Haptic Perception of Edge Sharpness in Real and Virtual Environments

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Abstract—We investigate the accuracy with which the haptic sharpness perception of a virtual edge is matched to that of a real edge and the effect of the virtual surface stiffness on the match. The perceived sharpness of virtual edges was estimated in terms of the point of subjective equality (PSE) when participants matched the sharpness of virtual edges to that of real edges with a radius of 0.5, 2.5, and 12.5 mm over a virtual stiffness range of 0.6 to 3.0 N/mm. The perceived sharpness of a real and a virtual edge of the same radius was significantly different under all but one of the experimental conditions and there was a significant effect of virtual surface stiffness on the accuracy of the match. The results suggest that the latter is presumably due to a constant penetration force employed by the participants that influenced the penetration depth and perceived sharpness of virtual edges at different surface stiffness levels. Our findings provide quantitative relations for appropriately offsetting the radii of virtual edges in order to achieve the desired perceived sharpness of virtual edges.

Index Terms—Perception and psychophysics, tactile display, virtual reality

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1 INTRODUCTION

The present study is a part of an ongoing research program to develop a tactile display that can render cutaneous contact information on the fingertip when used to augment a force feedback device. A contact location display (CLD) [1] is mounted on a commercially available PHANToM force-feedback device to form a CLD system that provides a user with both cutaneous and kinesthetic information when interacting with a virtual environment. The user can feel the sensation of touching a virtual object at the fingertip with contact location information and kinesthetic cues provided by the CLD unit and the force-feedback device, respectively.

Despite progresses of haptic technologies, there still remain obstacles in creating realistic virtual objects. Many haptic interfaces are still limited in their abilities to render realistic representations of virtual surface properties. For example, the stiffness of a wood surface is calculated as 10^6 N/mm, which is significantly higher than the maximum stiffness of most commercially available haptic interfaces nowadays [2]. Also, haptic rendering methods often do not strictly follow contact mechanics, for the sake of computational efficiency. For instance, the popular proxy model for haptic rendering does not follow the Hertzian contact models in calculating contact forces with spring-damper models [3], [4]. These technical limitations can cause the haptic perception of a virtual object to be different from that of a real object. Previous studies comparing the perception of virtual and real objects have shown that the parameter values at which to match the perception of virtual and real objects are not necessarily identical (e.g., [5], [6]). This motivates us to investigate the matching relation (i.e., accuracy) between the perception of virtual and real objects using the CLD system in order to render realistic-feeling virtual objects that are quantitatively accurate in terms of perceived physical properties.

Among various surface features of an object, curvature is known to provide crucial geometric information in haptic shape perception, as demonstrated by van der Horst and Kappers [7]. However, there is limited information on how the perception of virtual object's curvature is matched to that of a real object, especially with high curvatures. Major concerns of most previous studies on haptic perception of virtual curvature were on identifying the information affecting haptic curvature perception [8], [9], [10], [11]. The haptic interfaces in the studies provided users with contact orientation information by tilting flat plates to render virtual curvatures, which were supposed to range around relatively lower values (~ 13 m^{-1}). Additional efforts are therefore necessary to gain insights for the perception of sharper curvatures.

In evaluating the human haptic perception of surface properties of virtual objects, the local surface stiffness can play an important role. When the traditional penalty-based haptic rendering technique ([3], [12]) is utilized, the surface stiffness can affect the position difference of the virtual proxy from the haptic interface and thus the perception of the virtual object. For example, Choi et al. demonstrated that variation of surface stiffness influences the perception of the surface geometry of a virtual object [13]. Yoon et al.

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showed that the variation of surface stiffness can affect haptic perception of concave shaped curvatures [14]. Therefore, any study of the matching of virtual and real objects needs to take into account the effect of surface stiffness on the perception of virtual objects.

The hand used to feel a virtual object may also affect human haptic perception of the object's surface property. Lederman et al. showed that handedness did not result in a significant difference in haptic perception of texture [15]. Likewise, Kappers and Koenderink demonstrated that there is no significant difference in haptic curvature perception between dominant and non-dominant hands [16], [17]. However, Tomlinson et al. showed that handedness affected haptic perception of centeredness judgement [18]. Thus, care should be taken for whether the hand used to feel the stimuli is dominant or non-dominant for a rigorous evaluation of haptic perception.

The addition of cutaneous feedback to force-feedback is found to improve haptic perception and manipulation of virtual objects. Frisoli et al. demonstrated that the addition of cutaneous information improved the perception of a virtual object's surface orientation [19]. In a study by Minamizawa et al., the addition of a slip display to a fingertip force feedback display resulted in improved perception of virtual objects' weight [20]. Pacchierotti et al. conducted a peg-in-hole experiment with a two-finger grip haptic system where a 3-DOF cutaneous display was incorporated into a force-feedback device [21]. The experimental condition with both cutaneous and force feedback resulted in an improved task completion time as compared to the condition with force feedback only. Kuchenbecker et al. conducted an experiment with the CLD system for a contour following task, which is known to provide information on an object's shape [22], [23]. The results indicate that contact location information resulted in a significant decrease in task completion time.

There have been a series of studies that utilized the CLD system to evaluate its effectiveness in haptic rendering of virtual objects. In the first study with the CLD system, human curvature discrimination thresholds were measured with virtual and real curvature models. The results indicate that human discrimination thresholds for virtual curvatures are comparable to those for real curvatures [1]. We continued to study the mechanism for discrimination of virtual curvatures rendered with the CLD system and found that the discrimination of virtual edge sharpness/curvature is mainly due to the kinesthetic cues from the force-feedback device [24], [25]. We verified that the contact location information alone can also deliver sharpness information to a user but it is dominated by the force cues when presented with the force-feedback information. One known advantage of the CLD system lies in assisting a user with contour following as shown in an early study [22]. We also studied the detection of small surface features during a contour following task with the CLD system and found that the contact location information is useful for detecting small surface features [26].

In the present study, we investigate the extent to which the haptic sharpness perception of a virtual edge rendered by the CLD system is matched to that of a real edge. Our objectives are to i) derive the relation between perceived sharpness of virtual and real edges; and ii) study the effect of virtual surface property, namely surface stiffness, on the matching relation. For the first objective, we hypothesize that a virtual edge's perceived sharpness may not necessarily be matched to that of a real edge with the same nominal dimension. For the second objective, we hypothesize that the perceived sharpness of virtual edges may be affected by the surface stiffness since penetration depth is affected by the surface stiffness which in turn influences the kinesthetic information received by the user. The relation between perceived sharpness of virtual and real edges was measured for real objects whose radii ranged between 0.5 and 12.5 mm. The smaller radius of 0.5 mm was chosen to be significantly less than the size of a fingertip, down to the level of micro texture [27]. The larger radius of 12.5 mm was chosen to be around the size of a fingertip. Since the effect of the contact location information on the perception of curvature for varying surface stiffness was not well established, the relation was derived under the condition where both contact location and kinesthetic information was available.

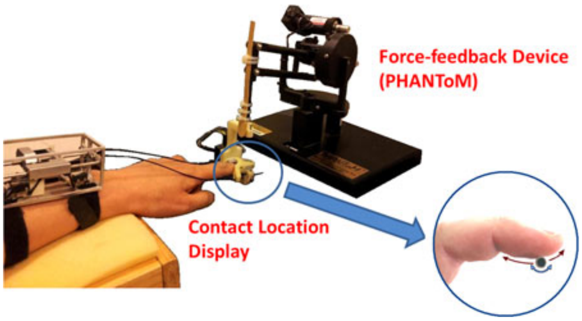


Fig. 1. The CLD system used for the experiment. A roller suspended beneath the fingertip provides the contact location information and a force feedback device provides the kinesthetic cues to a user.

The remainder of this paper is organized as follows. The next section presents the general methods for the experiments. The results from the experiments are shown in Section 3. In the last section, we discuss the implications of the results.

2 GENERAL METHODS

2.1 Apparatus

Fig. 1 shows the CLD system that was used to render virtual edges. The system consists of a commercially available PHANToM for force-feedback and a 1-DOF CLD unit for tactile feedback of contact location information. The contact location information is delivered to a user by the relative movement of a roller suspended beneath the fingertip. When the user's fingertip comes in contact with a virtual object, a cylindrical roller suspended beneath the fingertip is moved to touch the fingertip at the contact location. The roller position is controlled by a pair of push-pull wires whose endings are connected to a linear actuator (see Fig. 2). A DC motor (1724-024S, Faulhaber, Germany) is used to drive the linear actuator, and is controlled by a PID controller. More details of the CLD system can be found in [1].

For the real curved edges, two rigid samples were made with an Eden 260 V Objet 3D printer (Stratasys, Ltd., MN, U.S.A.) using VeroWhitePlus material (modulus of elasticity, 2~3 GPa). Each real edge consists of two parts, an upper edge with a radius of 0.5, 2.5 or 12.5 mm and a common base (see Fig. 3). A pair of foot switches was used by the participants to provide responses during the experiment.

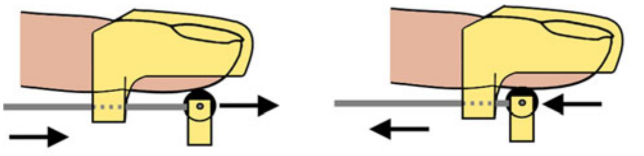

(a) Forward movement of the contact location (b) Backward movement of the contact location

Fig. 2. Control of the contact location by a pair of push-pull wires. (a) Forward movement of the contact location by pushing the wires forward. (b) Backward movement of the contact location by pulling the wires backward.

2.2 Haptic Rendering

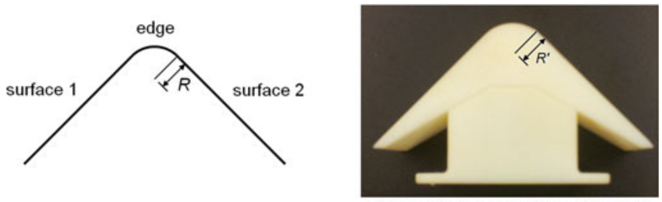
Haptic rendering for the present study followed the method described in [24]. The virtual space was divided into three regions around the virtual edge to find the most likely contact point vector on the fingertip ($\boldsymbol{x}_f$). The concept of a virtual proxy proposed by [3], [28] was used to provide a constraint for the proxy to stay on the surface of a virtual object during interaction. Once a collision is detected between the fingertip and a virtual object, the contact force was calculated by the following equation:

$$\boldsymbol{F} = K(\boldsymbol{x}_p - \boldsymbol{x}_f), \tag{1}$$

where $\boldsymbol{x}_p$ is the proxy position and also the most likely point of collision on the object surface; $\boldsymbol{x}_f$ is the most likely contact point on the fingertip; and K is the stiffness of the virtual surface whose value is between 0.6 and 3.0 N/mm. The target position of CLD's roller was set to $\boldsymbol{x}_f$. More details of the haptic rendering method can be found in [24]. The minimum and maximum of the lower four stiffness values, 0.6 and 1.8 N/mm were chosen from pilot experiments that determined the stiffness values for an object to feel soft and stiff enough, respectively. The highest virtual stiffness value of 3.0 N/mm was added later to determine if the matching accuracy at the lower four values would continue when the virtual stiffness is set at a higher value. This stiffness value was picked from our previous experiment for rendering an object as stiff as possible [24].

2.3 Stimuli

Virtual stimuli for the present study consisted of the 2D profile of a cylindrical edge adjoining two flat surfaces (see Fig. 4a). The projection of the edge was rendered as a circular arc occupying 90°, and that of the two surfaces as straight lines. The radius of the edge (R) varied from 0 to 80 mm. The top of the virtual edge was set at a constant height regardless of the radius.



(a) a virtual edge with radius R (b) a real edge specimen with edge radius R'

Fig. 4. 2D profiles of (a) a virtual edge with radius R and (b) a real edge with radius R'.

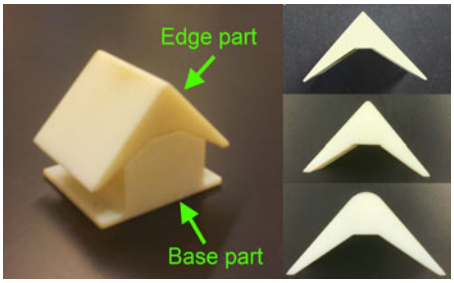


Fig. 3. (Left) The real edge sample consists of a top edge part with the desired radius and a bottom base part for support. (Right) Three edge parts with three different edge radii were fabricated for the experiments.

The real stimuli for the present study were real edge samples introduced in the previous section. The upper edge part of the real object was 3D-printed to have the same 2D profile as the virtual object (see Fig. 4b). The projected 2D arc portion of the real edge had a fixed radius R' that was either 2.5 or 12.5 mm. The height of the real edge's apex was fixed to be 45 mm from the base.

2.4 Procedures

A one-up one-down adaptive procedure was employed to match the perceived sharpness of a virtual edge to that of a real edge [29], [30]. For each real object, a point of subjective equality (PSE) was estimated by using the real edge as the reference and varying the virtual edge's sharpness (i.e., the radius R) using the adaptive procedure. The estimated PSE thus provided a measure for the virtual edge's radius that felt equivalent to that of the real edge in perceived sharpness.

On each trial of the experiment, the participant was presented with one real and one virtual edge. If the real edge felt sharper than the virtual edge, the radius of the virtual edge was decreased. Otherwise, the radius of the virtual edge was increased. After the first three reversals, the step size was changed to a smaller value. The larger initial step size facilitated a faster convergence and the smaller step size improved the precision of the PSE estimates. Each experimental run was terminated after 12 reversals at the smaller step size. The number of trials in each run ranged from 15 to 40 trials. An example of the virtual edge radii by trial number during one run of trials is shown in Fig. 5. The participant was asked to repeat a run if the data failed to converge as judged by the experimenter.

Training was available at the beginning of each run to familiarize the participants with the virtual edges. During

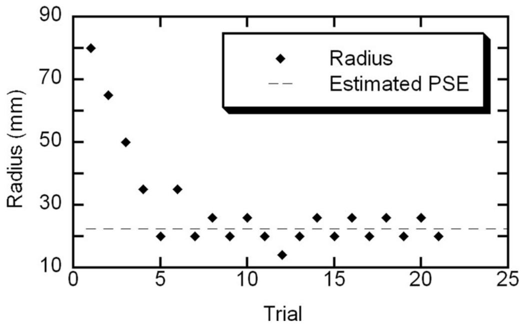


Fig. 5. An example run of the one-up one-down adaptive procedure. The filled diamonds represent the virtual edge radius for each trial and the dashed line indicates the estimated PSE value.

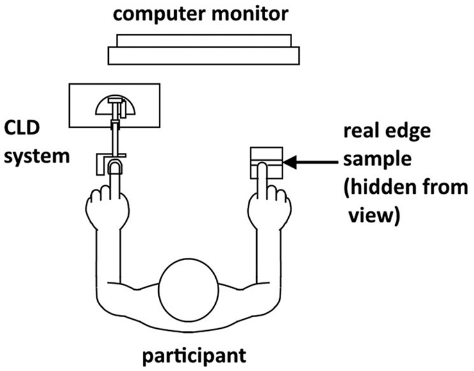


Fig. 6. Top view of the experiment setup for feeling the real and virtual edges simultaneously.

the training, the participant could see and feel the virtual edges by varying the edge's radius but was not allowed to feel the real edge sample. The training was terminated when the participant was ready.

Once the main experiment started, the participant was allowed to feel the real edge with the index finger of one hand and feel the virtual edge with the CLD system installed on the index finger of the other hand (see Fig. 6). The real edge was hidden inside a box to block any possible visual cue. The participant was asked to move the left and right fingers as synchronously as possible to feel the virtual and real edges simultaneously.

At the beginning of each trial, a virtual finger indicating the participant's the CLD installed index finger position appeared on the screen along with a horizontal line to indicate where the virtual finger should be. Once the virtual finger was above the horizontal line, a green dot located at the top of the virtual edge appeared and the participant was asked to move the virtual finger towards the green dot. Once the distance between the virtual finger and the green dot was less than 2 mm, all visual cues on the screen including the virtual finger, virtual edge and horizontal line disappeared. Thus, the participant perceived the virtual edge through the sense of touch alone. The participant judged the relative sharpness of virtual and real edges. S/He was instructed to press on the foot switch on the side of the CLD system if the virtual edge felt sharper, and to press on the foot switch on the side of the real sample if the real edge felt sharper. The radius of the virtual edge was then increased or decreased, respectively. Whenever a participant pressed a foot switch, an audible tone was heard through the earphones to confirm the participant's response. The values of the virtual radius and the participant's response were recorded for each trial. In addition, the proxy position x_p, the most likely contact point on the fingertip x_f, and the collision depth were recorded at a rate of 40 Hz.

The participant was asked to wear earphones and circumaural headphones (Peltor, with a nose reduction rating of 30 dB) over the earphones to block possible audio cues or noise from the haptic devices. The participant's hand with the CLD device was covered with a black cloth to block possible visual cues. The real edge sample was also hidden from the view in a box. After each run, the participant took a 5-min break. The experiments followed protocols approved by the Purdue University IRB.

2.5 Data Analysis

For each participant and each run, the estimated PSE was calculated from the peak and valley virtual radius values over the last 12 reversals at the smaller step size. Six PSE values were estimated by averaging the six pairs of peak/valley radius values for the 12 reversals. The mean and the standard error for the PSE were calculated from the six PSE estimates.

3 RESULTS

In this section, we first present the results of a preliminary experiment where we examined the effect of handedness in the perception of real and virtual edge sharpness. We then present the main results that establish the relation for matching the perceived sharpness of virtual edges to that of real edges. Finally, we present additional data that extend the relation to a wider range of curvature by including a smaller edge radius of 0.5 mm.

3.1 Preliminary Results: Effect of Handedness in Edge Sharpness Perception

Five male participants took part in the psychophysical experiment. None of them had any known problem with their sense of touch. All were right handed by self-report. Each participant conducted two experimental runs by switching the hands used to touch the virtual or real edges. Only the 2.5 mm radius real edge was used. The order of the hand used to feel the virtual edges was randomized for each participant. The initial radius of the virtual edge was 30 mm and the step size was changed from 5 to 2 mm after the first three reversals.

The PSE estimates averaged 14.02 ± 9.49 mm and 17.93 ± 10.25 mm for the left and right hands to feel the virtual edges, respectively. When a pairwise t-test was conducted for the estimated PSE values, no statistically significant difference between the left and right hands was found ($t(4) = 1.45$, $p = 0.22$). Therefore, we conclude that handedness does not significantly affect edge sharpness perception, and do not include it as a factor in the main experiment.

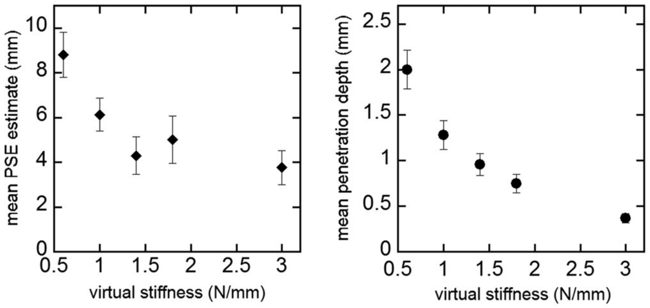
3.2 Main Results: Relation for Matching Virtual Edge Sharpness to Real Edge Sharpness

The goal of the main experiment was to derive a linear relation between perceived sharpness of virtual and real edges and to assess the effect of surface stiffness on the matching relation.

3.2.1 Methods

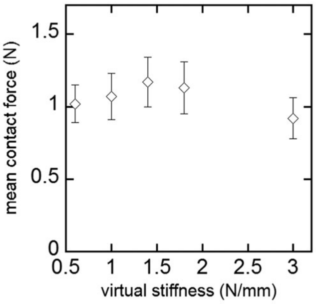
Twelve participants (6 females, 28 to 35 years old) took part in the experiment. None of them had any known problem with their sense of touch. All were right handed by self-report.

The experiment consisted of two sessions for two radius values of real edges: 2.5 and 12.5 mm. A half of the participants were randomly assigned to be tested with the 2.5 mm radius edge first, while the other half were presented with the 12.5 mm radius edges first. Each session consisted of five runs where the stiffness of the virtual edge was set to one of five values: 0.6, 1.0, 1.4, 1.8 or 3.0 N/mm. The order of the virtual surface stiffness values for the runs was randomized for each participant. Two warm-up experimental



(a) mean estimated PSE

(b) mean penetration depth



(c) mean contact force

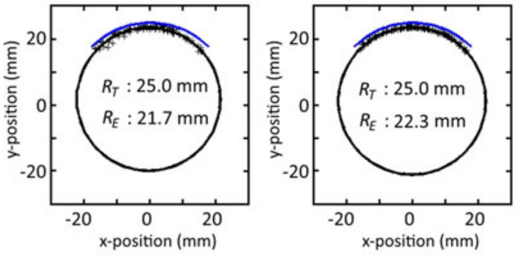
Fig. 7. Experimental results for the real edge with a radius of 2.5 mm. Error bars indicate standard error.

runs with a virtual surface stiffness of 1.2 N/mm (not used in data collection) were conducted prior to data collection and the results were not analyzed.

The initial radius of the virtual edge was 30 or 80 mm for the real edge with a radius of 2.5 or 12.5 mm, respectively. After the first three reversals, the step size was changed from 5 to 2 mm for the 2.5 mm real edge and from 15 to 6 mm for the 12.5 mm real edge. It took approximately two hours for each participant to complete the two sessions of the experiment.

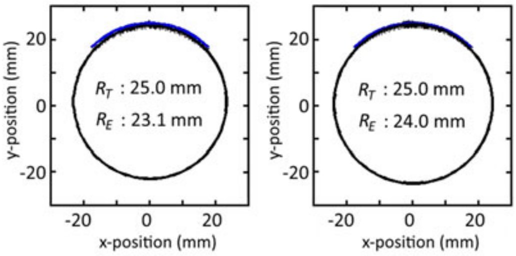
3.2.2 Results

Experimental results for the 2.5 mm radius real edge are shown in Fig. 7. Estimated PSE, collision depth and contact force calculated from (1) were averaged over the 12 participants. In Fig. 7a, the average PSE estimate is plotted as a function of the virtual surface stiffness. A one-way repeated measure ANOVA with the factor virtual surface stiffness indicates that the virtual stiffness had a significant effect on PSE estimates $[F(4,44) = 8.38, p < 0.001,\ \eta_P^2 = 0.43]$. In a subsequent Tukey HSD test, the PSE estimates were grouped into two overlapping subsets of $3.0, 1.8, 1.4,$ $\text{and}\, 1.0\,\text{N/mm}\, [p = 0.29]$ and $1.0\ \text{and}\ 0.6\,\text{N/mm}\, [\text{p} = 0.183]$. When the PSE estimate at each virtual stiffness value was compared to 2.5 mm by one-sampled t-tests with the null hypothesis $\mu_{PSE} = 2.5\,\text{mm}$, a significant difference was found at each stiffness value except for the highest stiffness value of $3.0\,\text{N/mm}\,[\text{t}(11) = 6.59,\ \text{p} < 0.001\,\text{for}\,0.6\,\text{N/mm};$ $\text{t}(11) = 5.12,\ \text{p} < 0.001\,\text{for}\,1.0\,\text{N/mm};\ \text{t}(11) = 3.09,\ p = 0.01$ $\text{for}\,1.4\,\text{N/mm};\ \ \text{t}(11) = 2.48,\ \text{p} = 0.03\,\text{for}\,1.8\,\text{N/mm};\ \text{t}(11) =$ $1.76,\ p = 0.11\,\text{for}\,3.0\,\text{N/mm}]$. These results indicate that at the lower virtual stiffness values, the virtual edges tend to feel sharper than the real edge of the same radius, and a larger virtual radius was required in order to match the virtual edge to a real edge.



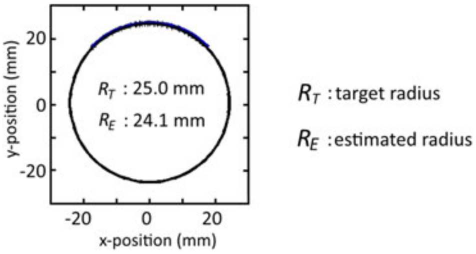
(a) 0.6 N/mm

(b) 1.0 N/mm



(c) 1.4 N/mm

(d) 1.8 N/mm

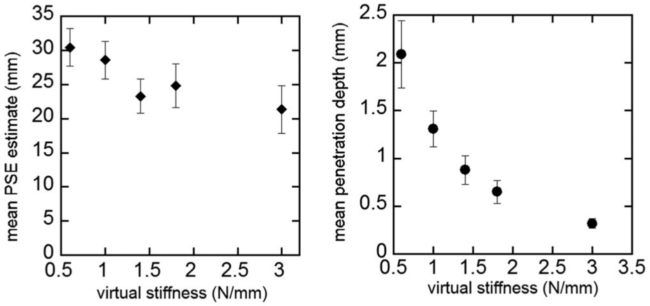


(e) 3.0 N/mm

Fig. 8. Plots of a participant's recorded finger contact points for virtual edges with a 25 mm radius as a function of virtual stiffness. Blue lines, crosses, and black circles indicate the contours of the virtual edge, recorded positions of finger contact points, and the best-fitting circle calculated from the method of least-square errors, respectively.

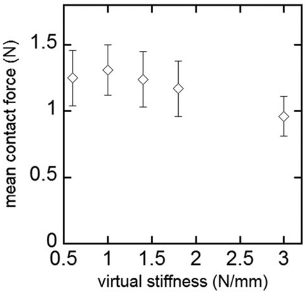
In order to gain insight into the results obtained, we present an example of a participant's recorded finger contact positions along with the contour of virtual edges with a radius of 25 mm that was selected from the test with a 2.5 mm radius real edge as seen in Fig. 8. The radius 25 mm was selected because the participants felt the radius at all the virtual stiffness values. A black circle in each plot indicates the best-fitting circle calculated from the recorded finger contact positions by the method of least-square errors. The radii of the best-matching arcs decreased as the virtual stiffness decreased; so were the collision depths. The estimated radii are 21.7, 22.3, 23.1, 24.0, and 24.1 mm for 0.6, 1.0, 1.4, 1.8, and 3.0 N/mm, respectively. At the higher virtual stiffness values, the PSE values for virtual edges approached the radius value of the real edge.

In Fig. 7b, the mean penetration depth is plotted against the virtual stiffness value. A one-way repeated measure ANOVA indicated that the virtual stiffness had a significant effect on the collision depth $[F(4,44) = 56.77, p < 0.001,$ $\eta_P^2 = 0.84]$. In Fig. 7c, the mean contact force is plotted against the virtual stiffness. A significant effect of virtual stiffness was found for the mean contact force $[F(4,44) = 3.81, p = 0.01,\ \eta_P^2 = 0.26]$. When the mean contact force is analyzed for the lower four virtual stiffness values, no significant difference was found $[F(3,33) = 1.64,$ $p = 0.158,\ \ \eta_P^2 = 0.13]$.



(a) mean estimated PSE

(b) mean penetration depth

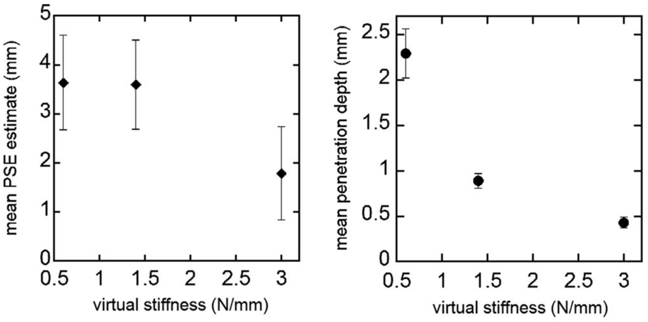


(c) mean contact force

Fig. 9. Experimental results for the real edge with a radius of 12.5 mm. Error bars indicate standard error.

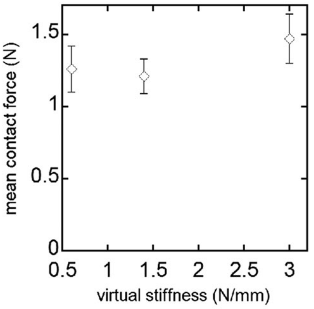
Fig. 9 shows the experiment results for the real edge with a radius of 12.5 mm. In Fig. 9a, the average PSE estimate is plotted as a function of the virtual surface stiffness. A one-way repeated measure ANOVA with the factor virtual surface stiffness indicates that the virtual stiffness had a significant effect on PSE estimates $[F(4,44) = 5.85, p = 0.001, \quad \eta_P^2 = 0.35]$. In a subsequent Tukey HSD test, the PSE estimates were grouped into two overlapping subsets of 3.0, 1.8, 1.0 and $0.6\,\mathrm{N/mm}$ $[\mathrm{p} = 0.13]$ and 1.8, $1.4\,1.0$ and 0.6 $[p = 0.36]$. When the PSE estimate at each virtual stiffness value was compared to 12.5 mm by one-sampled t-tests with the null hypothesis μ_{PSE}=12.5 mm, the difference was significant for all virtual stiffness values $[\mathrm{t}(11) = 6.81, \mathrm{p} < 0.001$ for $0.6\,\mathrm{N/mm}$; $t(11) = 6.12, p < 0.001$ for $1.0\,\mathrm{N/mm}$; $t(11) = 8.16, p < 0.001$ for $1.4\,\mathrm{N/mm}$; $\mathrm{t}(11) = 3.99, p = 0.002$ for $1.8\,\mathrm{N/mm}$; $t(11) = 2.44$, $\mathrm{p} = 0.033$ for $3.0\,\mathrm{N/mm}]$. Considering the decreasing trend of estimated PSE values, virtual stiffness values higher than 3.0 N/mm would be required for a good match of virtual and real edges at the same radius. In Fig. 9b, the mean collision depth is plotted against virtual stiffness values, which had a significant effect on the collision depth $[F(4,44) = 33.43$, $p < 0.001, \ \eta_P^2 = 0.75]$. In Fig. 9c, the mean contact force is plotted against virtual stiffness values. A significant effect of virtual stiffness was found for the mean contact force $[F(4,44) = 3.56, p = 0.01, \ \eta_P^2 = 0.24]$. When the mean contact force is analyzed for the lower four virtual stiffness values, no significant difference was found $[F(3,33) = 1.07, p = 0.38, \quad \eta_P^2 = 0.09]$, meaning that the contact force remained more or less constant until it dropped for the highest virtual stiffness value of 3.0 N/mm.

In summary, we observe that the PSE values for virtual edge radius tend to decrease as the virtual stiffness value increases. The virtual stiffness has a significant effect on the mean contact force, although not for the lower four virtual stiffness values.



(a) mean estimated PSE

(b) mean penetration depth



(c) mean contact force

Fig. 10. Experimental results for the real edge with a radius of 0.5 mm. Error bars indicate standard error.

3.3 Follow-up Results with a Smaller Edge Radius

The results of the main experiment indicate that estimated PSE values decreased and the contact force tended to remain constant as the virtual stiffness increased. We investigate whether the trends continue for a real edge with a significantly smaller radius than 2.5 mm. Twelve participants (3 females, 25 to 35 years old) who did not participate in the main experiment took part in the follow up experiment. None of them had any known problem with their sense of touch. All were right handed by self-report. A 0.5 mm real radius edge was used and the experiment consisted of three runs where the stiffness of the virtual edge was set to one of three values: 0.6, 1.4, or 3.0 N/mm. The stiffness values were selected to cover the same stiffness range used in the main experiment. The order of virtual surface stiffness for the runs was randomized for each participant. The initial radius of the virtual edge was 6.0 mm. After the first three reversals, the step size was changed from 1.0 to 0.2 mm. It took approximately 40 minutes for each participant to complete the experiment.

Fig. 10 shows the experimental results for the real edge with a radius of 0.5 mm. In Fig. 10a, the average PSE estimate is plotted as a function of the virtual surface stiffness. A one-way repeated measure ANOVA with the factor virtual surface stiffness indicates that the virtual stiffness had a significant effect on PSE estimates $[F(2,22) = 4.31$, $p = 0.03, \ \eta_P^2 = 0.28]$. In a subsequent Tukey test, however, the PSE estimates were grouped into one subset. When the PSE estimate at each virtual stiffness value was compared to 0.5 mm by one-sampled t-tests with the null hypothesis $\mu_{PSE} = 0.5\,\mathrm{mm}$, a significant difference was found at each stiffness value except for the highest stiffness value of

$3.0\,\mathrm{N/mm}$ [$\mathrm{t}(11) = 3.43$, $\mathrm{p} = 0.01$ for $0.6\,\mathrm{N/mm}$; $\mathrm{t}(11) = 3.57$, $p = 0.004$ for $1.4\,\mathrm{N/mm}$; $\mathrm{t}(11) = 2.48$; $\mathrm{t}(11) = 1.98$, $\mathrm{p} = 0.08$ for $3.0\,\mathrm{N/mm}$]. In Fig. 10b, the mean penetration depth is plotted against virtual stiffness values, which had a significant effect on the penetration depth [$F(2, 22) = 35.28$, $p < 0.001$, $\eta_P^2 = 0.76$]. In Fig. 10c, the mean contact force is plotted against virtual stiffness values. No significant effect of virtual stiffness was found for the mean contact force [$F(2, 22) = 1.36, p = 0.28$, $\eta_P^2 = 0.11$].

A two-way ANOVA was conducted for PSE estimates with the factors virtual stiffness (0.6, 1.4, and $3.0\,\mathrm{N/mm}$) and real edge radius (0.5, 2.5, and 12.5 mm). There was a significant main effects of virtual stiffness ($F(2, 99) = 7.46, p = 0.001$, $\eta_P^2 = 0.13$) and real edge radius ($F(2, 99) = 177.48$, $p < 0.001$, $\eta_P^2 = 0.78$) on the PSE estimates. Also, a significant interaction of virtual stiffness and real edge radius was found ($F(4, 99) = 2.93, p = 0.03$, $\eta_P^2 = 0.11$). A Tukey test indicates that the PSEs at the lower two virtual stiffness values were grouped together. With a two-way ANOVA for contact force, we found no main effect of virtual stiffness ($F(2, 99) = 0.27, p = 0.76$, $\eta_P^2 = 0.1$) or real edge radius ($F(2, 99) = 2.31, p = 0.11$, $\eta_P^2 = 0.04$). There was no significant interaction of the two factors ($F(4, 99) = 1.1, p = 0.36$, $\eta_P^2 = 0.04$).

Finally, from the PSE estimates gathered with the three real edge samples, a linear relation between the perceived virtual edge sharpness and real edge sharpness was derived from the experimental data using the least squares regression as follows:

$$\begin{array}{l} R' = 2.21\,R + 2.88 \text{ at } 0.6 \text{ N/mm} \\ \qquad (r^2 = 0.80,\ F(1, 34) = 144.24,\ p < 0.001) \\ R' = 2.50\,R + 0.69 \text{ at } 1.4 \text{ N/mm} \\ \qquad (r^2 = 0.85,\ F(1, 34) = 202.61,\ p < 0.001) \\ R' = 1.64\,R + 0.66 \text{ at } 3.0 \text{ N/mm} \\ \qquad (r^2 = 0.60,\ F(1, 34) = 54.37,\ p < 0.001) \end{array}. \tag{2}$$

where R', R and r denote virtual and real edge radii and the coefficient of determination, respectively. It should be noted that the relation at each virtual stiffness value was derived from only three real edge radii so the linearity assumption needs further testing with more data collected from experiments using more real radius values. In summary, we observe that the PSE values for virtual edge radius tend to decrease for all three real edge radii as the virtual stiffness value increases. Data analysis for all three real edge radii showed that the virtual stiffness values did not have a significant effect on the contact force. In the next section, we discuss the implications of these results.

4 DISCUSSION AND CONCLUSIONS

The present study investigated the relation between perceived sharpness of virtual and real edges and the effect of the virtual stiffness on the relation. A preliminary experiment showed no significant effect of handedness in edge sharpness perception. The PSE values for virtual edges were estimated when virtual edges were matched with real edges at radius values of 0.5, 2.5, and 12.5 mm, over a virtual stiffness range of 0.6 to 3.0 N/mm. It was found that the virtual surface stiffness had a significant effect on the perceived sharpness of the virtual edge except at the highest stiffness of 3.0 N/mm. Given a real edge radius, more compliant surfaces tended to result in a higher PSE, which corresponds to a larger curvature. This implies that the participants tend to judge the virtual edges with the same radius as being sharper when the virtual surface is more compliant. Linear relations were derived between the virtual edge radii matched to that of the real edges in perceived sharpness. The virtual surface stiffness did not have a significant effect on the contact force.

The difference in the perceived sharpness between the virtual and real edges can be attributed to the limitations of current haptic interfaces and haptic rendering methods. All haptic interfaces have a limited z-width and there is no exception for the CLD system which has a nominal maximum virtual stiffness of 3.5 N/mm. This stiffness value is significantly lower than that of the real edges used in the present study. It is also notable that the CLD system does not provide local curvature information since the contactor has a fixed cylindrical radius. This conflicting cutaneous cue may have interfered with the participants' ability to perceive the sharpness of virtual curvatures, as demonstrated by prior research. For example, Srinivasan and LaMotte showed that the response of SA1 afferents vary as the curvature of contacting object changes [31]. Goodwin et al. also demonstrated that humans can perceive local curvature within the size of fingertip with cutaneous information only [32]. However, we showed in our previous study that the cutaneous information provided by the CLD system was found to be dominated by the force cues, regardless of the roller radius [24]. In the study, we also compared the performance of haptic curvature discrimination in previous references and the Weber fraction with the CLD system ($0.25\ \mathrm{m}^{-1}$) was larger than that of the study with real cutaneous curvatures ($0.11\ \mathrm{m}^{-1}$). Thus, current design of the CLD system lacks the ability to provide as much cutaneous curvature information as that from a real curvature. Finally, it should be noted that the popular penalty-based haptic rendering method allows penetration of the haptic tool tip into a virtual surface for rendering contact force (eq. (1)) [3], [12]. Therefore, there is a dimensional discrepancy between a virtual object's nominal surface and the actual contacting surface due to the penetration depth, affecting the matching of perceived sharpness between the virtual and real edges as shown by the results from the present study.

The effect of virtual surface stiffness on the perceived sharpness of virtual edges and its matching trend with real edges can be explained with the recorded finger contact points and the mean penetration depth. Considering the trend of larger mean penetration depth for less stiff or more compliant surfaces, we can expect that a participant's fingertip would travel over a shape more compressed down from the virtual object's nominal surface as it becomes more compliant. For a virtual edge, more compression of the nominal surface results in a sharper edge, which is consistent with the smaller estimated radius from recorded finger contact points for the less stiff virtual surfaces in Fig. 8. This can also explain the result of sharper perceived virtual edges for less stiff virtual surfaces (see Figs. 7a, 9a, and 10a). The compression of surface due to compliant surface can

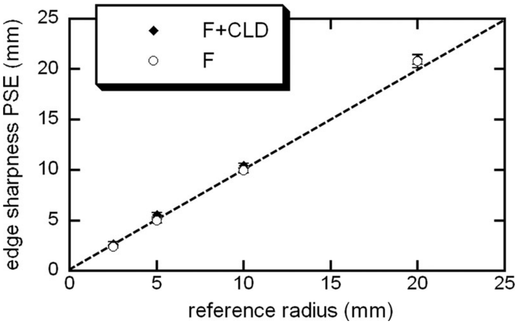


Fig. 11. Mean estimates of PSE for force-feedback (F) and force-feedback-plus-CLD (F+CLD) conditions plotted by reference radii, 2.5, 5.0, 10.0, and 20 mm. The dashed line indicates the equation ‘edge sharpness PSE = reference radius’

also shift the top position of the curvature. Local height of curvature, however, was found not to affect the perception of curvature as shown by Wijntjes et al. [9]. Therefore, the trend of larger penetration depth for less stiff virtual surface can account for the effect of virtual surface stiffness on the perception of sharpness.

The trend of larger mean penetration depths for less stiff virtual surfaces is consistent with the force constancy hypothesis proposed by Choi et al. [13]. In their study, the users tended to maintain a constant contact force while touching virtual surfaces rendered with the penalty-based method. The force constancy hypothesis held well over a certain virtual surface stiffness range and it is also consistent with the results of our experiment where the contact force tends to be constant for the lower four virtual stiffness values. Given that contact force is determined by the multiplication of virtual stiffness and penetration depth, constant contact force over a range of virtual stiffness values means that a less stiff virtual surface will result in more penetration, which is consistent with the results of the present study.

The linear relations between the perceived virtual edge sharpness and real edge sharpness derived in the present study can also be applied to a force-feedback system without contact location display. This can be verified by examining the effect of adding contact location information to force feedback on the perceived sharpness, in terms of precision and accuracy. First, the effect of contact location information on the JND of perceived sharpness was shown to be insignificant in our previous studies on virtual edge sharpness discrimination [24], [25]. Next, when we compare the PSE’s between force-feedback and force-feedback-plus-CLD conditions of [24], the effect of contact location information on the accuracy of perceived sharpness is insignificant. Fig. 11 shows mean estimates of PSE for the two experimental conditions of [24] as a function of reference radius. A two-way repeated measures ANOVA with the factors experimental condition and reference radius indicates that the reference radius was a significant factor $[\mathrm{F}(3,39) = 1036.72, \mathrm{p} < 0.001]$ but the experimental condition was not $[\mathrm{F}(1,13) = 4.44,\ \mathrm{p} = 0.55]$. Also, when a pairwise t-test was conducted at each reference radius, none of the PSE pairs was significantly different $[\mathrm{t}(13) = 0.99,\ \mathrm{p} = 0.34$ for the reference radius of 2.5 mm; $\mathrm{t}(13) = 1.77,\ \mathrm{p} = 0.1$ for 5.0 mm; $\mathrm{t}(13) = 1.65,\ p = 0.12$ for 10.0 mm; $\mathrm{t}(13) = 13 = 0.29,\ \mathrm{p} = 0.78$ for 20.0 mm$]$. The results indicate no significant difference in PSE between the two experimental conditions of force-only and force-plus-contact-location information. Therefore, the insignificant effect of contact location information in terms of both accuracy and precision suggests that the linear relation between the virtual edge sharpness and real edge sharpness in the present study can be applicable to a haptic system with force-feedback information only.

The results of the present study shed light on how the perception of virtual objects rendered by a haptic system match that of real objects, in this particular case a curved edge. Current haptic interfaces are still limited in their ability to deliver haptic information as complete and realistic as that of a real object, such as the discrepancy in perceived sharpness between real and virtual edges as demonstrated in the present study. The results of our work suggest that the discrepancy can be reduced by increasing surface stiffness. Finally, the matching trend of perceived sharpness between a real and virtual edge can provide a reference for the haptic rendering of virtual objects’ sharpness. For example, if we want to render a virtual edge that is perceived to have a radius of 5 mm at a surface stiffness of 1.8 N/mm, then according to (2), we should render a virtual edge with a radius of 9.95 mm.

The matching relation between the perception of virtual and real edges can be further generalized by considering the effect of surface properties other than the virtual surface stiffness. For example, surface friction was found to affect the matching of virtual curvature perception as demonstrated by Christou and Wing [33]. Also, a real object’s compliance can affect the curvature perception. The present study can be extended in the future by conducting additional experiments with a wider real edge radius range, varied friction properties of real edges, and a range of simulated surface friction properties of virtual edges in order to derive a more general relation between real and virtual edge perception.

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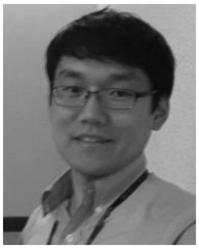

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