Surface Haptic Feature Attenuation due to Contact on Opposing Surface

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ABSTRACT

In fingertip interaction with a virtual surface, the illusion of a protruding bump can be created even in the absence of out-of-plane forces or motions, by presenting just the lateral forces associated with sliding over a bump [19]. We found that when a virtual bump on one side of a planar haptic display surface is explored with a fingertip, adding contact with the opposing side of that surface as well (pinch grip) decreases the virtual bump's perceived height. Using two motor-driven sliding contact surfaces (one for either side of the display plane), we determined when a bump traversed with the index finger alone subjectively matched a comparison bump explored with simultaneous thumb contact on the opposing side (the point of subjective equality, or PSE). The decrease in perceived bump height due to opposing surface contact was on the order of 10%.

KEYWORDS: Surface haptics, bumps, psychophysics, multi-finger, multi-surface.

INDEX TERMS: H.5.2 User Interfaces, H.5.2.i Interaction styles, H.5.2.o Theory and methods.

1 INTRODUCTION

The present study demonstrates that pinch contact attenuates the perceived height of bumps displayed on a haptic surface, relative to contact with the index finger alone. Specifically, we studied the feature attenuation effect by measuring points of subjective equality (PSEs) between small Gaussian bumps (heights of 3.4 to 6.6 mm and standard deviations of 8 mm) felt with and without contacting the rear side of a haptic surface. We chose to investigate active touch, both because many display technologies tend to utilize finger movement [16] [1], and because exploration of the world is inherently active [10].

It is well known that our internal representations of geometric features are created using both proprioceptive as well as cutaneous information. However, Robles-de-la-Torre and Hayward [20] showed that even in the absence of out-of-plane motion cues, shear force cues at the fingertip are sufficient for individuals to perceive bumps on a flat surface. Others have explored the relationship between the perception of bumps and contributing sensory cues such as static local curvature and orientation [18], contact patch trajectory [3], local surface orientation [26], exploratory behavior [6], [21] and material properties [5], in addition to lateral forces and proprioception.

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Our interest is particularly in shear forces as a cue to surface curvature, because recent surface haptic techniques are beginning to make control of these forces on a fingertip more practically feasible [16], [1], [23], [3]. Many of these underlying interaction principles, combined with more efficient and compact actuators, could be used to add haptic forcing capabilities to interfaces on personal electronic devices such as tablet computers and mobile phones.

There has been some previous work specifically on bumps simulated using surface shear forces on a fingertip [20], [22] while others tend to rely instead on kinesthetic cues displayed via actuated thimbles [15], [6]. While these studies reveal many aspects of cue integration within a single finger, little is known about multi-finger exploration of such "surface features", particularly on multiple surfaces. An example of multi-finger, multi-surface exploration--although not specifically exploration of surface *features*--is the recent study by Frisoli et al. [9] on the relative effects of local surface orientation and proprioceptive cues presented to opposing fingers. A multi-touch, multi-surface virtual object (e.g. one that spans the front- and rear-side haptic surfaces on a handheld device) would allow more natural exploratory motions, since everyday haptic exploration tends to involve multiple fingers enclosing objects.

With multi-surface haptic displays on the horizon, it will become increasingly important to understand how the mind integrates sensory input across fingers and surfaces. Understanding cue integration is particularly significant for haptic rendering, because hardware limitations generally preclude all cues (e.g. local curvature, pressure, shear force, etc.) being displayed by a single device.

In particular, the maximum-likelihood estimator (MLE) model for integration [8] applied to curvature would dictate that the percept of curvature is a weighted average of estimates of curvature based on available sensory inputs. Drewing et al. [5] and Kaim et al. [15] studied the effect of sensory information reliability on the relative weighting of force vs. position information at the fingertip. Drewing et al. found [5] that in virtual bump exploration, decreasing the reliability of position information by introducing surface compliance shifted the force/position signal weighted average, supporting the applicability of the MLE model to curve parameterization.

While cue integration is generally thought of as a mechanism for optimizing perception, in the presence of cue limitations it can have other consequences, as signals from reduced cues can impact the perceptual properties mediated by other, more reliable sources. In this study, we measured one such consequence, namely, the decrease in apparent height of a virtual feature on the front side of a haptic surface resulting from contact with the same hand on the featureless rear side of a haptic display surface (a pinch grip).

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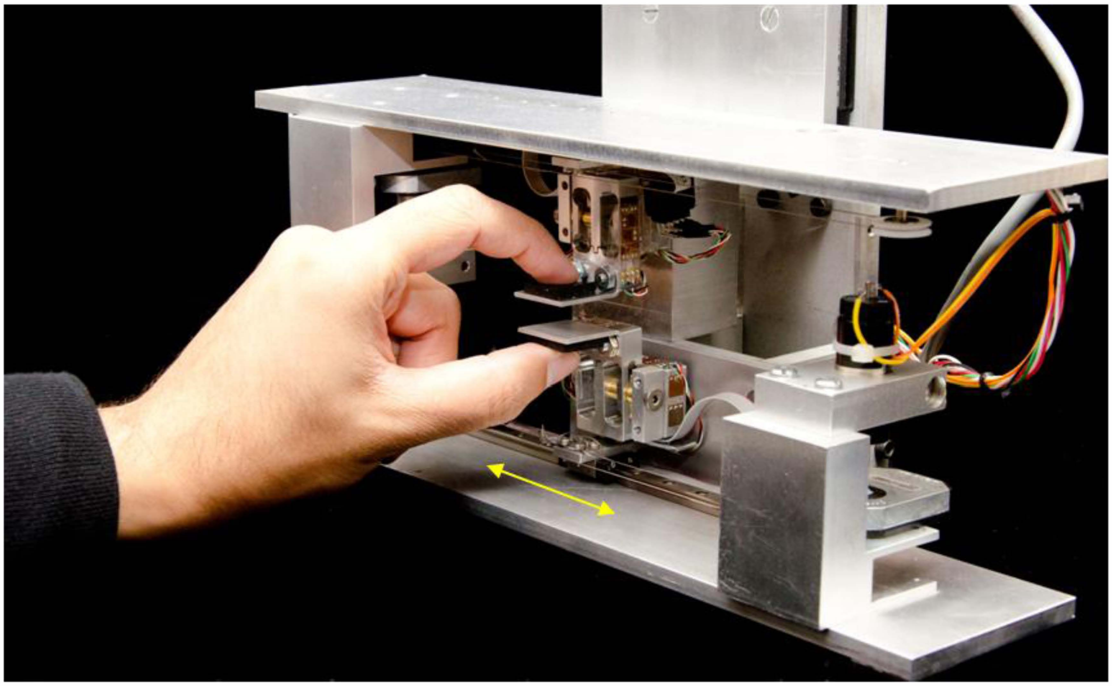

Figure 1. Slider apparatus. Each cable-driven slider surface can be moved independently and slides along its own rail.

2 MATERIALS AND METHODS

2.1 Apparatus

Our experimental setup consisted of two opposing slider surfaces for the fingertips, constrained to slide along parallel axes independently of one another. Each slider surface was mounted on its own cable-driven slider equipped with load cells to measure forces exerted by the finger on the slider surface on an axis normal to the surface as well as on the axis of travel. Normal force was recorded, but not used for control.

Each slider was driven using a force control loop closed around the slider's lateral direction load cell, in order to mask the inertia of the slider and drive mechanism. The control loop operated at 1 kHz and was computed on a PC/104 stack running an xPC Target real-time operating system. Automation of the experimental protocol was done on a PC running a Matlab script, communicating with the PC/104 stack.

Maxon RE-16 motors drove the sliders with up to 1 N of force, although the experiment required less than 0.7 N to effectively render bumps. We used Futek LSM250 parallelogram load cells with a full-scale reading of 1.1 N. Rubber pads were used as the slider surfaces to ensure zero slip even at low levels of applied normal force. The upper slider mechanism was mounted to a linear actuator capable of varying the vertical separation between the two slider surfaces. For the experiments reported here, the vertical separation was fixed at 22 mm.

Lateral forces (representing bumps) were rendered irrespective of the subject's applied normal force; the lateral force applied by the device was a function of slider position alone. We assumed a normal force magnitude of 0.5 N for the purposes of computing lateral force. This contrasts with an idealized frictionless bump in which lateral force would be proportional to the participant's applied normal force. Subjects were trained to maintain approximately constant normal force, as will be detailed below.

Because the experiment requires subjects to extend the elbow, we used a forearm sling to reduce fatigue. The sling's support wires extended 8 feet upward to the ceiling, so the direction of tension during movement was largely insensitive to the position of the arm. In addition, to prevent visual cues from affecting responses, a curtain was drawn between the subject and the device.

2.2 Participants

The participants were 5 males and 1 female Northwestern University graduate students between 22 and 34 years of age, who gave their informed consent. All were right handed and used their dominant hand for the experiment. Most participants had previously used surface haptic devices from the authors' lab; however, all were naive as to the purpose of this experiment.

2.3 Protocol

2.3.1 Force Consistency Training

Participants were seated comfortably in a chair in front of the device with their dominant (right) arm resting in the sling. To the participant's side was a monitor that displayed a plot of fingertip normal force as measured on the upper slider, as a function of time. Participants were instructed to contact the upper slider lightly and slide with broad slow movements while maintaining a normal force close to 0.5 N. Training ended when participants felt confident that they could maintain the desired normal force during movement without looking at the monitor, which typically took around 5 min.

2.3.2 Stimuli and Task

On each trial, participants felt a base bump of amplitude 5 mm and a comparison bump, which had amplitudes of 3.4, 3.8, 4.2, 4.6, 5.4, 5.8, 6.2 or 6.6 mm. The participant then reported which bump was subjectively higher.

The bumps were all Gaussian with a standard deviation of 8 mm, and always occurred in the same location. We chose Gaussian profiles because of the amount of literature for that shape [6] [20] [22] as opposed to semicircular [5] or sinusoidal bumps. Gaussian bumps also have the advantage of being geometrically continuous with a perceptually flat surround, which eliminates noticeable force discontinuities that could serve as additional cues.

One bump was felt with the index finger only (single contact) and the other with the index finger on the bump and thumb on an opposing flat surface (pinch contact). The order of contact types was consistent within a given participant, such that half of the participants always felt the first bump with single contact and the second with pinch contact, and the remainder used the reverse order of contacts. For each participant there were 15 presentations of each comparison bump height in both orders of base vs. contrast (e.g. a subject using single contact followed by pinch contact would do the following: base bump with single contact followed by comparison bump with pinch contact, vs. comparison bump with single contact followed by base bump with pinch contact), for a total of 240 trials, which were presented in randomized order. The entire experiment lasted about 2 hours and was broken into 2-3 sessions.

2.3.3 Procedure

Even though the contact types were presented in a fixed order, participants were given audible cues through a headset before each stimulus to remind them as to which contact type to use, single or pinch. A single beep indicated the appearance of the first bump. Exploration always started on the left end of the surface and proceeded with three roundtrip passes over the bump, for a total of 6 traversals of each bump. Upon completion of the third pass, participants heard a double beep signalling them to explore the second bump in the same fashion except with the other contact style (pinch vs. single). Upon completion of those three passes, participants heard a unique sound marking the end of the trial. Participants then entered their response as to which bump had greater height on a keypad, using their other (left) hand.

Participants were instructed to make slow passes completely clearing the tails of the bump each time. They were also instructed to make their responses on the basis of their impression of bump height rather than maximum lateral force.

3 RESULTS

3.1 Maintaining Normal Force

The average fingertip normal force (measured across +/- 10 mm of the bump center) ranged across participants from .37 N to .70 N. Notably, although participants were instructed to maintain a consistent index finger normal force between single contact and pinch contact, the force applied during pinch contact averaged .58 N (*s.d.* 0.10 N) , as compared to .52 N (*s.d.* 0.10 N) for single contact, a significant difference, $t(5) = 3.83$, $p < .01$. The difference did not depend significantly on bump height, $F(7,35) < 1$. Across participants, the standard deviation of the mean within-trial normal force, computed over trials, ranged from 10% to 33% of the participant's mean normal force.

3.2 Measured Points of Subjective Equality (PSE) and Just Noticeable Differences (JND)

Figure 2 plots individual participants' psychometric curves: the proportion of trials for which the comparison bump was perceived as greater than the base bump. The curve fit using a maximum likelihood procedure that assumes a cumulative Gaussian

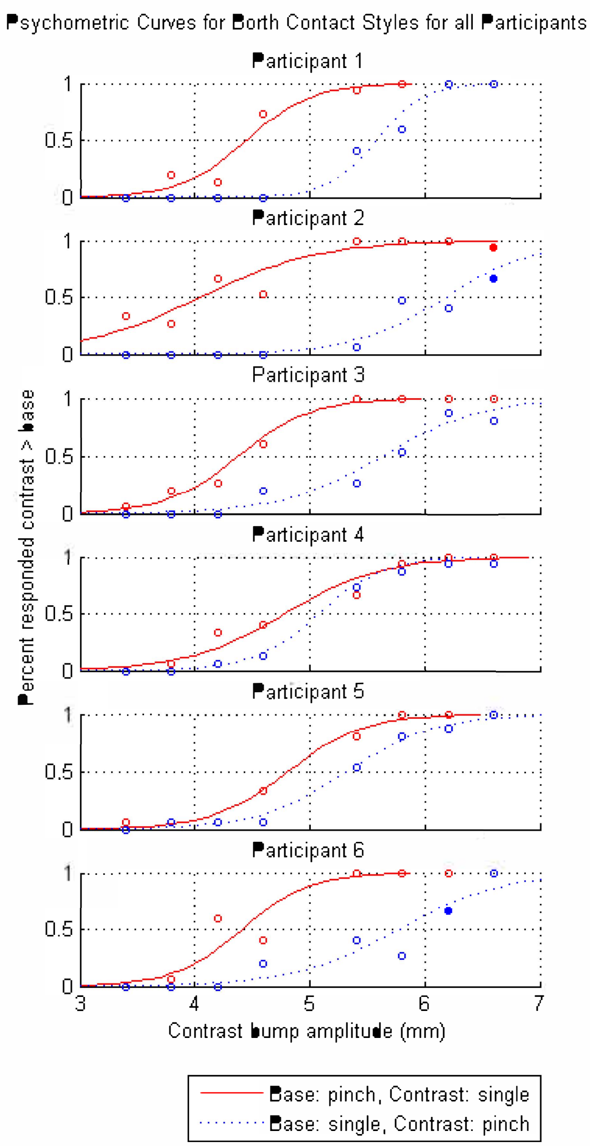

Figure 2. Psychometric curves for each participant showing proportion of trials in which the comparison bump amplitude is perceived as greater than the base bump amplitude (5 mm), as a function of comparison bump amplitude. Cumulative Gaussian functions have been fit to the data. Solid red line: comparison bumps felt with pinch contact compared to 5 mm bump felt with single contact. Dotted blue line: comparison bumps felt with single contact compared to 5 mm bump felt with pinch contact.

distribution [25]. The PSE is then the x-axis value at which the fit curve crosses 0.5 on the y-axis. The base bump height was fixed at 5 mm, so if single contact vs. pinch contact made no difference on perceived amplitude, the PSE value should be 5 mm. All participants showed PSEs less than 5 mm when comparing pinch contact to a 5 mm single-contact base bump, and all showed PSEs greater than 5 mm when comparing single contact to a 5 mm pinch-contact base bump. Individual participants' PSE deviation from 5 mm tended to be symmetric (averaging –.52 and +.59 mm). This indicates that the attenuation for the pinch contact is

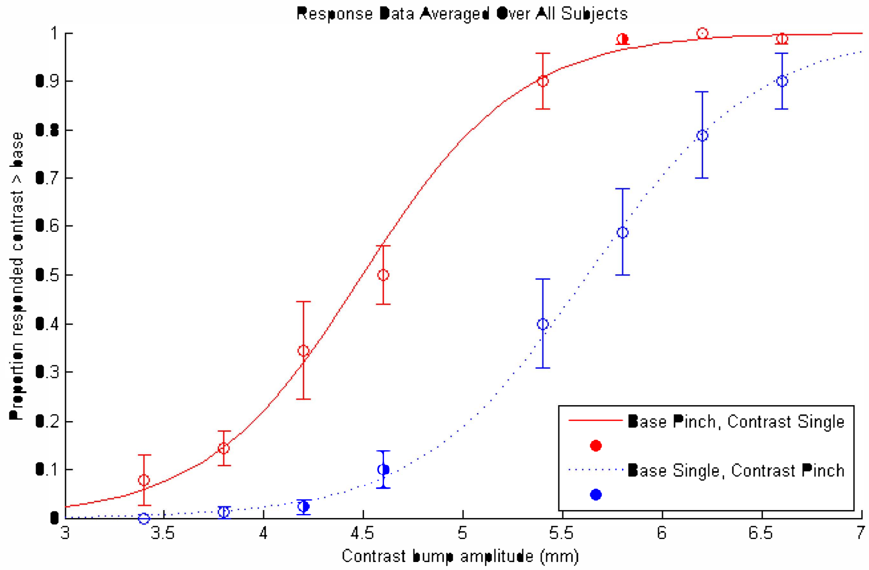

Figure 3. Psychometric curves representing averaged data collected from all participants. Solid red line: comparison bumps felt pinch contact compared to 5mm bump felt with single contact. Dotted blue line: comparison bumps felt single contact compared to 5mm bump felt with pinch contact. Error bars are between-subject s.e.m.

on the order of 10% of the presented value as compared to the single contact. The difference between PSEs was significant by paired t-test, $t(5) = 4.16$, $p < .01$.

Under the assumption of underlying normal distributions for the discrimination, the just noticeable difference (JND) was estimated for each participant as the difference between the PSE and the bump height at the 84% point of the curve. The mean JNDs in the two conditions were identical (.60 mm). Thus the underlying noise in the discrimination is not increased when the apparent amplitude of the comparison bump is reduced.

4 DISCUSSION

Our results provide an empirical demonstration that when a surface with a virtual bump is explored with a pinch contact, while the opposing surface is flat, the perceived bump height is attenuated. In comparison to the base value of a 5 mm bump height, the attenuation due to pinch contact is on the order of 10%. Contact type does not, however, increase noise in the discrimination.

Three general types of explanations can be considered for the feature height attenuation, at motor, sensory, or higher-order levels. These are not mutually exclusive, and multiple factors may be involved.

With respect to effects at the motor level, we find that there is a tendency to apply greater normal force when the pinch contact is used, although participants were initially trained to keep their force constant and reported trying to do so. Because lateral forces for all conditions were calculated assuming a constant normal force, the direction of the total force vector during the pinch contact corresponded on average to the surface normal of a smaller bump size. This reduced bump size can be estimated using the direction of the recorded total force vector to find the slope of the virtual surface at each point. The slope can then be integrated to reveal the “actual” bump profile. Normal forces during single and pinch contact explorations averaged 0.52 N (*s.d.* 0.10 N) and 0.58 N (*s.d.* 0.10 N) respectively. For our estimate, we calculated the total force profile using the commanded lateral force profile and the known average normal forces. We estimate a 10% decrease in bump size for the pinch contact case relative to the single contact. The similarity of the magnitude of the actual attenuation effect (about 10%) and the attenuation predicted by the increase in pinch force suggests that the attenuation might arise from the additional normal force.

Normal force may affect movement velocity as well, and other biomechanical differences might also be present. Informal reports of pilot participants suggested, for example, that the stiffness of the index finger in the lateral direction was greater when it was used in pinch contact, as opposed to single contact

The type of contact might also have effects at the sensory level. Grasping contact has been found to diminish the perception of thermal properties [12] and, contact with edges impedes shape perception [17]. It is possible that the pinch grasp also diminishes sensitivity of the lateral forces that are used to simulate bumps. A related phenomenon is the cancellation of self-generated cues [1], which could lead to discounting of forces encountered during pinch because of the expected contribution of the thumb.

Integration of cues from the two surfaces provides a specific model of a perceptual effect that could produce the present attenuation. According to the maximum-likelihood estimator (MLE) model for integration [8], cues from multiple input sources are combined, with weights that reflect their reliability. If, for instance, individuals find it difficult to attend to the upper surface alone while ignoring the lower one, they may integrate estimates of height from the two surfaces (e.g., [8]). As the lower surface is signalled to be flat, integration of this cue into the estimate would reduce apparent bump size relative to the index finger alone. For a similar phenomenon, the perceived roughness of a surface felt with one finger varies with the roughness of stimuli simultaneously applied to other regions of the same hand [14], [19], [24]. To test this, it would be useful to render bumps of variable height on the lower as well as the upper surface.

A related argument is that cue integration occurs across the cues from the index finger alone and the pinch type of contact. When the index finger is used in isolation, lateral forces would produce responses in kinesthetic (muscle/tendon/joint) and cutaneous (skin) sensors, possibly in response to sideways movement. These would signal a bump. When the index finger is opposed to the thumb, the distance between the digits provide an additional kinesthetic cue, which in the absence of vertical finger movement, signals no bump. The integrated percept from index finger and pinch posture should therefore be an attenuated bump.

Given this hypothesis, it is interesting to compare the present JND of 12% to those previously reported for the component cues. The JND for curvature perception with the index finger was reported by Gordon and Morison [11] to be 9% for young adults. The JND for the pinch grip has been measured to be approximately 1.3 mm for finger separations of 22 mm (interpolated using published fit line), or 6% [7]. According to the MLE model, the JND is inversely related to reliability, and the reliability of an integrated percept should be at least as great as the weaker component cue. As the present JND arises from a virtual signal, and not a physical curve, it is not surprising that it is still greater than the larger of the JNDs for the hypothesized components.

Although the present experiment is only an initial step, it demonstrates inter-digit interactions when three-dimensional virtual features are rendered by lateral forces. These interactions are likely to be of considerable importance as technologies are developed for surface haptics.

The feature attenuation effect is potentially broadly important in this context because it can be considered a failure of invariance. As discussed by Hayward [13], the notion of invariance is closely tied to that of robust perception. Hayward gives the example of a protrusion, which can invariably be characterized as four consecutive changes in curvature (zero-negative-positive-negative-zero). Other types of invariants, such as lateral force profiles and movement of the contact patch relative to the finger as a whole, can also be associated with perception of surface features. We want to understand how invariance succeeds or fails in multi-finger interaction and what cues a surface haptic display must manipulate in order to maintain robust perception.

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