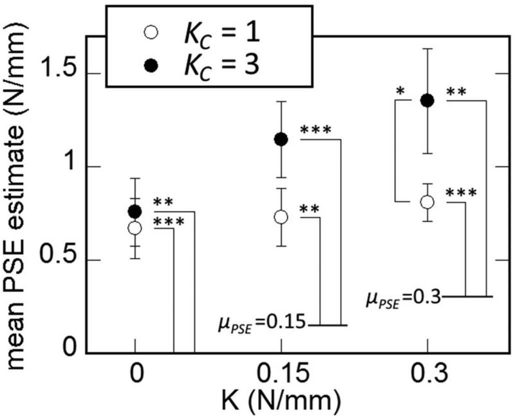
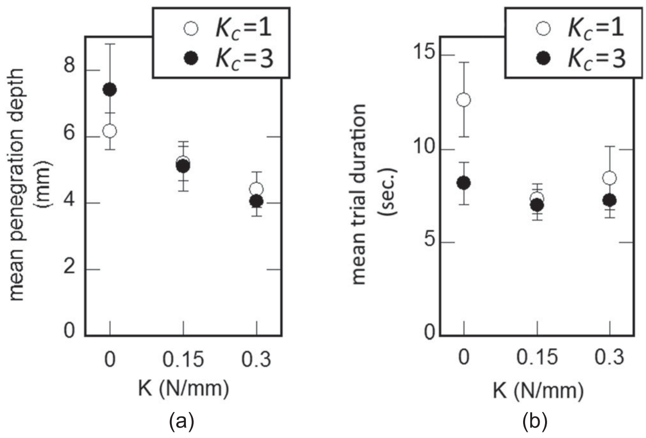


Fig. 6. Mean estimated PSE of perceived hardness by $(K_C, K)$ values in Exp. 1a. Error bars indicate the standard errors.

### 3.1.5 Results

In Fig. 6, the mean PSE estimates for the six $(K_C, K)$ reference stimuli are plotted against $K$. An analysis of the PSE estimates confirmed normality as addressed by Shapiro-Wilk's test and no outlier was found. To see the effect of cutaneous feedback, the PSE estimates were compared to the $K$ values of the reference stimuli by one-sample t-test ($H_0$: $\mu_{PSE} =$ K). The result indicated a significant difference between the PSE estimates and K values for all $(K_C, K)$ pairs [$\mathrm{t}(11) = 4.21, p = 0.001$ for (1, 0); $\mathrm{t}(11) = 3.78, p = 0.003$ for (1, 0.15); $\mathrm{t}(11) = 5.16, p < 0.001$ for (1, 0.3); $\mathrm{t}(11) = 4.15, p = 0.002$ for (3, 0); $\mathrm{t}(11) = 4.92,\ p < 0.001$ for (3, 0.15); $\mathrm{t}(11) = 3.73, p = 0.003$ for (3, 0.3)]. This means that with the addition of cutaneous feedback, the participants felt the virtual surface to be significantly harder than that of the virtual plane with the same nominal K rendered with kinesthetic feedback alone. To examine the effect of the additional cutaneous feedback on the perception of hardness, a two-way repeated measure ANOVA was performed with $K_C$ and $K$ as the within-participant factors. A significant interaction between the two factors was found [$\mathrm{F}(2, 22) = 3.94, p = 0.034,\ \eta_p^2 = 0.27$]. A simple main effects analysis showed that for $\mathrm{K} = 0.3\,\mathrm{N/mm}$, the virtual surface felt harder ($p = 0.027$) with $K_C = 3$ than with $K_C = 1$ but there were no differences for K = 0 or 0.15 N/mm. Also, the perception of hardness was significantly affected by K when $K_C = 3$ ($p = 0.045$) while there was no significant difference for different $K$ values when $K_C = 1$ ($p = 0.603$). Therefore, the virtual surfaces felt harder with increasing $K$ values at larger $K_C$ values.



(a) (b)

Fig. 7. (a) Mean penetration depth and (b) mean trial duration by ($K_C$, K) values in Exp. 1a. Error bars indicate the standard errors.

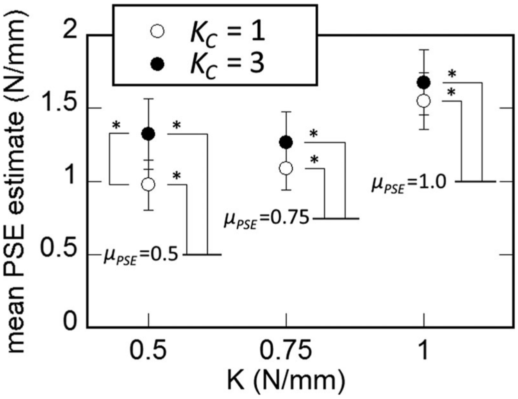


Fig 8. Mean estimated PSE of perceived hardness by $(K_C, K)$ values in Exp. 1b. Error bars indicate the standard errors.

Fig. 7a shows the mean penetration depth for $(K_C, K)$ pairs plotted against $K$. When a two-way repeated measure ANOVA was conducted with the within-participant factors of $K_C$ and $K$, a significant main effect was found for $K$ [$\mathrm{F}(2, 22) = 22.94,\ p < 0.001,\ \eta_p^2 = 0.68$] and the effect of $K_C$ was insignificant ($\mathrm{F}(1, 11) = 3.82, p = 0.076,\ \eta_p^2 = 0.26$). In a subsequent Bonferroni analysis, the mean penetration depth was not grouped together for any K pair, indicating a decreasing trend with the increase of K. When Pearson's correlations were conducted between $K$ and penetration depth, negative relations were found for both $K_C$ values [$\mathrm{r} = -0.57,\ p < 0.001$ for $K_C = 1$; $\mathrm{r} = -0.6, p < 0.001$ for $K_C = 3$]. In Fig. 7b, the mean trial duration for $(K_C, \mathrm{K})$ is plotted against the virtual surface stiffness K. There was a significant interaction between the two factors [$\mathrm{F}(2, 22) = 4.28, p = 0.027,\ \eta_p^2 = 0.28$]. The result of a simple main effects analysis indicated that there was a significant difference in the trial duration between the two $K_C$ values ($p = 0.004$) when $\mathrm{K} = 0\,\mathrm{N/mm}$.

## 3.2 Experiment 1b: Hardness Perception of Virtual Surfaces with High Stiffness Values ($K > 0.3$ N/mm)

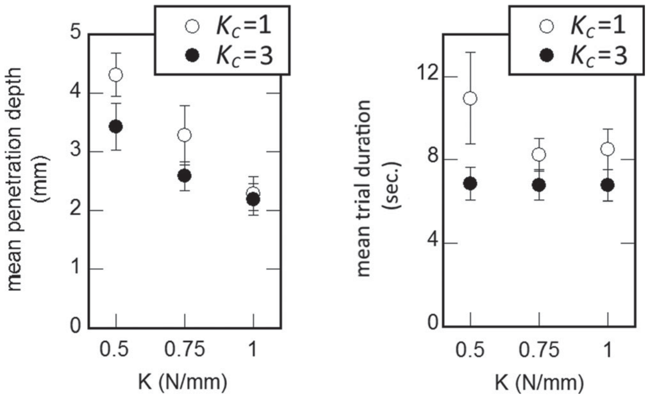
The results of Exp. 1a indicates that the addition of cutaneous feedback led the participants to perceive a virtual plane to be harder than that rendered by kinesthetic feedback alone. In Exp. 1b, the effect of cutaneous feedback on hardness perception is further investigated for virtual planes with higher stiffness values than those in Exp. 1a.

### 3.2.1 Methods

An additional twelve participants (2 females; 24-38 years old, average 29.1 years) were recruited for this experiment. All participants gave their informed consent. All participants had fully functional sensory systems. All but one participant were right-handed by self-report. The stimuli and procedures were the same as in Exp. 1a, except that the $K$ values were chosen to be 0.5, 0.75 and 1.0 N/mm.

### 3.2.2 Results

Fig. 8 shows the mean PSE estimates plotted against $K$ values of 0.5, 0.75 and 1.0 N/mm. No outlier was observed, and Shapiro-Wilk's test confirmed that there was normality



(a)

(b)

Fig. 9. (a) Mean penetration depth and (b) mean trial duration by ($K_C$, K) values in Exp. 1b. Error bars indicate the standard errors.

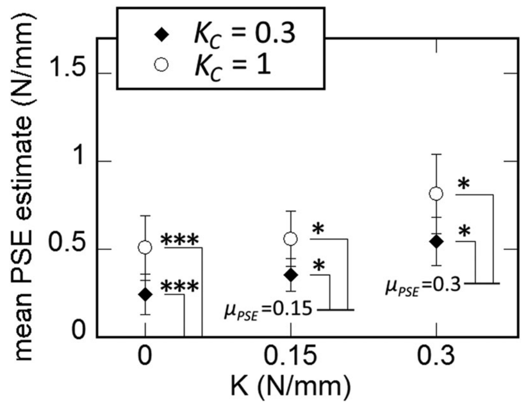


Fig. 10. Mean estimated PSE of perceived hardness by ($K_C, K$) value in Exp. 1c. Error bars indicate the standard errors.

in the PSE estimates. One sample t-tests were conducted to compare the PSE estimates to the K values of the reference stimuli ($H_0$: $\mu_{PSE} = K$). As was with Exp. 1a, there were significant differences among the PSE estimates and the reference K values for all the ($K_C$, K) pairs [$\mathrm{t}(11) = 2.85$, $p = 0.016$ for (1, 0.5); $\mathrm{t}(11) = 2.4$, $p = 0.035$ for $(1, 0.75)$; $\mathrm{t}(11) = 2.94$, $p = 0.013$ for $(1, 1.0)$; $\mathrm{t}(11) = 3.57$, $p = 0.004$ for $(3, 0.5)$; $\mathrm{t}(11) = 2.6, p = 0.025$ for $(3, 0.75)$; $\mathrm{t}(11) = 3.17, p = 0.009$ for (3, 1.0)]. This trend means that the addition of cutaneous cues increased the perceived hardness of the virtual planes. When a two-way repeated measure ANOVA was conducted on the PSE estimates, both $K_C$ and $K$ were found to be significant factors [$\mathrm{F}(1, 11) = 5.16, p = 0.044$, $\eta_p^2 = 0.32$ for $K_C$; $\mathrm{F}(2, 22) = 9.69, p = 0.001$, $\eta_p^2 = 0.47$ for $K$]. In a subsequent Bonferroni test, the PSE estimates were grouped into two overlapping subsets of 0.5 and 0.75 N/mm. The results indicate that by adding cutaneous feedback, the virtual surfaces felt significantly harder for the higher stiffness values tested and the effect of $K_C$ was significant.

Fig. 9a shows the mean penetration depth for ($K_C, K$) pairs in Exp. 1b. When a two-way repeated measure ANOVA was conducted on the mean penetration depth with within-participant factors $K_C$ and K, significant main effects were found for $K$ [$\mathrm{F}(2, 22) = 39.85, p < 0.001$, $\eta_p^2 = 0.78$] and $K_C$[$\mathrm{F}(1, 11) = 7.51, p = 0.019$, $\eta_p^2 = 0.41$]. In a subsequent post-hoc test, we used a Bonferroni procedure considering the small number of comparisons. The results of the comparison show that mean penetration depths were not grouped together for any K pair. When Pearson's correlations were conducted between $K$ and penetration depth, negative relations were found for both $K_C$ values [$\mathrm{r} = -0.53, p = 0.001$ for $K_C = 1$; $\mathrm{r} = -0.44, p = 0.008$ for $K_C = 3$]. In Fig. 9b, the mean trial duration is plotted against $K$. When a two-way repeated measure ANOVA was conducted, $K_C$ was found to be a significant factor [$\mathrm{F}(1, 11) = 16.72, p = 0.002$, $\eta_p^2 = 0.6$] while the effect of $K$ was insignificant [$\mathrm{F}(2, 22) = 2.56, p = 0.1$].

## 3.3 Experiment 1c: Hardness Perception of Virtual Surfaces with Low Cutaneous Stiffness Values ($K_C = 0.3$ and 1.0)

In this experiment, the effect of cutaneous feedback on the perception of hardness is investigated for a smaller $K_C$ value than those used in Exps. 1a and 1b.

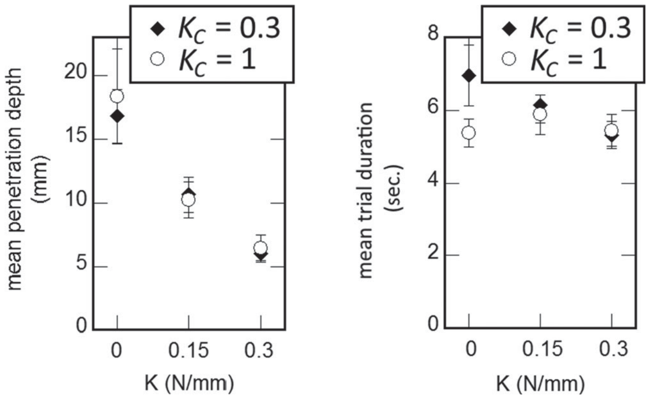
### 3.3.1 Methods

Twelve participants (2 females; 24-37 years old, average 29.0 years) completed this experiment with informed consent. Seven of them (6 males and 1 female) participated in Exp. 1b. All the participants had fully functional sensory systems. They were all right-handed by self-report. The stimuli and procedures were the same as in Exp. 1a, except that the $K_C$ values were 0.3 and 1.0, which were lower than the values used in the previous experiments.

### 3.3.2 Results

Fig. 10 shows the mean PSE estimates plotted against the virtual stiffness $K$. No outlier was found but the PSE estimates were not normally distributed as addressed by the Shapiro Wilk's test. Considering the positively skewed data, a log transformation was applied to the PSE estimates. When the log-transformed PSE estimates were compared to the $K$ values of the reference stimuli with a one-sample t-test ($H_0 : \log_{10}\mu_{PSE} = \log_{10}K$), there were significant differences for all ($K_C$, K) pairs [$\mathrm{t}(11) = 10.28, p = 0.001$ for (0.3, 0); $\mathrm{t}(11) = 2.69, p = 0.021$ for $(1, 0.15)$; $\mathrm{t}(11) = 2.35, p = 0.038$ for $(0.3, 0.3)$; $\mathrm{t}(11) = 9.39, p = 0.001$ for $(1, 0)$; $t(11) = 3.08$, $p = 0.01$ for $(1, 0.15)$; $\mathrm{t}(11) = 2.92, p = 0.014$ for (1, 0.3)]. The result of a two-way repeated measure ANOVA indicates that both $K_C$ and $K$ were significant factors for the transformed PSE estimates [$\mathrm{F}(1, 11) = 5.68, p = 0.036$, $\eta_p^2 = 0.34$ for $K_C$; $\mathrm{F}(2, 22) = 16.49, p = 0.001$, $\eta_p^2 = 0.6$ for $K$]. When a Bonferroni test was conducted, no significantly different K pair was found.

In Fig. 11a, the mean penetration depth is plotted for ($K_C$, $K$) pairs in Experiment 1c. The result of a two-way repeated measure ANOVA indicates that $K$ had a significant effect on the mean penetration depth [$\mathrm{F}(2, 22) = 18.88, p < 0.001$, $\eta_p^2 = 0.63$] but $K_C$ did not ($\mathrm{F}(1, 11) = 0.24, p = 0.63$, $\eta_p^2 = 0.02$). In a subsequent Bonferroni post-hoc analysis, the mean penetration depths were not grouped together for any K pair. When Pearson's correlations were conducted between $K$ and the penetration depth, negative relations were found for both $K_C$ values [$\mathrm{r} = -0.56, p < 0.001$ for $K_C = 0.3$; $\mathrm{r} = -0.52, p = 0.001$ for $K_C = 1$]. Fig. 7b shows the mean trial duration in Experiment 1c. When a two-way repeated measure ANOVA was conducted, no significant effect was found for either $K_C$ [$\mathrm{F}(1, 8) = 3.03, p = 0.12$, $\eta_p^2 = 0.28$] or $K$ [$\mathrm{F}(2, 16) = 3.31, p = 0.063$, $\eta_p^2 = 0.29$].



(a) (b)

Fig. 11. (a) Mean penetration depth and mean trial duration by ($K_C$, K) values in Exp. 1c. Error bars indicate the standard errors.

## 4 EXPERIMENT II: EFFECT OF CUTANEOUS FEEDBACK ON HARDNESS PERCEPTION WITH A TWO-FINGER GRIP

The goal of Experiment 2 is to examine the effect of cutaneous feedback on the perception of hardness for a two-finger grip. The same values of the parameters $K_C$ and $K$ as in Exp. 1a are used for Exp. 2a. Experiment 2b investigates the effect of a virtual object's thickness on the perception of a virtual object's hardness. Bergmann Tiest and Kapper studied the human perception of a real object's compliance with a two-finger grip. Their results indicated that human perception of an object's hardness is better characterized with the Young's modulus than with the stiffness value [5]. Considering that the Young's modulus depends on the size of an object ($Y = \frac{F/A}{\Delta L/L} = K\frac{l}{A}$), the effect of cutaneous feedback may also depend on the size of a virtual object. This prompted us to investigate the effect of a virtual object's thickness on hardness perception in Exp. 2b. The experiment protocol was approved by the Korea Institute of Science and Technology IRB.

### 4.1 Experiment 2a: Hardness Perception of Virtual Objects with a Two-Finger Grip

#### 4.1.1 Methods

The twelve participants (2 females; 22-37 years, average 27.6 years) who participated in Exp. 1a completed this experiment with informed consent. The two experiments were conducted on different days due to the change of experimental setup. All the participants were right-handed by self-report.

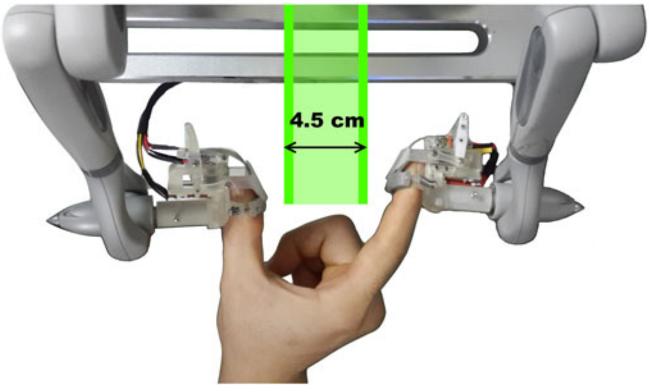


Fig. 12. The experimental apparatus (two Touch kinesthetic feedback interfaces with our cutaneous interfaces attached at the two end effectors). The stimulus consists of two parallel sagittal planes (colored in green).

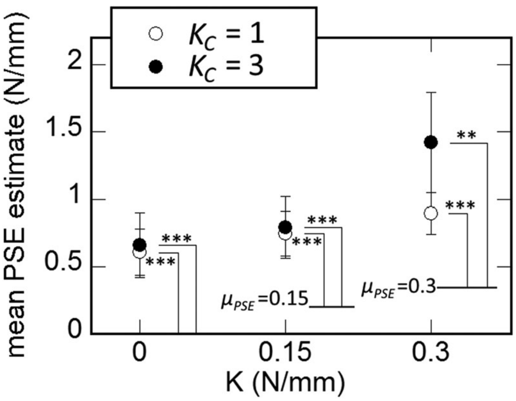


Fig. 13. Mean estimated PSE of perceived hardness by ($K_C$, $K$) values in Exp. 2a. Error bars indicate the standard errors.

#### 4.1.2 Stimuli

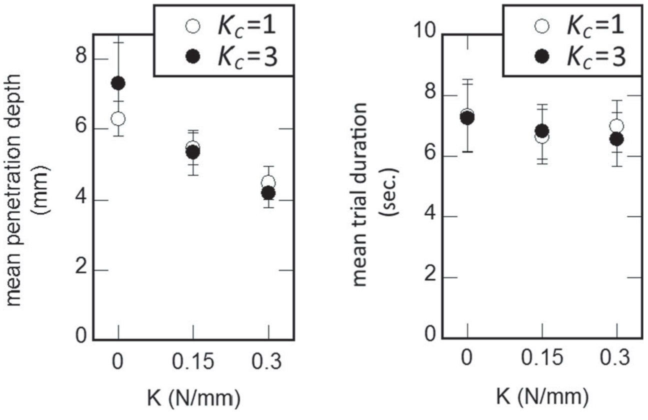
The stimuli were virtual objects whose surfaces consisted of two sagittal planes separated by 4.5 cm (see Fig. 12). The hardness values of the planes for the reference stimuli were selected from the same combination of $K_C$ (1 and 3) and $K$ values (0, 0.15 and 0.3 N/mm) as in Exp. 1a.

#### 4.1.3 Procedure

The experimental apparatus combined two Touch force-feedback devices on whose end effectors the cutaneous interfaces were installed (Fig. 12). At the beginning of the experiment, the participant was instructed to insert the index finger and thumb of the dominant hand inside the thimbles of the cutaneous interfaces. To feel the hardness of a virtual object, the participant was asked to first hold his/her thumb and index finger apart and then squeeze them. Once one of the fingertips was as close as 5 mm to a surface plane of the virtual object, the haptic feedback was initiated. A one-up one-down adaptive procedure with the same experimental parameters as in Exp. 1a was employed to estimate the PSE of the perceived hardness of the virtual object. It took approximately 1 hour and 20 minutes for each participant to complete the six runs of the experiment.

#### 4.1.4 Results

In Fig. 13, the mean PSE estimates for $(K_C, K)$ reference stimulus pairs in Exp. 2a are plotted against the virtual surface stiffness $K$. No outlier was found but the PSE estimates were not normally distributed as addressed by the Shapiro Wilk's test. Considering the positively skewed data, a log transformation was applied to the PSE estimates. When the transformed PSE estimates were compared to the $K$ values of the reference stimuli by a one-sample t-test ($H_0: \log_{10}\mu_{PSE} = \log_{10}K$.), significant differences were found for all the $(K_C, K)$ pairs [$\mathrm{t}(11) = 13.68, p < 0.001$ for (1, 0); $\mathrm{t}(11) = 8.81, p < 0.001$ for (1, 0.15); $\mathrm{t}(11) = 5.6, p < 0.001$ for (1, 0.3); $\mathrm{t}(11) = 13.09, p < 0.001$ for (3, 0); $\mathrm{t}(11) = 4.5, p = 0.001$ for (3, 0.15), $\mathrm{t}(11) = 4.18, p = 0.002$ for (3, 0.3)]. A two-way repeated measure ANOVA was conducted with $K_C$ and $K$ as the within-participant factors. A significant interaction between the two factors was found [$\mathrm{F}(2, 22) = 3.64, p = 0.043$,



(a) (b)

Fig. 14. (a) Mean penetration depth and mean trial duration by ($K_C$, K) values in Exp. 2a. Error bars indicate the standard errors.

$\eta_p^2 = 0.25$]. A simple main effects analysis showed no significant differences in the transformed PSE estimated between $K_C = 1$ and $K_C = 3$ at any K value.

In Fig. 14a, the mean penetration depth for $(K_C, K)$ pairs in Exp. 2a are plotted against *K*. The result of a two-way repeated measure ANOVA indicated a significant main effect of K ($\mathrm{F}(2, 22) = 36.81, p < 0.001$, $\eta_p^2 = 0.71$) while the effect of $K_C$ was insignificant ($\mathrm{F}(1, 11) = 0.39, p = 0.54$, $\eta_p^2 = 0.03$). The result of a Bonfrerroni post-hoc analysis indicated that the mean penetration depths were not grouped together for any K pair. When Pearson's correlations were conducted between *K* and the penetration depth, negative relations were found for both $K_C$ values [$\mathrm{r} = -0.41, p = 0.012$ for $K_C = 1$; $\mathrm{r} = -0.42, p = 0.011$ for $K_C = 3$]. Fig. 14b shows the mean trial duration for $(K_C, K)$. When a two-way repeated measure ANOVA was conducted, no significant effect was found for either $K_C$ ($\mathrm{F}(1, 11) = 5.77$, $p = 0.08$, $\eta_p^2 = 0.25$) or $K$ ($\mathrm{F}(2, 22) = 3.46, p = 0.05$, $\eta_p^2 = 0.24$).

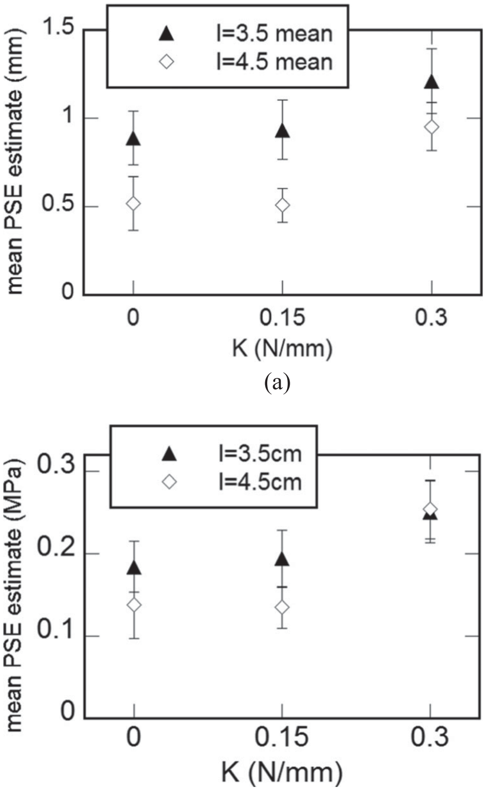
## 4.2 Experiment 2b: Effect of a Virtual Object's Thickness on Hardness Perception

### 4.2.1 Methods

A new group of twelve participants (2 females, 24-38 years old, average 28.6 years) was recruited for this experiment. All participants gave their informed consent. All the participants had fully functional sensory systems. None of them had any known problem with their sense of touch. All the participants were right-handed by self-report. Two thickness values of $l = 3.5$ and 4.5 cm were chosen to examine the effect of object thickness on hardness perception. $K_C$ was set to 1, which means the contact plate moved to the fingertip as deep as the penetration depth. It took approximately 1 hour and 30 minutes for each participant to complete the six runs of the experiment.

### 4.2.2 Results

Fig. 15a shows the mean estimated PSE for $l = 3.5$ and 4.5 cm against the virtual stiffness value *K*. No outlier was found, and the Shapiro-Wilk's test confirmed that there was normality in the PSE estimates. When a two-way ANOVA was conducted, the effects of the two factors *l* and *K* were found to be significant [$\mathrm{F}(1, 11) = 17.01, p = 0.002$, $\eta_p^2 = 0.61$ for $l$; $\mathrm{F}(2, 22) = 9.88, p = 0.001$, $\eta_p^2 = 0.47$ for $K$]. In a subsequent Bonferroni analysis, the mean PSE estimates were grouped together for $K = 0$ and 0.15 N/mm, indicating an increasing trend of the PSE estimates with the increase of *K*. When paired samples t-tests were conducted on the PSE estimates, significant differences were found between $l = 3.5$ cm and 4.5 cm for the three K values ($\mathrm{t}(11) = 4.02, p = 0.002$ for $\mathrm{K} = 0\,\mathrm{N/mm}$; $\mathrm{t}(11) = 3.42, p = 0.006$ for $\mathrm{K} = 0.15\,\mathrm{N/mm}$; $p = 0.035$ for $\mathrm{K} = 0.3\mathrm{N/mm}$). This confirms a significant effect of an object's thickness on its perceived hardness. Additionally, the mean estimated PSE values measured in stiffness were converted to Young's moduli considering that human perception of compliance can be better characterized with the Young's modulus. The area of the virtual object A was set to be 169 $\mathrm{mm}^2$ which is the mean fingertip contact area at the displacement of 2.5 mm as measured in Section 2.2. Fig. 15b shows the mean estimated PSE values after they were converted to Young's modulus as a function of the virtual stiffness *K*. When a two-way ANOVA was conducted, the effect of *K* was found to be significant [$\mathrm{F}(2, 22) = 10.87, p = 0.001$, $\eta_p^2 = 0.5$] and that of *l* was not [$\mathrm{F}(1, 11) = 3.31, p = 0.096$, $\eta_p^2 = 0.23$]. The result of a Bonferroni post-hoc analysis indicates that the converted mean PSE estimates were grouped for $K = 0.0$ and 0.15 N/mm. This implies that the perceived hardness of virtual objects did not change with the variation of virtual object's thickness. In the next section, we discuss the implications of the results.



(b)

Fig. 15. Mean estimated PSE of perceived hardness for $l = 3.5$ and 4.5 cm. The errors indicate the standard errors. (a) Mean PSEs estimated directly from the experiment, and (b) mean PSEs expressed as Young's modulus assuming $\mathrm{A} = 169\,\mathrm{mm}^2$, the fingertip contact area found in Section 2.2.

## 5 DISCUSSIONS

The results of Exps. 1a and 1b show that the addition of cutaneous feedback led participants to judge a virtual surface as being significantly harder than that rendered with kinesthetic feedback only. The effect of the $K_C$ value was significant for $K = 0.3$ (Exps. 1a) and $K = 0.5$ N/mm (Exp. 1b). The mean penetration depths decreased monotonically as the *K* value increased. Experiment 2 investigated the effect of cutaneous feedback on the perception of a virtual object's hardness with a two-finger grip. The results of Exp. 2a show that virtual objects felt significantly harder when the additional cutaneous feedback was available than when there was only kinesthetic feedback. This trend is consistent with the results of Exp. 1. The results of Exp. 2b indicate that the variation in a virtual object's thickness can affect its perceived hardness when the hardness was expressed in stiffness. However, the effect of thickness became insignificant when the perceived hardness was expressed in Young's modulus.

One important finding of the experimental results is that perceived hardness of a virtual object shifted to a larger value with the addition of cutaneous cues. This can be partly explained by the optimal integration model suggested by Ernst and Banks for multimodal sensory integration [8]. Let the estimate of hardness be a combination of a purely cutaneous sensation and a purely kinesthetic sensation. (Note that the purely cutaneous sensation of hardness is different from that in our eerimental condition $(K_C, K) = \{(1, 0), (3, 0)\}$ where kinesthetic cues were available because the force-feedback device was always active.) If the perception of hardness follows the maximum likelihood estimate rule, it can be represented as a weighted sum of the hardness estimates from cutaneous and kinesthetic cues, as follows:

$$\hat{S}_{hardness} = w_C \hat{S}_C + w_K \hat{S}_K, \tag{7}$$

where $\hat{S}_C$ and $\hat{S}_K$ are estimates of hardness from cutaneous and kinesthetic information, respectively, and $w_C$ and $w_K$ are their respective weights. Assuming that $\hat{S}_C > \hat{S}_K$, the combined probability density for perceived hardness will shift towards a larger PSE than that of $\hat{S}_K$. Thus, the perceived hardness will be matched to a larger *K* with the addition of cutaneous cues than that with kinesthetic feedback alone. The variation of the mean PSE estimates between the two $K_C$ values per *K* value can be viewed from different perspectives. One possible explanation is that both $w_C$ and $w_K$ vary as *K* changes. The Weber fraction is not constant throughout the full range of stimulus intensities [41]. Then, the relative weights can vary as the *K* value moves out of the constant Weber fraction region. On the other hand, the variation of $\hat{S}_C$ can be ascribed to the varied effect of the different $K_C$ values.

The results of Exps. 1a and 1b show that the effect of adjusting $K_C$ was effective on the perception of hardness for a virtual stiffness range between 0.3 and 0.5 N/mm. A possible explanation for this non-linear effect of $K_C$ can be found by examining the relationship between the perceived contact force change and the fingertip displacement. If we assume that $w_C$ and $w_K$ in Eq. (7) are invariant by the change of *K*, the effect of the cutaneous and kinesthetic feedback can be viewed in an additive manner. Then the perceived stiffness from the cutaneous information can be separately estimated by taking the ratio of the contact force at the fingertip over the displacement $\Delta l$. It follows that the difference in the perceived hardness between the two values of the rate of cutaneous stiffness, e.g. $K_C = 1$ and 3, can be expressed as a function of *K*, such as

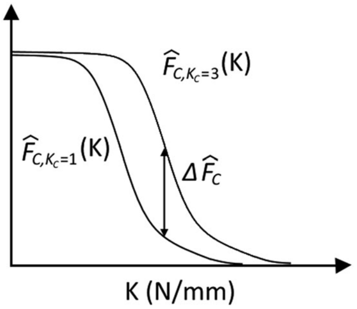


Fig. 16. $\hat{F}_{C,K_C=1}$, $\hat{F}_{C,K_C=3}$ and $\Delta\hat{F}_C$ values satisfying the two conditions of i) a monotonic decrease of $\hat{F}_{C,K_C=1}$ and $\hat{F}_{C,K_C=3}$ with an increase in *K*, and ii) $\hat{F}_{C,K_C=3} \geq \hat{F}_{C,K_C=1}$ for the same *K*.

$$\Delta\hat{K}_{cutaneous}(K) = \frac{\Delta\hat{F}_C}{\widehat{\Delta l}} = \frac{\hat{F}_{C,K_C=3} - \hat{F}_{C,K_C=1}}{\widehat{\Delta l}}, \tag{8}$$

where $\hat{F}_C$ and $\widehat{\Delta l}$ are the estimates of the contact force and displacement, respectively. Previous studies on haptic interaction with kinesthetic feedback reported that the penetration depth is decreased with an increased virtual stiffness [42], [43]. Then $\hat{F}_{C,K_C=1}$ and $\hat{F}_{C,K_C=3}$ will be monotonically decreasing functions of *K* by Eq. (5). Considering the effect of $K_C$ on the contact plate's maximum displacement, $\hat{F}_{C,K_C=3} \geq \hat{F}_{C,K_C=1}$ given the same *K*. Fig. 16 shows the trends of $\hat{F}_{C,K_C=1}$ and $\hat{F}_{C,K_C=3}$ satisfying the aforementioned two conditions, where $\Delta\hat{F}_C$ has a maximum at a medium *K* and a decreasing trend for $> \arg\max_K \Delta\hat{F}_C$. Then $\Delta\hat{K}_{cutaneous}(K)$ will also have a maximum at the medium *K*. This can explain the non-linear effect of adjusting $K_C$, i.e. the difference in the estimated PSEs is significant for $\mathrm{K} = 0.3 \sim 0.5\,\mathrm{N/mm}$.

If we take the view of an optimal sensory integration as discussed in Section 3.4, the partial contribution of cutaneous feedback on hardness perception with a two-finger grip can be estimated. We estimate Young's modulus for the cutaneous feedback by assuming the additive contribution of cutaneous and kinesthetic feedback. Since $Y = \frac{F/A}{\Delta L/L}$, the estimate of partial Young's modulus for the cutaneous feedback can be expressed as follows:

$$\hat{Y}_{cutaneous} = \frac{\hat{F}_{cutaneous}}{\widehat{\Delta l}} \frac{l}{A}, \tag{9}$$

where $\hat{F}_{cutaneous}$ and $\widehat{\Delta l}$ are the estimates of the perceived force from cutaneous cues and displacement, respectively. Assuming an independence of perceived force from cutaneous and kinesthetic cues and the additive contribution of the two cues, $\hat{F}_{cutaneous}$ can be expressed as

$$\hat{F}_{cutaneous} = \hat{F} - \hat{F}_{kinesthetic}, \tag{10}$$

where $\hat{F}$ and $\hat{F}_{kinesthetic}$ are the estimates of the net perceived force and the perceived force from kinesthetic feedback, respectively. Then, $\hat{F}$ and $\hat{F}_{kinsthetic}$ can be estimated as follows:

$$\hat{F} = \hat{K}_{PSE}\widehat{\Delta l} \text{ and } \hat{F}_{kinesthetic} = K\widehat{\Delta l}, \tag{11}$$

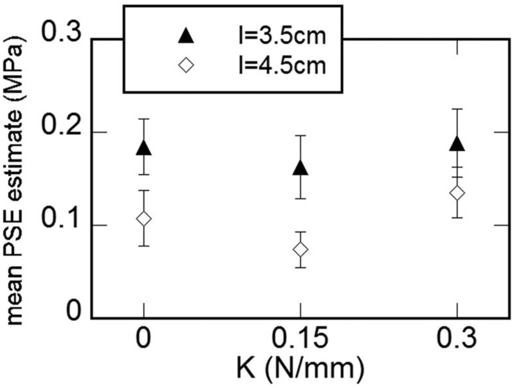


Fig. 17. $\hat{Y}_{cutaneous}$ derived from the results of Exp. 2 with Eq. (9). Error bars indicate the standard errors.

where $\hat{K}_{PSE}$ is the mean PSE estimate and $\widehat{\Delta l}$ is estimated with the mean penetration depth of the two fingertips in Exp. 2. It follows that $\hat{Y}_{cutaneous}$ is calculated by applying Eqs. (10) and (11) to Eq. (9). Fig. 17 shows $\hat{Y}_{cutaneous}$ calculated from the results of Exp. 2b. The result of a two-way repeated measure ANOVA with the factors $l$ and $K$ indicates a significant effect of $l$ [$\mathrm{F}(1,11) = 17.01, p = 0.002$, $\eta_p^2 = 0.61$] but not $K$ [$\mathrm{F}(2,22) = 2.46, p = 0.11$, $\eta_p^2 = 0.18$]. This means that $\hat{Y}_{cutaneous}$ varied with the change of the virtual object's thickness. A possible explanation can be found in the participants' behavior and their responses to virtual objects. Some participants commented that the hardness of virtual objects with $l = 3.5$ cm seemed to be attributable to the collision between the fingers. If a virtual object's stiffness is low and its thickness is small, collisions between the fingers may occur. This may have caused an additional bias in the perceived hardness of the virtual objects.

In a follow-up experiment, five additional naïve participants (23-32 years old) were asked to compare the perceived hardness of two virtual objects, one rendered with both cutaneous and kinesthetic (K+C) feedback and the other rendered with kinesthetic (K) feedback only. The participants described the K+C object as "a rubber ball with a rigid surface", "a soft baseball" or "a rubber-like object with a seed inside." They described the K type object as "a rubber block" or "a hard object," etc. They were also asked to describe the difference between the objects rendered with cutaneous (C) feedback and kinesthetic (K) feedback. The description of the K object was similar to that of the earlier comparison. The participants described the contact with the C object to be like "hitting the surface of water" and "touching fresh cream." The participants' descriptions of the C and K+C type objects indicate that they were indeed able to perceive the differences in hardness.

The experimental setup of this study used an arm support which allowed free motion of hand from the wrist to the fingers. Previous studies show that hand motion can affect the haptic perception of a virtual object's properties, including force direction and surface roughness [44], [45]. To see if the movement of hand affected the perception of a virtual object's hardness, we conducted another follow-up experiment with five participants (25-29 years old, who participated in Exp. 2b). They completed two experiments with procedures identical to those in Exp. 1a, with or without a wrist brace which restricted hand movement. A two-way repeated measure ANOVA for perceived hardness revealed a significant effect of virtual stiffness K ($\mathrm{F}(2,8) = 1.04$, $p = 0.007$, $\eta_p^2 = 0.72$) and no significant effect of experimental conditions ($\mathrm{F}(2,8) = 0.011, p = 0.92$, $\eta_p^2 = 0.003$). This reassured us that hand movement did not play a significant role in hardness perception in the present study.

While our results indicated that cutaneous feedback can affect human perception of hardness, one remaining issue was whether the use of a fixed virtual fingertip size may have affected the perception of hardness. To address this issue, the size difference between a participant's finger and a virtual finger model was translated into the corresponding shift of virtual surface position during haptic rendering. Considering a constant contact force tendency as observed in previous studies [42], [43], it seemed unlikely that the finger size difference affected the contact force. We therefore find it unlikely that the fixed virtual fingertip model could have significantly affected the trend found in the present study.

## 6 CONCLUSIONS AND FUTURE WORK

The present study investigated the human perception of a virtual object's hardness when cutaneous feedback was added to kinesthetic feedback. We proposed a cutaneous interface and rendering strategy to control the cutaneous feedback on a user's fingertip. Two experiments were conducted to investigate the effect of cutaneous feedback, one for one-finger touch and the other with a two-finger grip of virtual objects. A common trend of the results from the two experiments is that the addition of cutaneous feedback led to an increase in the perceived hardness of the virtual objects. Furthermore, changing the rate of cutaneous hardness $K_C$ significantly affected the perceived hardness at the virtual stiffness $K = 0.3$ and $0.5$ N/mm (Exp. 1). When a virtual object's hardness was perceived with a two finger grip, the effect of thickness was found to be significant when measured in stiffness and insignificant when it was converted to Young's modulus (Exp. 2). This implies that for the two-finger grip, the perceived hardness may be better characterized by the Young's modulus values.

The findings and the proposed rendering method in the present study are expected to contribute to the design of wearable haptic interfaces and their control. Since a virtual object can feel significantly harder with the addition of cutaneous feedback, a kinesthetic feedback interface does not necessarily need to exert a high torque. Consequently, the weight of the actuator can be reduced so that a wearable haptic system can become lighter. In addition, the stability issues that are often encountered for rendering highly stiff surfaces with kinesthetic feedback interfaces can be avoided with the addition of cutaneous interfaces.

Our approach and results can be compared to other studies that also provided hybrid haptic feedback to improve the perception or manipulation of virtual objects. Frisoli et al. showed that the addition of cutaneous feedback to kinesthetic feedback significantly improved the perception of virtual wall orientations [46]. Quek et al. demonstrated that the perceived stiffness felt via a tool can be significantly affected by the addition of lateral cutaneous and kinesthetic cues [27] [28]. It should be noted that the cutaneous feedback used in these studies and that in our present study has the same direction and orientation as force feedback. This implies that the use of hybrid haptic feedback needs to consider the accordance of cutaneous and kinesthetic feedback in terms of direction and orientation to maximize the effect of the augmented sensation.

The contribution of our proposed method can also be viewed in the applications of teleoperation and virtual and augmented reality (VR/AR) environments. In a tele-operated system, a communication delay or a packet loss can cause the system to become unstable at a high stiffness. There are various ways to preserve the passivity of the system, during which the transparency tends to be reduced or lost. Pacchierotti et al. demonstrated that the loss of transparency with a passivity controller can be restored with cutaneous feedback [21]. Alternatively, one can render a virtual surface with cutaneous feedback that matches that of a high-stiffness surface, given the results of the present study. Regarding a VR/AR application, the stiffness perception of a real object can be modulated with cutaneous interface worn on a user's fingertip [30], [47]. Our proposed method can also be used to enhance the perceived stiffness of a real object.

Several challenges remain for generalizing our experimental results. First, our experiments were conducted with parameters of limited ranges. The range of stiffness used ($K\colon 0 \sim 1\,\mathrm{N/mm}$) was typical for most of commercially available kinesthetic feedback interfaces, but further investigation will be necessary for high-force interfaces which can render higher stiffness. The same applies to the choice of $K_C$ (0.3, 1 and 3). While the addition of cutaneous cues had significant effects on the perception of hardness, the effect of choosing $K_C$ values lower than 0.3 or higher than 3 needs to be analyzed. Instead of the grounded kinesthetic interfaces used in the present study, we plan to integrate the cutaneous interface and rendering strategy of the present study into a glove-type haptic interface. The effect of cutaneous feedback will be further investigated in terms of other haptic interactions including the manipulation of virtual objects. Finally, we will continue to investigate the effect of various types of cutaneous cues including hardness and skin stretch on human perception of haptic properties.

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