Easy-to-Recognize Bump Shapes using only Lateral Force Cues for Real and Virtual Surfaces

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***Abstract*—Friction-variable-type surface texture displays can present macroscopic bumps and dents on flat touch panels. In this study, bumps and dents of different shapes were identified only when frictional or lateral resistance forces were presented. Shapes that were easy to recognize were then investigated. The tested surfaces varied in height and width, whereas their maximum gradients were the same; those with greater widths also exhibited greater heights or depths. We conducted experiments with these surfaces under virtual conditions using an electrostatic friction display (Experiment 1) and under real conditions, where actual bumps and dents were explored using a lateral force presenter (Experiment 2). The experimental results were not consistent between the virtual and real conditions. In the virtual condition, bumps and dents with moderate heights/depths and widths were most likely to be recognized as bumps and dents. This suggests that adjusting the heights and widths of the bumps and dents increases their perceptual clarity when the maximally applicable voltages are limited owing to safety regulations. Under real conditions, we did not observe significant differences among the different bump shapes. Pursuing the incongruency between virtual and real conditions will lead to a better understanding of the haptic perception for macroscopic surface shapes.**

***Index Terms*—electrostatic texture display, surface display, dent, Gaussian**

I. INTRODUCTION

A technique for delivering macroscopic bumps and dents on a flat touch panel (e.g., [1]–[3]) may lead to a variety of new applications for surface tactile displays. For example, the simultaneous tactile presentation of fine textures and local bumps on touch panels [4]–[6] produces entertaining multimodal contents. As described in Section II, the bump presentation is achieved via the lateral or frictional forces generated by the friction-variable-type surface display. Such lateral forces are perceived when a fingertip traverses local bumps on a flat plane.

A drawback of the surface bump presentation technique is that the bumps delivered by surface tactile displays are not necessarily felt with clarity [7]. This is potentially due to the inherent flatness of the touch panel and limited variation of the friction forces on the panel. In the case of electrostatic friction displays, the presentation of large friction requires large-voltage applications, which may be hazardous or limited by hardware. In an earlier study, bumps and dents presented on electrostatic tactile displays were less likely recognized than fine textures by approximately 20% with no visual cues [7]. This motivated us to conduct the present study.

The objective of this study was to investigate the shapes of macroscopic bumps and dents that are easy to recognize using only lateral resistance forces under virtual and actual conditions. To date, such shapes have not been pursued, although shape recognition under different multimodal conditions [1] and realisms [2] has been studied. In a study by Sun et al. [6], participants categorized a randomly presented convexity as either Gaussian, triangular, or sinusoidal. The Gaussian convex was judged most correctly. In our study, the primary concern was whether the virtual shape was correctly categorized as a bump or dent. Thus, the research question is completely different from that of earlier studies. Furthermore, studies on shape perception typically involve three-dimensional force and displacement cues (e.g., [8]), whereas only lateral forces are involved in the present study.

In this study, under the virtual condition, we use electrostatic friction forces on touch panels. In contrast, under the actual condition, a force decoupling mechanism using a leaf spring is used to transmit lateral forces generated by the contact between a bump and spherical contactor. It is important to confirm whether the perceptual properties of the actual and virtual stimuli are consistent. Understanding the reasons for the inconsistency is critical for advancing the rendering techniques. We used exponential bumps and dents for which the height and width were varied, and their maximum gradients are restricted to the same values. This equal maximum gradient indicates that the maximum voltages applied to the electrostatic tactile displays are the same for different bumps and dents, which is consistent with the hardware limitations of the tactile displays. Furthermore, as described in Section II, gradient cues are a major determinant of lateral resistance in sliding over bumps. The findings of this study are expected to provide knowledge for delivering clear bumps on surface texture displays.

II. BUMP AND DENT PERCEIVED ON FLAT SURFACES

For the haptic perception of macroscopic bumps during stroking, the contact force between the finger pad and bumpy surface is a major perceptual cue [9]. Fig. 1 shows the relationship between the surface gradient and contact forces at the contact point. The fingertip, indicated by a black point, moves from left to right. An early study demonstrated that

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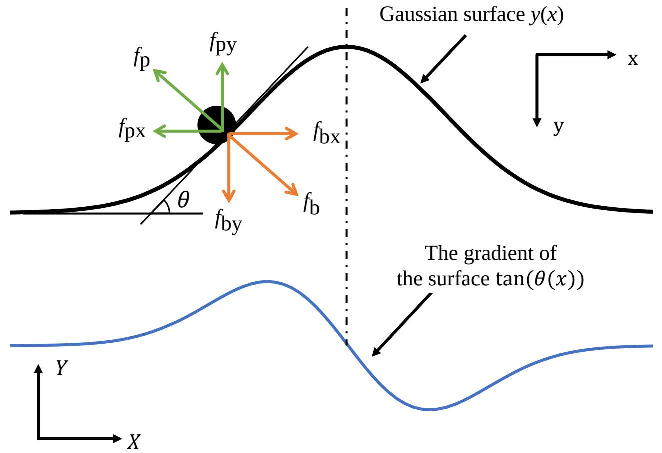

Fig. 1. Action and reaction forces generated on a Gaussian bump (upper) and its gradient (lower). The fingertip, represented by a black point, moves from left to right. Lateral reaction force f_{px} is proportional to the gradient of the surface.

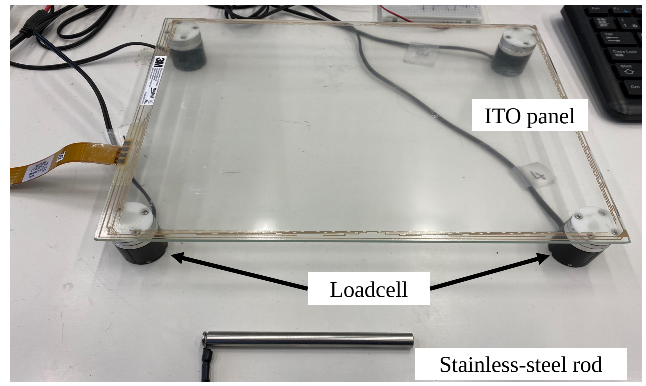

Fig. 2. Electrostatic friction surface display used in Experiment 1. The participants slide their fingers on the panel holding stainless-steel rod to perceive virtual bumps.

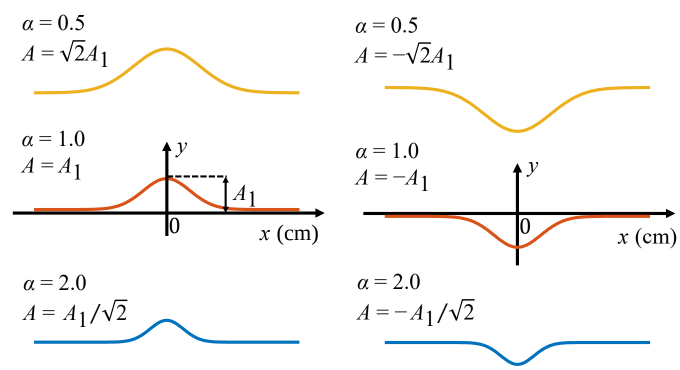

Fig. 3. Gaussian virtual bumps and dents used in Experiment 1, where α and A are the exponent and height, respectively. The maximum and minimum gradients of all the shapes are equal.

humans feel a surface bump only with a lateral resistance force, without an actual surface gradient and displacement [9]. This principle was subsequently used in surface tactile displays to present bumps and dents on flat touch panels (e.g., [1]–[4], [6], [7]). The lateral force imparted to the finger pad of the user is proportional to the surface gradient.

$$F_{\mathrm{px}} = F_{\mathrm{py}} \tan \alpha(x). \tag{1}$$

As shown in Fig. 1, the lateral resistance force increases on a rising slope and decreases on a descending slope. In this study, we used an electrostatic friction display to change the lateral force when a finger strokes a flat touch panel. Furthermore, a force decoupler was used to transmit only the lateral component of the contact force generated by a spherical tip traversing a bump or dent.

III. Methods of Experiment 1 using electrostatic friction display

A. Apparatus: Electrostatic surface friction display

Electrostatic friction displays manipulate the frictional force applied to the finger by creating an electrostatic attraction force between the finger and touch panel [10], [11]. This electrostatic attraction increases adhesive friction when the finger pad slides on the panel. In the experiments, we used electrostatic friction displayed in Fig. 2. Voltage was applied to the electrostatic touch panel with indium tin oxide (ITO) electrodes (SCT3260, 3M, MN), and the participant touched the virtual surface while holding a stainless-steel rod connected to the ground. The applied voltage was amplitude modulated at a carrier frequency of 2 kHz and amplified (PD-206-150B; Matsusada Precision Inc., Japan). The upper surface of the electrostatic touch panel was insulated, and the current does not flow through the participant's body. Load cells (USLG25, TecGihan Co., Ltd., Japan) were placed at the four corners of the panel, and the positions of the fingers on the panel were estimated from the center of gravity of the load. Similar systems were used by Otake et al. [12], [13].

B. Stimuli: Virtual bumps on electrostatic friction display

Three types of macroscopic virtual bumps and dents were used (Fig. 3). These virtual surfaces are expressed using Gaussian functions, as follows:

$$y = \pm A(\exp(-\frac{x^2}{\sigma^2}))^{\alpha} \tag{2}$$

where $\sigma = 1$ cm. Their shapes differ because of the different power components α, by which the shape of the Gaussian function can be changed. The larger the value of α, the steeper and narrower is the slope. In contrast, the smaller the value of α, the more gradual and wider the gradient. In the experiment, α values were 0.5, 1.0, or 2.0. The height and depth parameters A were determined such that the maximum gradients of the six types of bumps and dents were identical. For the bump and dent with $\alpha = 0.5$, $A = \sqrt{2}A_1$. For the bump and dent with $\alpha = 2.0$, $A = A_1/\sqrt{2}$. Here, A_1 was 1.0. Equal maximum gradients are important for bumps and dents. As described in Section II, the lateral resistance force generated when sliding over a bump is proportional to its gradient. Therefore, the maximum voltages applied to the panel were the same for both the bumps and dents. This condition, that is, equal maximum voltages, was set considering that surface displays have limited applicable voltages.

The relationship between the lateral frictional force $F(x)$ and applied voltage $V(x)$ is determined according to the laws of electrostatic force and Coulomb friction, as follows:

$$F(x) = \mu\{W + kV^2(x)\} \tag{3}$$

where μ, W, and k are the coefficient of friction, finger load, and electrostatic force constant, respectively. Fig. 4 shows the resultant friction forces using this formula.

The lateral force generated when a finger slides over a bump surface is expressed as a function of the surface gradient [9], [14], [15]. Thus, the voltage $V_e(t)$ to be applied is expressed as

$$V(x) = GA\sqrt{\mp\frac{\sqrt{2\alpha}}{\sigma}\exp(\frac{1}{2}-\frac{\alpha x^2}{\sigma^2})x + \frac{\sqrt{2\alpha}}{\sigma}\exp(-\frac{1}{2})} \tag{4}$$

The positive and negative signs correspond to bumps and dents, respectively. The value of G was adjusted for each participant during the training session because the perceived intensity of the stimuli varied among individuals. The resultant maximum applied voltages ranged 30–55 V among the participants.

C. Participants

Nine adults (four females) participated in the study after providing written informed consent. The participants were unaware of the study objectives.

D. Procedures

The experiments were divided into two parts: a training session and main session. Before the training session, the electrostatic friction stimulus was applied to each participant. The voltage gain gradually increased starting from a low value; it was fixed at a value where the participant could adequately perceive the stimulus.

During the training sessions, participants learned about the virtual stimuli. They were presented with six different tactile stimuli and told which stimulus corresponded to Fig. 3. Training was continued until the participants felt familiar with the stimuli.

In the main session, participants identified six randomly presented virtual surfaces. The number of trials was 60, and each stimulus was presented a total of 10 times. The participants were allowed to perceive a stimulus as many times as they wished during each trial. The experimental participant perceived the stimulus, that is, the bump or dent, from the left to right with the index finger of the right hand while holding a stainless-steel rod connected to the ground. The participants wore earplugs and earmuffs.

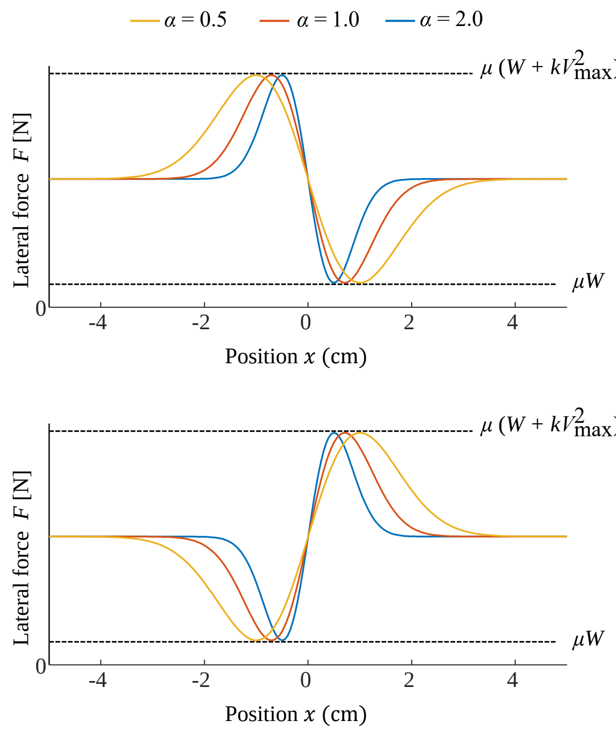

Fig. 4. Lateral forces applied to the finger while perceiving virtual bumps (upper) and dents (lower) in Experiment 1, where μ, W, and k are the coefficients of friction, load of the finger, and electrostatic force constant, respectively. $V_{\max}$ is the applied voltage, which is determined by the voltage gain adjusted to each participant.

E. Data analysis

We calculated the proportions in which the six types of stimuli were correctly identified by the participants; we also calculated the proportions in which the bumps and dents were judged correctly. For example, when a bump of $\alpha = 1.0$ was presented and the participant's answer was a bump of $\alpha = 2.0$, this answer was included in the latter proportion but not in the former. The two proportions were compared among the different stimuli.

IV. Methods: Experiment 2 using actual bumps

A. Apparatus: Lateral force presenter using leaf-spring force decoupler

The lateral force presenter shown in Fig. 5 was used when the actual bumps were perceived. The main components of the apparatus include a leaf spring, linear slider, and guide. Each participant laid his/her finger on the linear slider and moved it laterally. With this motion, the leaf spring also moved. A plastic sphere was fixed to the tip of the leaf spring, which is in constant contact with the bump and dent surfaces. The stiffness of the leaf spring is high in the lateral direction; therefore, the lateral force generated at this point is transmitted to the finger on the linear slider. In contrast, the participants could not perceive any normal displacement or force generated at the leaf-spring tip. Thus, the apparatus allowed us to remove

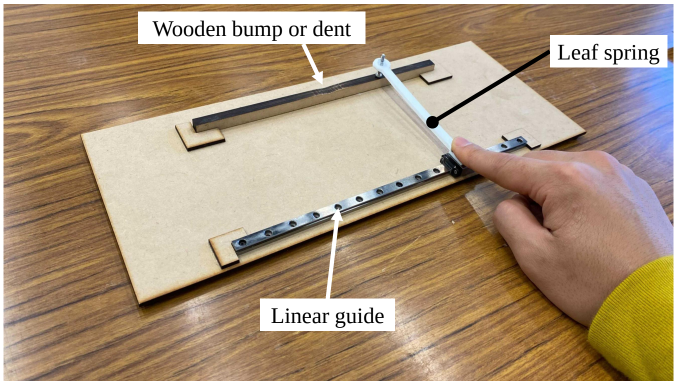

Fig. 5. Lateral force presenter using a leaf-spring force decoupler used in Experiment 2. This apparatus transmits only the lateral force generated at the contact point. The finger moves on a linear guide with no vertical displacement.

Fig. 6. Actual wooden bumps and dents used in Experiment 2. Three bumps and dents with different height/depth and width; their maximum gradients were equal.

normal cues, that is, force and displacement, when exploring surface bumps and dents.

B. Stimuli: Actual bumps

For actual surface bumps and dents, the surface displacement y (cm) along x (cm) was defined as

$$y = \pm B(\exp(-\frac{x^2}{\sigma^2}))^\alpha \tag{5}$$

where $\sigma = 1.0$ cm. Similar to Experiment 1, the α values were 0.5, 1.0, or 2.0. Their height or depth B values were determined such that their shapes could not be perfectly recognized. The surface heights were $B = 0.14$ cm for $\alpha = 0.5$, $B = 0.10$ cm for $\alpha = 1.0$, and $B = 0.071$ cm for $\alpha = 2.0$. The actual surface was created by cutting a medium-density fiberboard using a laser cutter (Hajime CL1, Oh-Laser Co., Ltd., Japan). Subsequently, the cut surfaces were polished using a #1500 sandpaper and greased. This reduced friction resulting from the surface roughness of the material.

C. Participants

Eight adults (three females) participated in the study after providing written informed consent. The participants were unaware of the study objectives.

D. Procedures of Experiment 2

Participants moved the linear slider along the x-axis using the index finger of their writing hand and explored the actual bumps and dents. The experiment consisted of training and main sessions. During the training session, they could look at and haptically explore each of the six actual bumps. This session lasted until the participants became familiar with the bumps, which typically required a few trials.

In the main session, the participants wore blindfolds and earmuffs to prevent visual and auditory cues. The number of trials was 60, with each surface shape presented 10 times in a random order. The participants were allowed to slide their fingers over a bump fewer than six times. With more or unlimited exploration, the participants could recognize the shapes nearly perfectly. After each trial, the participants answered the question that best suited their experience among the six shapes in a forced-choice manner.

E. Data analysis

We calculated the proportions in which each of the six types of stimuli was correctly identified by the participants. We also calculated the proportions at which the bumps and dents were judged correctly. The two proportions were compared among the different stimuli.

V. Results

A. Experiment 1: Virtual surface

Table I lists the mean and standard errors of the answer proportions obtained from the participants in Experiment 1. The table also shows the proportion of correct categorizations, wherein the categories of bumps and dents were judged correctly, as mentioned in Section III-E. Fig. 7 shows the correct categorization of each virtual surface. Bumps and dents with moderate height/depth and width of $\alpha = 1.0$ were most likely to be correctly categorized as bumps and dents. For the bump shapes, no significant differences were observed between $\alpha = 1.0$ and others (z-test, $p > 0.05$). For dent shapes, no significant difference was observed between $\alpha = 1.0$ and $\alpha = 0.5$; however, the shape with $\alpha = 1.0$ was significantly greater than the shape with $\alpha = 2.0$ (z-test, $p < 0.05$).

B. Experiment 2: Actual surface

Table II lists the results of Experiment 2. Fig. 8 shows the proportion of correct categorizations for each actual surface. For the bump, the shape with the greatest height and width at $\alpha = 0.5$ was most likely correctly categorized as a bump. In contrast, for the dent, the shape with the smallest depth and width with $\alpha = 2.0$ was most likely to be correctly categorized as a dent. Nonetheless, no significant differences were observed between these two α values and the others for the bumps and dents.

TABLE I

Experiment 1: Virtual condition using electrostatic tactile display. Mean and standard errors of answer proportions. Most right column shows the proportion of correct categorization into bump or dent.

			Answer						
			Bump			Dent			Correct
			$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 2.0$	$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 2.0$	categorization
Presented	Bump	$\alpha = 0.5$	0.48 ± 0.07	0.22 ± 0.06	0.12 ± 0.04	0.11 ± 0.02	0.04 ± 0.03	0.01 ± 0.01	0.82 ± 0.04
		$\alpha = 1.0$	0.26 ± 0.06	0.38 ± 0.04	0.23 ± 0.05	0.06 ± 0.03	0.06 ± 0.02	0.02 ± 0.02	0.87 ± 0.04
		$\alpha = 2.0$	0.17 ± 0.05	0.21 ± 0.05	0.41 ± 0.08	0.08 ± 0.03	0.06 ± 0.03	0.09 ± 0.04	0.79 ± 0.06
	Dent	$\alpha = 0.5$	0.04 ± 0.02	0.09 ± 0.04	0.04 ± 0.02	0.46 ± 0.09	0.21 ± 0.04	0.16 ± 0.06	0.82 ± 0.05
		$\alpha = 1.0$	0.03 ± 0.02	0.04 ± 0.02	0.03 ± 0.02	0.20 ± 0.06	0.43 ± 0.06	0.26 ± 0.07	0.89 ± 0.04
		$\alpha = 2.0$	0.02 ± 0.02	0.09 ± 0.04	0.12 ± 0.02	0.13 ± 0.06	0.20 ± 0.06	0.43 ± 0.10	0.77 ± 0.04

TABLE II

Experiment 2: Actual condition using lateral force presenter. Mean and standard errors of answer proportions. Most right column shows the proportion of correct categorization into bump or dent.

			Answer						
			Bump			Dent			Correct
			$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 2.0$	$\alpha = 0.5$	$\alpha = 1.0$	$\alpha = 2.0$	categorization
Presented	Bump	$\alpha = 0.5$	0.32 ± 0.09	0.31 ± 0.06	0.23 ± 0.05	0.04 ± 0.04	0.04 ± 0.02	0.04 ± 0.03	0.86 ± 0.06
		$\alpha = 1.0$	0.09 ± 0.03	0.34 ± 0.06	0.38 ± 0.07	0.07 ± 0.04	0.09 ± 0.05	0.03 ± 0.03	0.81 ± 0.07
		$\alpha = 2.0$	0.13 ± 0.05	0.19 ± 0.05	0.43 ± 0.08	0.08 ± 0.04	0.04 ± 0.03	0.12 ± 0.02	0.75 ± 0.06
	Dent	$\alpha = 0.5$	0.11 ± 0.06	0.06 ± 0.03	0.04 ± 0.02	0.34 ± 0.05	0.27 ± 0.04	0.18 ± 0.07	0.78 ± 0.06
		$\alpha = 1.0$	0.02 ± 0.02	0.10 ± 0.02	0.07 ± 0.02	0.20 ± 0.06	0.27 ± 0.05	0.34 ± 0.04	0.81 ± 0.03
		$\alpha = 2.0$	0.02 ± 0.02	0.06 ± 0.02	0.03 ± 0.02	0.12 ± 0.04	0.33 ± 0.04	0.43 ± 0.07	0.88 ± 0.02

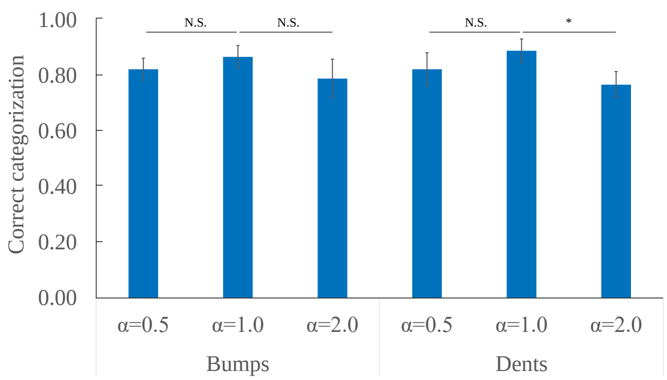

Fig. 7. Experiment 1: Virtual bumps and dents: The proportions and standard errors of correct categorization into bumps and dents. * indicates $p < 0.05$.

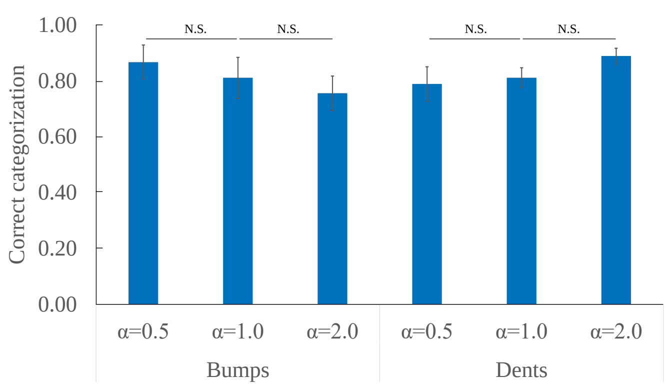

Fig. 8. Experiment 2: Actual bumps and dents: The proportions and standard errors of correct categorization into bumps and dents.

VI. Discussion

For the virtual bumps, shapes with moderate height/depth and width with $\alpha = 1.0$ tend to be correctly categorized, suggesting the existence of optimal height/depth and width for bumps/dents to be recognized. Interestingly, although the maximum gradients were the same for the three α values, the dent with $\alpha = 1.0$ was more likely to be correctly recognized as a dent. Intuitively, the maximum gradients appear to be the major determinants of the ease of recognition of the shapes. However, other factors also influence the recognition of bumps on flat touch panels. One such factor is the rate of change of the friction force. As shown in Fig. 4, the rates of change differed for different α values. When $\alpha = 0.5$, the rate of change was the smallest and change in the virtual surface shape could not be easily recognized. With $\alpha = 2.0$, the rate of change was the highest, and the surface irregularity could have been easily recognized. However, bumps and dents with $\alpha = 2.0$ tend to be incorrectly categorized. According to introspective reports from the participants, for the bumps and dents with $\alpha = 2.0$, surface irregularity was easily detected; however, the participants occasionally confused the bumps and dents. It is possible that the large rate of change in the friction force over a short period is difficult to be recognized correctly. In other words, with $\alpha = 2.0$, the change in the friction force might have been too rapid to correctly classify bumps and dents.

In the actual conditions, for both bumps and dents, no significant difference was observed in the proportions correctly categorized as a bump/dent for each shape. Moreover, the participant responses seemed different for bumps and dents. A possible explanation for this is the difference in the perceptual properties for the rate of change of the lateral force during the increase and decrease. The bump shape reached a maximum lateral force and subsequently decreased to a minimum. However, the dent shape reached a minimum in the lateral force; subsequently, it increases to a maximum. The rate of change of lateral force decreased with smaller power values α and increased with larger power values. A smaller rate of change is more likely to be perceived during an increase, whereas a larger rate of change is more likely to be perceived during a decrease, which may explain this tendency. Provided that the Weber's law holds for friction perception [16], where the just-noticeable level of friction change is nearly a constant percentage of the reference friction level, a rapid increase in friction after a rapid decrease is easier to recognize than a rapid decrease in friction after a rapid increase. Thus, the perceptual performances against bumps and dents can be different.

It is intriguing that the easy-to-recognize α values differed between the actual and virtual conditions. The root cause of this difference is unknown; however, one of the major differences between the two experimental conditions may have caused this difference in the results, that is, the slippage of the finger pad. In the virtual condition of Experiment 1, the finger pad slipped onto the touch panel, whereas it was constantly in contact with the linear slider in the actual condition of Experiment 2. Therefore, the microscopic contact conditions differed significantly between the two experiments.

VII. Conclusion

Friction variable surface tactile displays can deliver macroscopic shapes on flat touch panels. However, when the applicable voltage is limited, it is difficult to discriminate between bumps and dents based solely on the lateral force cues. We investigated the surface shapes that were easy to recognize under actual and virtual conditions, which the previous studies have not pursued. We used bumps and dents with different heights and widths; however, their maximum gradients were identical. The virtual bumps and dents with moderate heights, widths, and change rates in the friction force were likely to be recognized, suggesting that optimal ranges exist for these parameters. For the actual bumps and dents, although the statistical differences were not observed, distinctive trends were seen for the bumps and dents. Bumps with large heights and widths and dents with small depths and widths tended to be correctly recognized with relative ease. The features of easy-to-recognize bumps and dents should be studied in the future. Such studies will help developers of surface displays to present clear surface features on touch panels.

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