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Compensation of Perceived Hardness of a Virtual Object with Cutaneous Feedback

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Abstract— **Wearable glove type haptic interfaces are often required to be light weight, which constrains the actuator to exert low torques. This causes a virtual object to feel compliant, reducing the range of presented surface properties. To overcome the limitation, we propose to compensate the hardness of a virtual object with cutaneous feedback. A cutaneous haptic interface is designed to present the hardness to a user's fingertip along with a force-feedback interface and the corresponding rendering strategy is proposed. Two experiments were conducted to evaluate the proposed approach for one-finger touch and two-finger grip for stiffness values under 0.3 N/mm. Experimental results indicate that the addition of cutaneous feedback led the virtual surface to feel significantly harder than the nominal stiffness felt by force-feedback alone. In addition, the perceived hardness was significantly affected by the rate of hardness rendered with cutaneous interface when the nominal stiffness was increased.**

I. INTRODUCTION

Recent advancement of vision and display technologies enables end users to experience more immersive virtual environment than ever. However, there is still a lack of available haptic interfaces that allow users feel virtual objects via the sense of touch with their hands. Most stylus/trackball type force-feedback interfaces are not appealing to the users due to their heavy weight and relatively small workspace. In contrast, wearable glove type force-feedback interfaces can avoid the problem of limited workspace since they are non-grounded. To remain light weight, glove type haptic interfaces should have not only light mechanism but also light-weighted actuators. However, such an actuator is capable of exerting a relatively small torque, which limits the surface stiffness of virtual objects. This will significantly reduce the reality and the range of virtual object's surface properties. We encountered this problem while working on a research program developing wearable haptic interfaces. We addressed the problem by providing cutaneous feedback along with force feedback [1].

Previous studies indicated that the hardness/compliance of virtual surface can be effectively represented when both kinesthetic and cutaneous information is available. As shown by Tan et al., humans can discriminate an object's compliance with two finger grip without cutaneous information on surface deformation [2]. Lawrence et al. proved that perceptual hardness can be effectively represented with the ratio of initial contact force and initial velocity when virtual surface is rendered with a force-feedback interface [3]. However, as Srinivasan and LaMotte demonstrated, neither kinesthetic nor cutaneous information is sufficient for haptic softness discrimination for objects with deformable surfaces [4]. Bergmann Tiest and Kappers also showed that the surface deformation of an object provides crucial information for haptic perception of compliance [5]. Therefore, for realistic and effective rendering of virtual object's hardness, not only kinesthetic but also cutaneous information needs to be provided to a user.

There have been constant attempts to develop haptic interfaces that effectively deliver cutaneous information to a user. Researchers including Frisoli and Prattichizzo have proposed a variety of haptic interfaces to present diverse tactile cues on the fingertips including contact location, orientation and force [6-8]. Bicchi et al. proposed a haptic interface that can render surface compliance of a virtual surface. They found that the addition of cutaneous compliance information can enhance softness discrimination [9]. However, it is hard to find studies that provided a solution to the aforementioned problem of compliant virtual surface by providing additional cutaneous feedback.

Previous studies showed that cutaneous cues significantly affect the perception of an object's surface properties. However, it is not yet clear whether the addition of cutaneous feedback would resolve the problem of less hard surface due to inadequate torque of a force feedback interface. Our first objective is therefore to investigate how the perceived hardness rendered with both cutaneous and force feedback is matched to that with only force feedback. 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 there is only force-feedback. 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 at the skin, the perception of surface hardness is presumably processed with contact area change given normal displacement [10]. Then if we can effectively change the rate of contact area increase [9] a user may perceive an object's surface as being harder. Thus, for the second objective, we hypothesize that the perceived hardness of virtual objects can be modulated by changing the rate of increase of contact area.

The rest of the paper is organized as follows. In the next section, we describe hardware and rendering strategy to present contact and hardness on the fingertip with cutaneous

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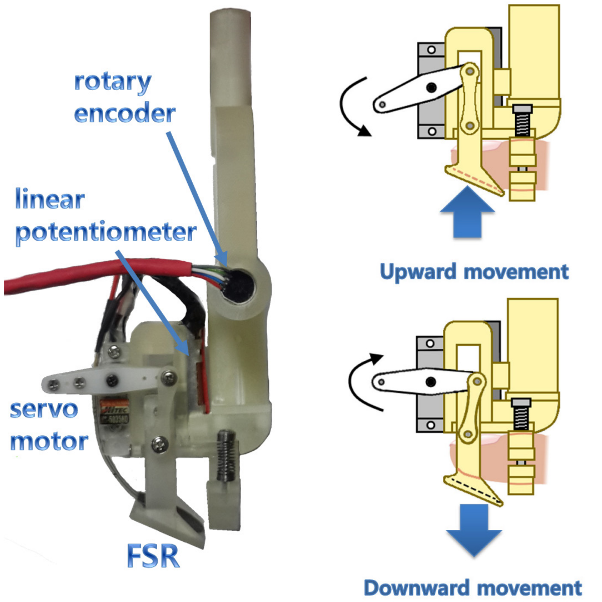
and force feedback. Next, the effect of cutaneous hardness is evaluated for one finger and two fingers with two psychophysical experiments. In the last section, we summarize our findings along with future work.

II. PRESENTING HARDNESS AT THE FINGERTIP WITH CUTANEOUS AND FORCE FEEDBACK

A. Hardware Setup

Fig. 1(a) shows a 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. Fig. 1(b) describes the upward and downward movement of the plate with the rotation of the motor to increase or decrease the contact area at the fingertip. The motor's nominal maximum force is 8 N (model HS-5035HD, Hitec RCD Korea Inc., Korea) and the weight of the cutaneous interface is 28 g. A force sensing resistor is attached on 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.



(a) Profile of the cutaneous hardness interface.

(b) Upward movement of contact plate to increase contact area (top) and downward movement to decrease contact area (bottom).

Figure 1. Profile of the cutaneous contact hardness interface and description of control scheme to increase/decrease contact area.

The cutaneous interface is designed to be installed on commercially available force-feedback interfaces, PHANToM Premium and Touch (3D Systems Inc., SC, USA). Then, a user can feel a virtual object's surface hardness by both cutaneous and kinesthetic feedback. For installation of on a PHANToM Premium, the cutaneous interface is attached to a link with 1-DOF rotation (Fig. 1 (a)), which is read by a miniature magnetic rotary encoder with an accuracy of $\pm 0.3°$ (RM08, RLS, Slovenia). The weight of the cutaneous interface with the link is 46 g.

B. Rendering of Surface Hardness

In this subsection, we describe haptic rendering scheme of hardness 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. A minimum distance finding scheme is used to track the contact point between the fingertip avatar and a virtual plane. For this paper, we only consider the contact between a curved fingertip surface and a virtual plane. Then, the minimum distance point relation between two surfaces [11] reduces to the following form:

$$\boldsymbol{F}(u,v) = \begin{bmatrix} A(u,v)_z \left(\frac{\partial A(u,v)}{\partial u}\right)_z \\ A(u,v)_z \left(\frac{\partial A(u,v)}{\partial v}\right)_z \end{bmatrix} = \boldsymbol{0} \tag{1}$$

where an x-y plane is assumed for the virtual plane ($0 \le u,v \le 1$) and z denotes the z-axis component. The minimum distance point on the fingertip $\boldsymbol{x}_f$ is readily tracked with a Newton's method,

$$\boldsymbol{x}_{f,i+1} = \boldsymbol{x}_{f,i} - \boldsymbol{J}^{-1}(u,v)\boldsymbol{F}(u,v) \tag{2}$$

where $\boldsymbol{J}(u,v)$ is the Jacobian of $\boldsymbol{F}(u,v)$ [12]. 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 by using a typical spring model:

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

where K denotes the stiffness of the virtual plane.

For the rendering of contact hardness with the cutaneous interface, the contact plate is first moved downward until it barely touched the fingertip at the beginning of an experiment. Then the plate is moved upward until a contact is sensed by a force sensing resistor. Let the displacement at the contact be denoted as d_c. Then, the reference position of the contact plate d_{ref} is decided as:

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

where K_C defines the virtual hardness by the cutaneous interface. We call this parameter the *rate of* cutaneous *hardness*. Then the contacting plated is moved to the reference position by a PID controller ($\tau_{out} = \left(K_p + \frac{K_i}{s}\right)\left(d_{ref} - d\right) - K_d s l$, 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 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 [13], 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 (ω) follow the relation:

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

where $E^*$and R denote Hertz elastic modulus and the sphere radius, respectively [14]. By combining (4) and (5), when there is a contact between a virtual fingertip and the plane, contact area becomes

$$A = \pi R\omega = \pi R(cos\theta_c K_C|\boldsymbol{x}_p - \boldsymbol{x}_f|) \qquad (6)$$

where θ_c is the tilting angle of the contact plate. 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.

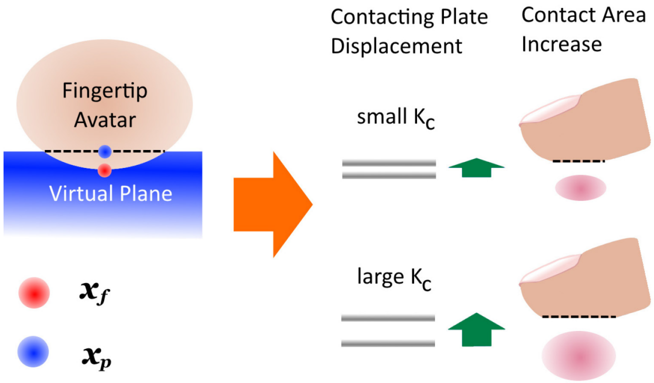


Figure 2. The effect of the rate of cutaneour hardness K_C. Given the same penetration depth, a larger K_C will result in a larger displacment of the contact plate and a larger increase of the contact area.

III. EXPERIMENT I: EFFECT OF CUTANEOUS FEEDBACK ON HARDNESS PERCEPTION FOR ONE-FINGER TOUCH

The goal of Experiment 1 is to examine the effect of cutaneous feedback on the perception of hardness for one finger touch. The virtual stiffness values K were chosen to be less than 0.3 N/mm to see if the cutaneous feedback can enhance the perception of hardness for force-feedback interfaces that cannot exert a large torque. The experiment protocol was approved by the Korea Institute of Science and Technology IRB.

A. Methods

Participants

Twelve participants (2 females; 22-37 years old, average 28.3 years) were recruited for this experiment. All participants gave signed consent. None of them had any known problem with their sense of touch. All but one participant were right-handed by self-report.

Stimuli

Stimuli for the experiments were virtual transverse planes whose surface hardness was defined by K_C and K for cutaneous and force 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). There was no cutaneous but only force feedback for the comparison stimuli.

Procedure

A one-up one-down adaptive procedure was employed to match the perceived hardness of a virtual plane rendered with both cutaneous and kinesthetic feedback to that rendered only with kinesthetic feedback [15]. For each reference stimulus, a point of subjective equality (PSE) for perceived hardness was estimated by varying the stiffness of comparison stimuli using 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 by the reference stimuli (2 K_C × 3 K). The order of reference stimuli was randomized for each participant. On each trial, participant was presented with two virtual planes: a reference plane rendered both with cutaneous and kinesthetic feedback and a comparison plane rendered only with force feedback. If the participant responded that the reference plane felt harder than the comparison plane, the stiffness of the comparison plane was decreased. Otherwise, the stiffness of the comparison plane was increased. 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.

Fig. 3 shows the profile of experiment 1 setup. At the beginning of each experimental run, a participant was seated in front of the experiment 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. S/he also put on noise cancelling 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 to the haptic interface. The participant's hand was covered with a cloth to block possible visual cues.

Prior to the main experiment, the participant pushed his/her finger downward to feel the hardness of virtual planes rendered with cutaneous and force feedback or only with force feedback during a training session. Virtual fingertips were visually displayed along with the virtual plane. When the participant felt ready for the main experiment, the training was terminated.

In the main experiment, the order of reference and comparison planes was randomly decided on each trial. At the beginning, a virtual fingertip was displayed on the screen along with a horizontal line indicating the virtual plane. Then, 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 on 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. By hitting the enter key, the participant moved to the next phase to feel the other stimulus. Then, the participant was asked to indicate which stimulus felt harder. The answer, collision depth and trial time were recorded for each trial. After each run, the participant took a 5-min break.

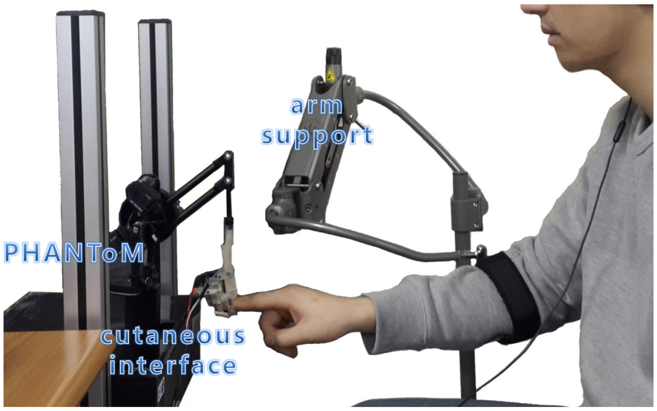


Figure 3. The profile of experiment 1 setup. An index finger is inserted inside the haptic interface and the arm is rested on an anti-gravity arm support. The participant wears noise cancelling headphones to minimize audio cues.

After the completion of all the experimental runs, the participant was prompted to feel three additional virtual surfaces for three (K_C, K) pairs: (3, 0), (0, 0.3) and (3, 0.3), which presented cutaneous feedback, force-feedback and cutaneous & force-feedback, respectively. Then the participant was asked to rate the realism of each stimulus on a 5-point Likert scale. It took approximately 1 hour and 20 minutes for each participant to complete the six runs of the experiment.

Data Analysis

For each experimental run, the PSE was calculated from the peak and valley values of K over the 12 reversals at the smaller step size. Then the mean of 6 peak-valley pairs was taken to estimate the PSE of K estimated for each (K_C, K) pair for the reference stimulus of each run.

B. *Results*

In Fig. 4, the mean PSE estimates for (K_C, K) reference stimulus pairs are plotted against the virtual surface stiffness K. To see the effect of cutaneous feedback, PSE estimates were compared to the K's of the reference stimuli by one-sample t-test with the null hypotheses $\mu_{PSE} = K$. The result indicated significant difference for all the (K_C, K) from K (t(11)=4.21, p=0.001 for (1, 0); t(11)=3.78, p=0.003 for (1,0.15); t(11)=5.16, p<0.001 for (1,0.3); t(11)=4.15, p=0.002 for (3, 0); t(11)=4.92, p<0.001 for(3,0.15), t(11)=3.73, p=0.003). This means that with the addition of cutaneous feedback, the participants felt the virtual surface to be harder than the virtual plane with the same nominal K rendered with kinesthetic feedback alone. To see the effect of the rendering of cutaneous feedback on the perception of hardness, a two-way repeated measure ANOVA was performed (K_C and K are within factors). A significant interaction between the two factors was found (F(2,22)=3.94, p=0.034, η_p^2=0.27). Simple main effects analysis showed that for K=0.3 N/mm, the virtual surface felt harder (p=0.027) with K_C=3 than 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 differences among K when K_C=1 (p=0.603). Therefore, the virtual surfaces felt harder with a larger K_C for the high K value.

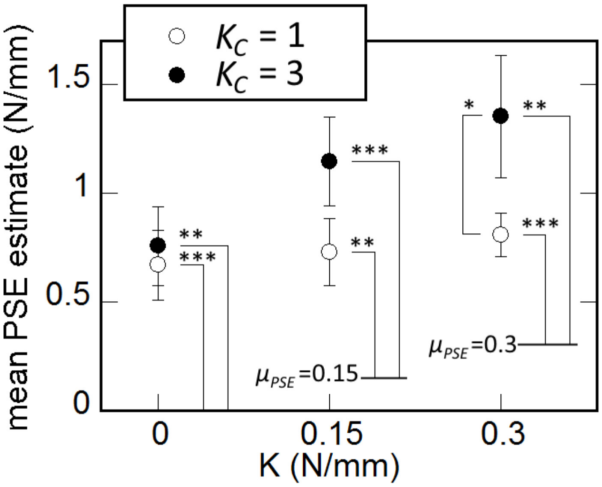
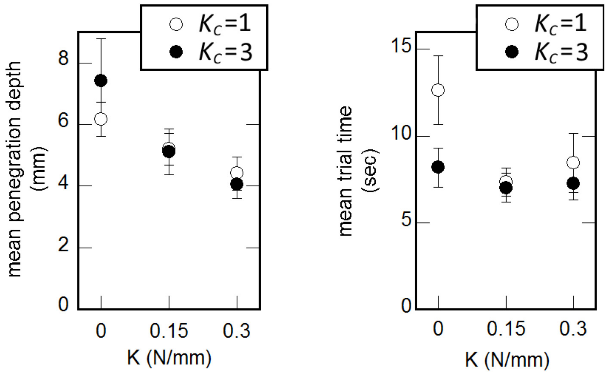


Figure 4. Mean estimated PSE of perceived hardness by (K_C, K) in Experiment 1. Error bars indicate the standard errors.

Fig. 5(a) shows the mean penetration depth for (K_C, K) pairs plotted against the virtual surface stiffness K. When a two-way repeated measure ANOVA was conducted with as within factors of K_C and K, a significant main effect was found for K (F(2,22)=22.94, p<0.001, η_p^2=0.68) and the effect of K_C was insignificant (F(1,11)=3.82, p=0.076, η_p^2=0.26). In a subsequent Tukey test, mean penetration depth was grouped together for K=0.15 and 0.3 N/mm, indicating decreasing trend with the increase of K. In Fig. 5(b), the mean trial time for (K_C, K) is plotted against the virtual surface stiffness K. There was a significant interaction between the two factors (F(2,22)=4.28, p=0.027, η_p^2=0.28). The result of simple main effects analysis indicated that there was a significant difference (p=0.004) in the trial time between the two K_C values when K = 0 N/mm.



(a) Mean penetration depth (b) Mean trial time

Figure 5. Mean penetration depth and mean trial time by (K_C, K) in Experiment 1. Error bars indicate the standard errors.

Table I shows the result of the subjective ratings of rendering method at the end of the experiment. The participant rated the virtual surface rendered with both cutaneous and force feedback significantly higher than the one rendered with cutaneous feedback alone.

TABLE I. RATING OF RENDERING METHODS IN TERMS OF REALISM (5-POINT LIKERT SCALE: POINTS 1-5)

Type of stimulus	Mean	SD
cutaneous feedback	2.75	0.94
force feedback	3.46	0.5
cutaneous & force feedback	3.92	0.63

IV. EXPERIMENT II: EFFECT OF CUTANEOUS FEEDBACK ON HARDNESS PERCEPTION FOR TWO-FINGER GRIP

The goal of Experiment 2 is to examine the effect of cutaneous feedback on the perception of hardness for two-finger grip. The same values of the parameters K_C and K as in Experiment 1 were used.

A. Methods

Participants

Ten subjects (2 females; 22-37 years, average 27.6 years) who participated in Experiment 1 took part in this experiment. All the participants were right-handed by self-report.

Stimuli

Stimuli for the experiment were virtual objects whose surfaces represented two sagittal planes separated by 4.5 cm (see Fig. 6). The hardness of the planes for reference stimuli was tested at the same combination of K_C (1 and 3) and K values (0, 0.15 and 0.3 N/mm) as in Experiment 1.

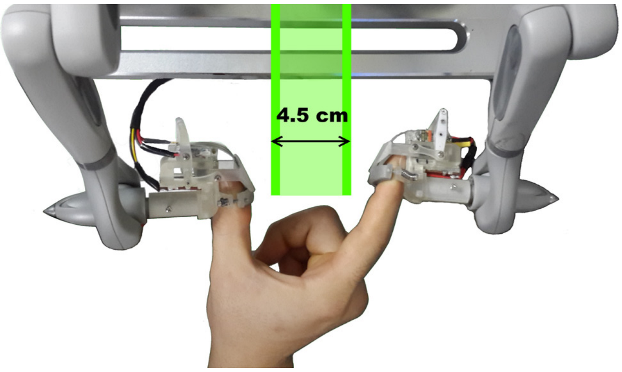


Figure 6. Experimental apparatus (two Touch force feedback interface with cutaneous interfaces attached at the two end effectors.). The stimulus consists of two parallel sagittal planes (colored in green).

Procedure

Experimental apparatus was built by combining two Touch force-feedback devices on whose endings the cutaneous interfaces were installed (Fig. 6). At the beginning of the experiment, a participant was instructed to insert his index finger and thumb of the dominant hand inside the thimbles of the cutaneous interfaces. To feel the hardness of a virtual object, a participant was asked to first hold apart his/her thumb and index finger and then squeeze them. Once one of the fingertips was as close as 5 mm to a surface plane of the virtual object, haptic feedback was initiated. A one-up one-down adaptive procedure 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.

B. Results

In Fig. 7, the mean PSE estimates for (K_C, K) reference stimulus pairs in Experiment 2 are plotted against the virtual surface stiffness K. When PSE estimates were compared to the K's of the reference stimuli by one-sample t-test (H_0: $\mu_{PSE} = K$.), significant differences were found for all the (K_C, K) pairs (t(9)=3.61, p=0.01 for (1, 0); t(9)=3.6, p=0.01 for (1,0.15); t(9)=3.83, p=0.004 for (1,0.3); t(9)=2.71, p=0.02 for (3, 0); t(9)=2.84, p=0.02 for(3,0.15), t(9)=3.05, p=0.01). A significant interaction between the two factors was also found (F(2,18)=6.12, p=0.009, η_p^2 =0.41). Simple main effects analysis showed that for K=0.3 N/mm, the virtual surface felt harder (p=0.04) with K_C=3 than K_C=1 and no difference was found for K=0 or 0.15 N/mm. The perception of hardness was significantly affected by K for both K_C values (p=0.025 for K_C=1; p=0.00f for K_C=3). Overall, the virtual surfaces tended to feel harder with a larger K_C as K increased.

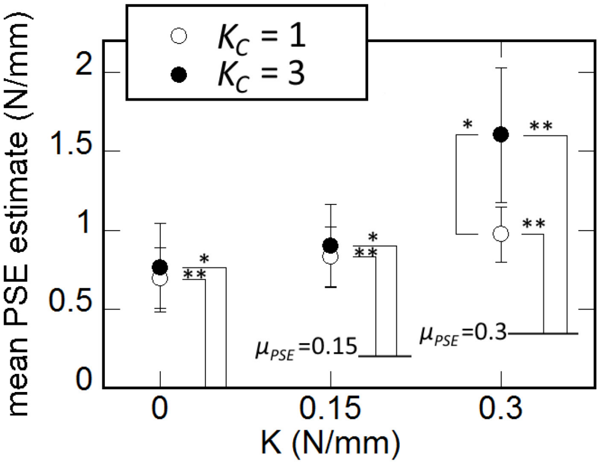
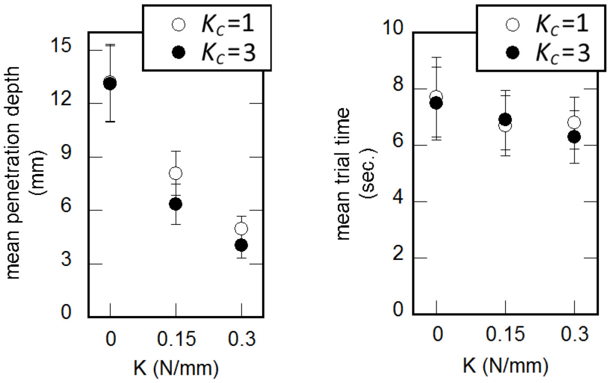


Figure 7. Mean estimated PSE of perceived hardness by (K_C, K) in Experiment 2. Error bars indicate the standard errors.



(a) Mean penetration depth (b) Mean trial time

Figure 8. Mean penetration depth and mean trial time by (K_C, K) in Experiment 2. Error bars indicate the standard errors.

In Fig. 8 (a), the mean penetration depth for (K_C, K) pairs in Experiment 2 are plotted against K. The result of two-way repeated measure ANOVA indicated a significant main effect of K (F(2,18)=24.38, p<0.001, η_p^2=0.73) while the effect of K_C

was insignificant (F(1,9)=0.49, p=0.5, η_p^2=0.05). The result of a Tukey post-hoc test indicated that mean penetration depth was grouped together for K=0.15 and 0.3 N/mm. Fig. 8(b) shows the mean trial time for (K_C, K). No significant effect was found for either K (F(1,9)=0.29, p=0.6, η_p^2=0.03) or K_C (F(2,18)=1.32, p=0.3, η_p^2=0.13).

V. CONCLUDING REMARKS

The present study investigated the effect of adding cutaneous feedback to force feedback on the perception of virtual surface hardness. We were particularly interested in how the perceived hardness with cutaneous and force feedback is matched to that with force feedback alone when the torque exerted by a force feedback interface is limited. A cutaneous interface was designed to render the hardness of virtual surfaces and an accompanying hardness rendering scheme was proposed. Two experiments were conducted for one-finger touch and two-finger grip to examine the hardness matching relation. The results of the two experiments showed a common trend that with cutaneous feedback, the hardness of a virtual plane was perceived to be significantly higher than that rendered by force-feedback alone. Also, the perception of hardness was significantly affected by the rate of cutaneous hardness as the normal hardness by force-feedback was increased.

One important finding of the experimental results is the significant shift of perceived hardness to larger values with the addition of cutaneous cues. Part of this can be explained with the optimal integration model suggested by Ernst and Banks for multimodal sensory integration [16]. Let the estimate of hardness be a combination of purely cutaneous sensation and kinesthetic sensation. (Note that the purely cutaneous sensation of hardness is different from that of our experiment condition (K_C, K) = {(1, 0), (3, 0)}, where kinesthetic cues were available as finger position information.). If the perception of hardness follows the maximum likelihood estimation rule, it will be represented as a weighted sum of the hardness estimated by cutaneous and kinesthetic cues ($\hat{S}_{hardness} = w_C\hat{S}_C + w_K\hat{S}_K$). Assuming $\hat{S}_C > \hat{S}_K$, the combined probability density for perceived hardness will shift towards a larger PSE than that of $\hat{S}_K$ as shown in Fig. 9 ($\hat{S}_{hardness} > \hat{S}_K$). Thus, the perceived hardness will be matched to a larger K with the addition of cutaneous cue than that with force feedback alone. The variation of the mean PSE estimates between the two K_C values per K value implies that the relative weights of the cutaneous and kinesthetic cues vary as K changes.

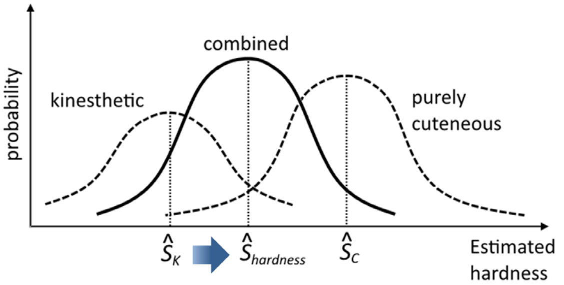


Figure 9. Shift of estimated hardness with the addition of cutaneous cues to kinesthetic cues.

The approach proposed in the present study can be exploited by a wearable haptic interface to create the effect of touching harder surfaces even when the actuators can only exert relatively low torques. Future work will further investigate the effect of cutaneous information on the perception of hardness for K values of reference stimuli larger than 0.3 N/mm. In addition, the effect of cutaneous cues will be examined for cutaneous K_C values less than 1 to achieve a more general relation between the perceived hardness and (K_C, K). Furthermore, the rendering method proposed in this study will be compared to another method using Young's module that's known to characterize human perception of hardness better than stiffness [5].

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