Short Papers

Bumps and Dents are Not Perceptually Opposite When Exploring With Lateral Force Cues

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***Abstract*—Virtual tactile bumps and dents are presented by controlling frictional forces on a surface tactile display, a flat touch screen with tactile feedback functions. This technology enables users to touch and feel three-dimensional objects. The resistive force against a sliding finger is increased and then decreased compared to a base level to present a bump. The order of increase and decrease is inverted for a dent. Thus, the difference between bump and dent presentations lies in the change order of the resistive force. However, bumps and dents are not simply opposite when investigating psychophysical functions with only lateral force cues available, without height and depth information. The results demonstrate that bumps are more easily detected with high surface gradients or resultant force changes and small widths. In contrast, these parameters do not influence the detection of dents among different participants. These findings contribute to a deeper understanding of tactile perception of surface shapes.**

***Index Terms*—Shape, convex, concave, surface tactile display, force shading.**

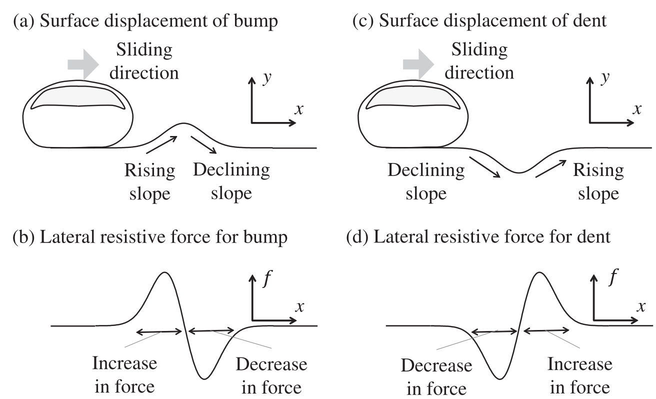

Fig. 1. Lateral resistive force when a finger slides over a bump or dent. Surface displacement and resistive force for (a, b) bump and (c, d) dent.

I. Introduction

Surface bump shapes can be discerned solely through lateral resistive forces without any vertical surface displacement by gliding a finger across the shape [1], [2], [3], as different surface shapes produce distinct lateral force patterns [4]. This discovery represents a groundbreaking advancement in surface tactile displays, creating virtual bumps and dents on flat touch panels equipped with variable friction display devices [5], [6], [7], [8], [9], [10] and facilitating more engaging and assistive haptic content development. However, surface shapes, whether bumps or dents, may not be correctly distinguished when the change in friction force is limited [11]. Hence, elucidating the specific resistive force patterns that promote accurate recognition of surface shapes is essential. However, what parameters of bumps and dents should be controlled to make them more identifiable using only lateral force cues?

Some researchers have investigated the perceptual aspects of bump stimuli in surface texture displays. Kim et al. compared preferences for three distinct friction patterns associated with bumps [5]. Their findings revealed that friction force could be better controlled by referencing the gradient of a virtual bump. This conclusion was also validated by a surface tactile display featuring force feedback capabilities [9], [12]. Haghighi Osgouei et al. demonstrated the effectiveness of increasing the base friction level in presenting bumps using an electrostatic friction-variable display, which only elevates surface friction [6]. Azechi and Okamoto compared the recognition of three types of electrostatic friction stimuli, each corresponding to the gradient functions of Gaussian functions with varying width and gradient parameters [11]. Smith et al. compared conditions involving the presentation of the bump's displacement and conditions involving the force field resulting from the surface gradient [3]. They also examined bump and dent classification in active and passive touch conditions. These studies aimed to identify effective friction patterns for presenting bumps in surface texture displays and investigate the perceptual mechanisms associated with surface shapes. However, their primary focus did not involve determining the specific parameters of force or shape profiles that influence bump and dent recognition.

Another area of research interest involves comparing bumps and dents. Previous studies [1], [3], [6], [13] have suggested that the key distinction between bumps and dents lies in the order of the rising and declining slopes, as depicted in Fig. 1. When a fingertip glides over a bump, it initially encounters the rising slope, increasing the resistive force required to overcome it. Subsequently, on the declining slope, the resistive force decreases due to the elastic properties of the skin. Hence, to simulate a bump, the friction force applied to the finger on a touch panel is first increased and then decreased. Conversely, for a dent, this order is inverted. However, our prior study [14] observed divergent discrimination behaviors among participants regarding bumps and dents. When designing their haptic content, tactile display developers must be aware of differences in the effective force profiles for bumps and dents.

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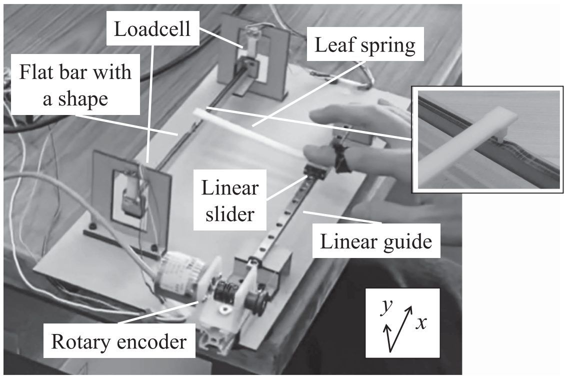

Fig. 2. Apparatus used to decouple the vertical displacement and lateral force. The specimen, a flat bar with a bump or dent at the center, was explored by a spherical end at the leaf spring tip.

This study addresses the scenario in which humans categorize surface shapes as either bumps or dents based on the variation in lateral resistive forces as a finger encounters a bump or dent. Specifically, we examine the effects of maximum gradient and width of Gaussian-shaped bumps and dents on their recognition. In the experiment, a finger is placed on a linear slider, through which a lateral resistive force is applied to the finger without its vertical displacement. A similar experiment was conducted in our previous study [14]; however, the gradient and width of the surface shape were not independently controlled, and a discussion of individual contributions to shape recognition was not undertaken.

II. Methods

A. Apparatus

We employed a force-displacement decoupling system in which a bump or dent was slid over with a plastic sphere measuring 2 mm in diameter. The resulting lateral force was transmitted to a fingertip through a leaf spring, as illustrated in Fig. 2. One end of the leaf spring was affixed to a linear slider, restricting its movement along the x-axis. Consequently, the fingertip on the slider did not experience any displacement in the y-direction (direction normal to the finger pad). A specimen bar featuring a bump or dent shape on its surface, as described in Section II-B, was positioned parallel to the linear guide. The apparatus is similar to that used in our previous experiment [14].

To measure the force profiles generated when exploring these shapes, we integrated two load cells (Micro load cell, Phidgets Inc., Canada) into fixtures designed to support the specimen. The specimen was secured by positioning the load cells with a preload on either side. The signals obtained from the load cells were processed using dynamic strain amplifiers (DPM-911 A, Kyowa Electronic Instruments Co. Ltd., Japan). The position of the linear slider along the x-axis was measured by an encoder (RE30E-500, Nidec Copal Electronics Corp., Japan, 500 pulses/revolution) with a string wound around a pulley (diameter of 10 mm) aligned with the encoder's axis of rotation. The force and position data were recorded using a data acquisition system (USB-6216, National Instruments Corp., TX) at a sampling frequency of 1 kHz. These data were not collected during the main experimental session involving the invited participants because participants would be distracted by a few tens of seconds required to reset the amplifiers.

B. Stimuli: Bump and Dent

As shown in Fig. 3, we employed Gaussian functions as the profiles for bumps and dents, with their maximum gradient and width

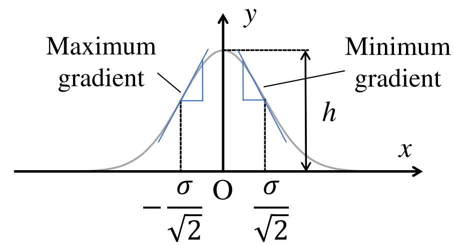

Fig. 3. Design parameters (maximum gradient and σ) of the two-dimensional Gaussian bump and dent.

TABLE I
Parameters of Bump and Dent Specimens

Maximum gradient (-)	0.0833	0.109	0.144
Width σ (mm)	5.0	8.4	14.1

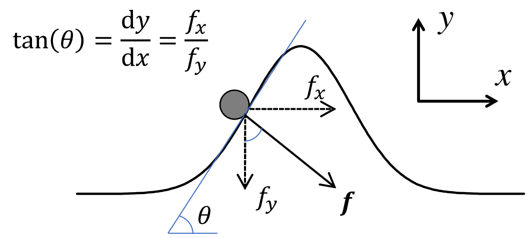

Fig. 4. Balance of contact force and gradient on a slope.

controlled across three levels, as outlined in Table I; these levels were established as geometric progressions with factors of 1.32 and 1.68, respectively. Thus, nine specimens were utilized for each bump and dent, corresponding to the three gradient levels multiplied by the three width levels. For selecting the parameter values, the authors and one of their colleagues tested 30 prototype specimens covering parameters in Table I. The parameters with which the mean proportions of accurate categorization were between 60% and 90% were then employed. These people were excluded from the main experiment.

The shapes of the bump and dent were determined using a Gaussian function as follows:

$$y(x) = \pm h \exp \frac{-x^2}{\sigma^2}, \tag{1}$$

where h and σ denote the height and width of the shape, respectively. The height or depth at $x = \sigma$ is 37% of that at $x = 0$. Gaussian functions were preferred by previous researchers [1], [3], [6] to benefit from its continuous derivative function.

When a bare finger interacts with these shapes, their height and width can be independently varied. The height and depth were not conveyed as normal displacement cues in our experimental setup. When only lateral forces were transmitted to a finger exploring the shape, the maximum and minimum lateral forces exerted a more significant perceptual influence than the height and depth. As discussed below, the gradient directly determines the maximum and minimum forces. Hence, we designated the maximum gradient as a design parameter for the stimuli.

As shown in Fig. 4, under the point contact and small-friction condition, the static contact force is balanced by

$$\frac{f_x}{f_y} = \frac{\mathrm{d}y}{\mathrm{d}x}, \tag{2}$$

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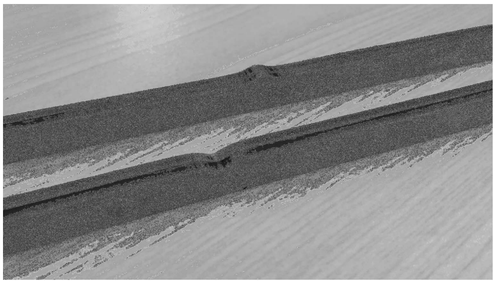

Fig. 5. Example of specimens made of middle-density fiber.

where the lateral and normal components of the contact force are denoted as f_x and f_y, respectively. This equation does not hold perfectly for the contact between a fingertip and bump [4], [13].

The maximum gradient occurs at $x = \pm\sigma/\sqrt{2}$, where the ratio of lateral to normal force reaches its peak. The maximum and minimum gradients are as follows:

$$\pm\frac{\sqrt{2}h}{\sigma}\exp\left(-\frac{1}{2}\right). \tag{3}$$

The maximum gradient depends on h and σ of the shape; hence, to independently control the maximum gradient and σ of the shape, we varied the value of h to determine the maximum gradient. For example, for a bump with a maximum gradient of 0.0833 and $\sigma = 5.0$ mm, $h = 0.49$ mm. Similarly, for a bump with a maximum gradient of 0.144 and $\sigma = 14.1$ mm, $h = 2.37$ mm.

As depicted in Fig. 5, the shape specimens were precision-cut from medium-density fiberboard using a laser cutter (Hajime, Oh Laser Co. Ltd., Japan). The cut surfaces were refined using fine abrasive papers after the cutting process. The highest and lowest parts of each specimen were measured by a caliper (Digimatic caliper, Mitsutoyo Corp., Japan; nominal resolution: 0.02 mm). The disparities in these values between the designed shapes and fabricated specimens were minimal, with errors of less than 5%.

Fig. 6 presents the lateral force profile when exploring the bumps and dents from left (negative direction of the x-axis) to right (positive direction of the x-axis). These profiles represent the mean profiles of ten measurements, during which the slider maintained a consistent speed of approximately 20–30 mm/s. The profiles for the bump and dent with the same σ and gradient values are symmetric.

C. Ethical Statement

This study was approved by the Institutional Review Board at the Hino Campus of Tokyo Metropolitan University (Approval ID: H22-31).

D. Participants

Ten university students, including two women, participated in the study and received compensation for their involvement after providing written informed consent. The study objectives were not disclosed to the participants prior to the experiment.

E. Procedures

In the training session, participants, while wearing earmuffs, placed their second finger of the writing hand on the linear slider and moved it along the x-direction. They explored bumps and dents not used in the subsequent main session to understand the lateral forces generated by these shapes' rising and declining slopes. Participants had the opportunity to visually inspect the specimen shape placed on the apparatus during this session. This training session lasted approximately 5 min, during which participants familiarized themselves with the resistive forces produced by these specimens. They were encouraged to determine an appropriate hand speed at which the shapes could be discerned and were instructed to use this speed in the subsequent main session. It was empirically shown that realizing an irregularity on a flat surface at extremely high speeds is easy, but classifying it into a bump or dent is difficult. In contrast, it is difficult to notice shapes at extremely slow speeds.

In the main session, participants were blindfolded, and 180 trials were conducted for each individual (comprising 18 types of specimens multiplied by 10 blocks). The specimens were presented in a randomized order within each block, comprising 18 trials. In each trial, participants were permitted to explore the shape twice. They moved the slider from left to right across the shape and then reversed from right to left before responding to whether the shape was a bump or a dent in a forced-choice manner. After every 36 trials, participants took a 3–5 min break.

TABLE II
MEAN PROPORTIONS AND STANDARD ERRORS OF CORRECT ANSWERS FOR BUMPS

		Maximum gradient (-)		
		0.083	0.109	0.144
Width (mm)	5.0	0.79 ± 0.048	0.84 ± 0.036	0.91 ± 0.028
	8.4	0.74 ± 0.039	0.80 ± 0.047	0.86 ± 0.039
	14.1	0.65 ± 0.036	0.64 ± 0.034	0.79 ± 0.033

F. Analysis

As shown in Fig. 7, for individual participants, the proportions of correct answers for either bumps or dents were approximated using a logistic curve, used to model a probability distribution function, with the maximum gradient and width of bumps or dents as the explanatory variables. The regression equation is as follows:

$$p = \frac{1}{2}\frac{1}{1+\exp\left(-(a_1x_1 + a_2x_2 + c)\right)} + 0.5, \tag{4}$$

where p, x_1, and x_2 denote the proportion of correct answers, maximum gradient, and width, respectively. The maximum gradient and width coefficients are denoted as a_1 and a_2, respectively, and the constant value in the exponential function is represented by c. For the approximation, the maximum-likelihood method was employed. In the exponential function, we employed the linear summation of the first-order terms. This is because, for most participants, the multiplicative term coefficients, including x_1^2, x_1x_2, and x_2^2, did not significantly differ from zero in the preliminary analysis when determining the model function using the least-squares method.

The χ^2 statistic was used to gauge the deviance level between the model equation and observed proportions. To test the goodness of fit of the model, the Hosmer-Lemeshow test, based on χ^2, was used, with a critical value for the rejection region set at $\chi^2(7) = 14.1$ at $p = 0.05$. If the data of a particular participant were determined not to fit the regression model, their data would not be used for subsequent analyses. However, all individuals' data were retained based on the Hosmer-Lemeshow test results.

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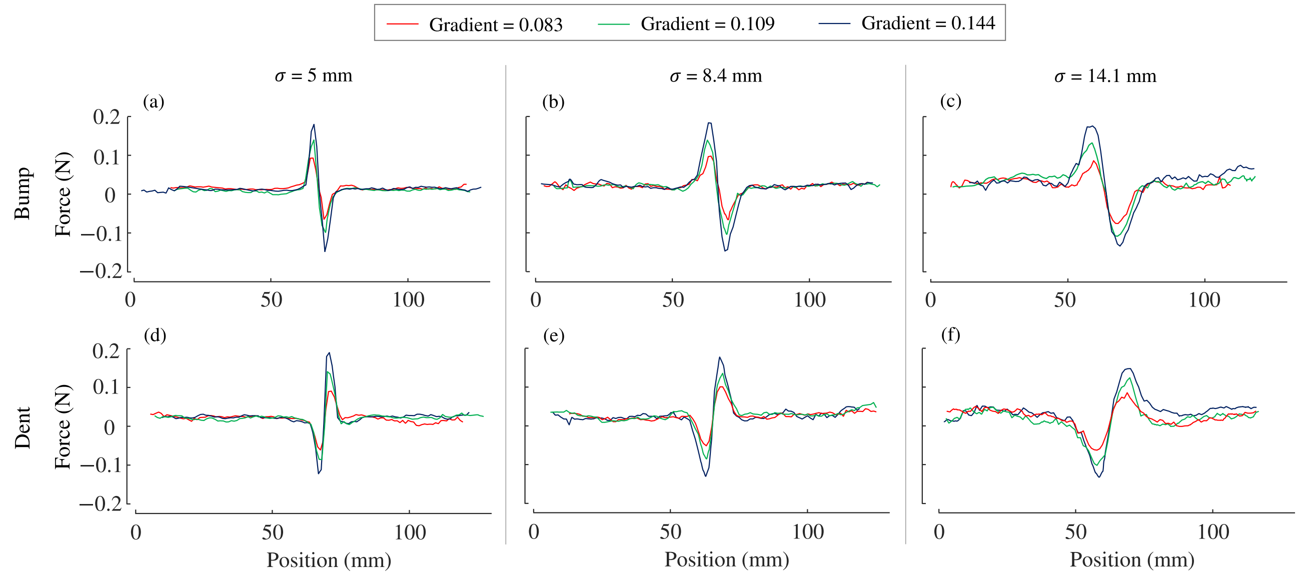

Fig. 6. Profiles of resistive forces when sliding a finger across a bump (a)–(c) and dent (d)–(f) from left to right. Each profile is the mean of ten measurements. Negative values indicate assistive force.

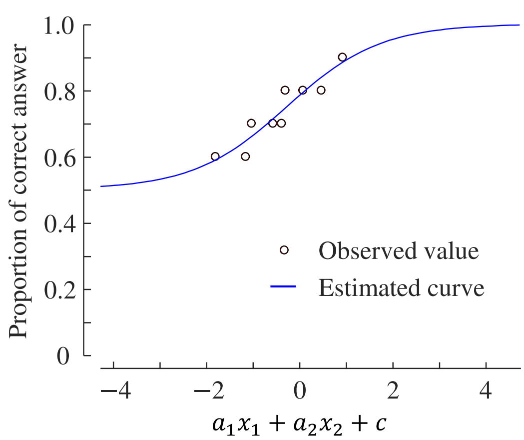

Fig. 7. Example of logistic regression analysis of the correct answer proportions against bumps. Data of Participant 9 (P9).

TABLE III
MEAN PROPORTIONS AND STANDARD ERRORS OF CORRECT ANSWERS FOR DENTS

		Maximum gradient (-)		
		0.083	0.109	0.144
Width (mm)	5.0	0.78 ± 0.062	0.76 ± 0.055	0.82 ± 0.054
	8.4	0.72 ± 0.021	0.79 ± 0.037	0.70 ± 0.055
	14.1	0.77 ± 0.048	0.67 ± 0.047	0.74 ± 0.053

III. RESULTS

Tables II and III display the mean correct answer proportions for bumps and dents, respectively. The mean correct proportions for bumps and dents were 0.78 and 0.75, respectively. A Wilcoxon signed-rank test revealed no significant difference between these proportions ($T = 1541$, $p = 0.12$).

Table IV provides the partial regression coefficients obtained from the logistic regression analysis. Regarding bumps, the mean coefficient for the gradient is significantly greater than zero ($t(9) = 3.36$, $p = 0.0084$, two-tailed t-test). Similarly, the mean coefficient for the width is significantly smaller than zero ($t(9) = -7.37$, $p = 4.22 \times 10^{-5}$, two-tailed t-test). These coefficients indicate that bumps with a steeper gradient and narrower width are more easily recognized. Appendix shows the logistic curve for bumps based on the average results among the participants. It also compares the influences of the maximum gradient and width on the accuracy of shape classification. In contrast, for dents, the mean coefficient for the gradient and width (($t(9) = -0.27$, $p = 0.79$, two-tailed t-test) and ($t(9) = -0.85$, $p = 0.42$, two-tailed t-test), respectively), are significantly different from zero. Thus, the accuracy of recognizing dents is not influenced by the gradient or width.

IV. DISCUSSION

The finding that bumps with greater gradients were more easily recognized is consistent with the idea that the lateral force magnitude is a key for recognizing surface shapes. A smaller width rapidly changes the lateral force, enhancing the detection of shape cues. The force change rate is more perceptually influential than the force magnitude, a concept supported by others [15], [16], [17]. However, making the width too small may not necessarily lead to easier shape categorization. If the force changes rapidly over a short time, of the order of tens of milliseconds, the order of force changes may not be correctly judged due to temporal masking effects [18], [19], [20]. While earlier studies on temporal masking effects have not specifically examined a situation similar to the problem in this study, excessive rapid lateral force changes could be prone to misjudgment. Exploring the effects of σ values smaller than those used in this study might reveal that the correct answer proportion for bumps could reach a local maximum at a certain σ value. However, bumps with even smaller σ values might not be accurately categorized due to the rapid changes in the produced force.

While the effects of gradients and widths of bumps on recognition were discernible, we identified no common perceptual influences of shape features when recognizing dents. One possible explanation is that participants might have chosen the "dent" option when uncertain whether they were encountering a bump. If such a negative bias were present, we would expect the correct answer proportion for dents

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TABLE IV
REGRESSION COEFFICIENTS OF LOGISTIC REGRESSION ANALYSIS

Participant	Bump				Dent			
	Max. gradient	Width (σ)	Constant	Deviance (χ^2)	Max. gradient	Width (σ)	Constant	Deviance (χ^2)
P1	51.2	-0.37	-1.3	4.7	-3.7	-0.17	0.8	3.7
P2	52.5	-0.20	-2.6	7.7	-26.1	0.0	2.9	3.4
P3	16.1	-0.23	-0.4	1.9	10.9	0.09	5.4	10.1
P4	57.0	-0.04	-5.2	13.3	35.2	-0.16	-0.9	7.3
P5	11.4	-0.27	1.4	2.0	8.6	0.26	-4.0	7.7
P6	-6.1	-0.17	3.2	13.5	6.0	-0.27	-2.4	9.8
P7	34.8	-0.28	-2.6	3.7	-7.3	0.31	-1.9	12.8
P8	-10.2	-0.24	4.2	3.9	-15.7	-0.12	3.9	7.2
P9	20.5	-0.17	-0.3	0.5	-8.6	-0.23	2.1	0.6
P10	24.7	-0.13	-1.7	0.5	-14.1	0.13	-0.3	0.8
Mean	25.2	-0.21	-0.5		-1.5	-0.06	0.7	
SE	7.5	0.03	0.9		5.5	0.07	0.8	

to be higher than that for bumps. However, the proportions of correct answers for bumps and dents were close, suggesting that dents were not consistently selected as the default response with increasing uncertainty.

Based on the introspective reports provided by participants after the experiment, most participants concurred on a common strategy for categorizing shapes. They categorized the shape as a bump if they perceived an increase in lateral force or a slight sticking sensation followed by a subsequent decrease in force. Conversely, when the order of these sensations was reversed, they categorized the shape as a dent. Furthermore, participants acknowledged that detecting the increase in force was relatively easy but had difficulty recognizing the decrease in force when exploring the surface.

This observation leads to the speculation that the accurate categorization of bumps and dents depends on how distinctly the drop in lateral force is perceived. If this speculation were accurate, one might expect recognizing bumps to be easier than that of dents because bumps cause a substantial drop in lateral force after reaching their peak, as shown in Fig. 6. However, the proportions of correct answers were nearly equal for bumps and dents, casting doubt on this speculation.

The distinction in recognizing bumps and dents might be influenced by the Weber fraction associated with lateral or friction forces [14], [21]. According to the concept of the Weber fraction, a slight change in force Δf is more perceptible when it follows an immediate decrease in the base force level F. Let F_0 and F_1 represent two base force levels, with $F_0 > F_1$. In such a scenario, the inequality of Weber fractions holds:

$$\frac{\Delta f}{F_0} < \frac{\Delta f}{F_1}. \tag{5}$$

However, in our problem, applying Weber fraction may not be straightforward. This is because the sign of the lateral force experienced by the participant changes when exploring the shape. When the tip of the slider traverses a rising slope, the lateral force is resistive (positive in Fig. 6); in contrast, when it descends a declining slope, the lateral force becomes assistive (negative in Fig. 6). Weber fractions have not been extensively discussed for situations involving such sign changes in lateral force.

Temporal masking effects [18], [19], [20] may also pertain to the difference between the bump and dent recognition. When encountering a bump, the succeeding decrease in the lateral force due to the declining slope may be perceptually obscure, provided an increase in the lateral resistive force is prominent. In contrast, for a dent, a rising slope may mask the immediately preceding decline in a backward manner. The temporal masking effects for the lateral force will be studied in the future.

The experimental results suggest that the factors influencing the recognition of bumps and dents differ, but the specific reasons remain unclear. Additional studies are needed to investigate this further. One promising approach is to expand the parameter space used in the experiment. In this study, the mean correct answer proportions for the nine types of bumps and dents ranged from 0.64 to 0.91 and 0.67 to 0.82, respectively. Therefore, it may be necessary to magnify the parameter space such that the correct answer ratios for dents vary more substantially to identify the feature parameters influencing the recognition of dents. Additionally, it is worth considering whether the exploratory motions employed for bumps and dents differ. In this study, participants were allowed to explore each shape twice, potentially adapting their second exploration based on their experiences from the first. Therefore, limiting the number of explorations to one could be considered. However, the experimenters observed no apparent differences in exploratory motion between bumps and dents.

Furthermore, differences in hand speed among the participants can be a key to elucidating the individual differences in the parameter coefficients in Table IV. Especially, the coefficients for dents than those for bumps varied among the participants. Such differences may be explained by analyzing participants' hand motions, although we did not record them in the main experiment. Therefore, we invited eight of the ten participants on different days and conducted tasks similar to the main experiment but including a small number of trials, i.e., 20 trials, while measuring the hand speeds. The mean hand speeds of individuals ranged from 25–44 mm/s with moderate variations. Further, the means and standard errors of the speed for the first (37.2 $\pm$ 8.1 mm/s) and second exploration (33.0 $\pm$ 7.3 mm/s) exhibit no substantial difference ($t(7) = 0.58$, $p = 0.62$, t-test for repeated measures).

V. CONCLUSION

For a considerable time, it has been established that macroscopic surface shapes can be conveyed using two-dimensional haptic or tactile displays without invoking normal displacements and forces [1], [2]. Nevertheless, the factors determining the discriminability between bumps and dents when presented via lateral forces remained unexplored. Our experiment revealed that bumps with greater gradients and narrower widths were recognized more accurately. However, these parameters did not exert a significant influence on dent recognition. Moreover, it was believed that the primary difference between bumps and dents lay solely in the order of the increase and decrease in lateral force. However, this study has unveiled the distinction in the perceptual criteria used to differentiate between them. These findings are specific to Gaussian-shaped bumps and dents, and further research is needed to explore their applicability to different shapes and scenarios in the future.

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