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Haptic perception of 2.5D surface feature height

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The present study investigates the human haptic perception of 2.5D dome-shaped surface features in terms of difference and absolute thresholds. We conducted two experiments to measure the thresholds, analyzing the effect of sample base area, or diameter, and surface material compliance. In Experiment 1, the difference threshold for 2.5D surface feature height was measured for three different sample base diameters, 1.4, 2.8, and 5.6 mm. The results indicated a decreasing trend in Weber fraction, i.e., higher sensitivity, with an increase in the sample base diameter. The effect of surface material compliance was found to be insignificant. Further analysis indicated the decreased Weber fraction with an increase in base diameter for shapes with a smaller reference height-to-diameter ratio. However, the effect of base diameter became insignificant for a larger reference height-to-diameter ratio. In Experiment 2, the absolute threshold was measured for three sample base diameters, 1.4, 2.8, and 5.6 mm. The experimental result showed a clear linearly increasing trend in the absolute threshold as the sample base diameter increased, which is consistent with a previous study.

A human can achieve subtle physical information, such as surface texture, shape, or geometry from the sense of touch, that cannot be readily acquired by visually seeing it. In this connection, current smart devices actively utilize the sense of touch by providing haptic feedback to a user. For example, many of the current smartphones have the functionality of creating the sensation of pushing a button by generating a vibratory signal. Among various types of current haptic technologies for smart devices, one of the advanced haptic feedback technologies is creating 2.5D shapes by physically changing the surface by using different types of actuators. A 2.5D shape can be defined as a height-relief surface that is not fully volumetric, as defined in previous studies[1,2]. Our research team recently implemented a surface-morphing display that can create not only haptic sensation but also provide visual information. However, various obstacles still have to be resolved, one of which is the lack of standards on how high the haptic surface resolution should be. This motivated us to study human perception for 2.5D shape on a flat surface.

Haptic perception of surface shape at the fingertip has long been studied in terms of absolute thresholds. Neurophysiologists conducted a series of studies on the absolute threshold for sub-millimeter surface features. Johansson and LaMotte measured human perception threshold height for dots with the radii ranging between 40 and 602 μm and found the absolute threshold increased as the diameter decreased[3]. LaMotte and Whitehouse's study indicates that the height absolute threshold for a raised dot with a diameter of 550 μm is between 1 and 3 μm, which can be explained with the response of RA mechanoreceptors[4,5]. Kennedy et al. used an active exploration task to detect microscale bumps for clinical assessment of neuropathy[6]. They established a healthy absolute threshold of 3.3 μm and demonstrated that it correlated strongly with the density of Meissner corpuscles in the fingertip. More recently, Reschechtko et al. explored the active movement strategies employed for the detection of single, microscale features (2–10 μm height) on a smooth surface[7]. In a paradigm restricting participants to a single exploratory sweep, they found that individuals used significantly higher contact forces (about 2 N) and moderate scanning speeds (45–50 mm/s) than observed in other tactile tasks. This strategy, which enabled reliable detection of features as small as 2 μm, was hypothesized to increase the predictability of sensory input by minimizing mechanical noise from 'stick-slip' events. The information on the absolute thresholds, however, still needs to be extended to larger shapes for practical applications.

Meanwhile, haptic discrimination has also been actively studied for relatively large surface shapes. Goodwin et al. measured the curvature difference threshold of 4.9 m^{-1} for spherical shapes around the size of a fingerpad and derived the Weber fraction around 0.1[8]. Louw et al. have extensively studied human haptic perception of curved surfaces sensed with an active touch[9–11]. Wheat and Goodwin investigated the discrimination of 'edge' curvature. Through experiments where annular segments were passively applied to the fingerpad, they found that humans could discriminate differences in curvature of approximately 20–23 m^{-1}[12]. Furthermore, by simulating peripheral neural population responses, they demonstrated that the spacing of receptive fields

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perpendicular to the edge was more critical for resolution than the overall innervation density. The results of previous studies indicate a human shape feature discrimination mechanism that largely depends on the slope/edge information of the shape. Overall, previous studies provide information on how humans perceive surfaces in a wide range, with tactile sensation. However, there is still missing information on the difference threshold for sub-fingerpad-size shapes.

While the haptic perception of compliance has been studied in depth so far, its effect on the haptic perception of surface features is a relatively less studied subject, especially when the surface is touched with a bare fingertip. Previous studies indicate that both cutaneous and kinesthetic information at the fingertip contribute to shape perception and object identification[13–18]. There are also grounds that cutaneous and kinesthetic information contribute to the haptic perception of compliance perception[19]. Then, assuming partial contributions of both cutaneous and kinesthetic information to the compliance perception, one can expect that the surface shape perception can be affected by the compliance. More direct ground for the significance of compliance to the perception of shape can be found in multiple studies. Previous studies where kinesthetic haptic interfaces rendered virtual objects showed significant effects of compliance on haptic shape perception[20–22]. Meanwhile, Song et al. investigated the effect of compliance on shape perception with relatively large samples and reported an insignificant effect of compliance[23]. Overall, while the effect of compliance on shape perception has been exclusively studied, its effect on shape perception still needs further investigation, especially when the size of the shape is less than the fingertip level.

This study investigates human perception of 2.5D surface feature size in terms of absolute and difference thresholds. Our research team has been developing a surface morphing tactile display that can be used for information transfer[24,25]. It can render haptic shape features in the form of a 2.5D dome on a flat surface. A dome shape was selected as a basic haptic shape unit because a combination of multiple domes can render an arbitrary 2.5D shape on a flat surface. We further investigated the haptic perceptual dimension of spatial height patterns, consisting of multiple dome shapes that can be rendered with a surface morphing display[26]. While the haptic perception of surface features has been actively studied in various features, we could not find perception data on the dome shape to serve as a reference for the surface morphing display that can render random 2.5D shape configurations.

Thus, the first goal of this study is to find the human perception threshold for a dome shape for different areas, i.e., diameters at the base. We focus on 2.5D dome shapes with fingerpad-relevant diameters ranging from 1.4 to 5.6 mm. Determining human size-perception thresholds is crucial, as these limits define the capabilities of current surface-morphing displays for haptic applications[26]. However, perceptual thresholds for dome shapes within this specific size range have not been systematically examined in prior work. Another practical question we encountered is how surface material affects the human perception of dome shapes, which could not be addressed in previous studies. In this regard, the next goal of this study is to evaluate the effect of sample compliance on the haptic perception of a dome shape. To achieve the answers to the research questions, we conducted two experiments that measured the absolute and difference thresholds for two different sample compliances.

The rest of this paper is organized as follows. The first experiment measured the difference threshold for the dome-shaped 2.5D feature height. Then, we present the second experiment that measured the absolute threshold for a dome shape. Finally, we discuss the implications of the experimental results.

Experiment 1: haptic difference threshold of 2.5D surface feature height

This experiment evaluated the difference threshold of a 2.5D dome shape feature height for the reference samples with three different base diameters, 1.4, 2.8, and 5.6 mm. The experiment was conducted as a psychophysics experiment paradigm, the method of limits[27]. The effect of compliance on the difference threshold was also tested by conducting the experiment with samples in two different materials.

The experimental methods were approved by Hongik University Institutional Review Board with No. 7002340-202203-HR-002 and the experiment was performed in accordance with the Declaration of Helsinki.

Methods

Participants

Fifteen participants (seven males and eight females; 19–28 years old, mean±SD = 22.53±2.07 yrs) took part in the experiment. The participants had no known sensory disorders by self-report and were compensated for the experiment. Informed consent was obtained from all participants.

Stimuli

Figure 1 shows the layout of a 2.5D surface feature sample. A 2.5D dome shape was embedded on a plane whose shape is defined as part of a sphere, with its height *h* and base diameter *d*. To see the effect of diameter and height of a dome on haptic discrimination of 2.5D surface features, three different diameters were used for reference stimuli. For each diameter, reference samples with four different heights were fabricated as $h_{ref} = \{0.05, 0.1, 0.2, \text{ and } 0.4\}/1.4 \times d_{base}$ (Table 1). The selected base diameters d_{base} values were decided to include the dot base diameter size by UEB (United English Braille) and the tactile display base size for the previous surface-morphing display study[25]. The range of reference sample height, h_{ref}, was decided to be proportional to d_{base}, to keep the slope information constant, considering the effect of slope on haptic shape discrimination. We also selected the h_{ref} values to encompass the height range achievable by the surface-morphing display in the previous study[25].

To test the effect of compliance, reference samples with two different compliances (*soft*: 8.5 MPa and *hard*: 1.6 GPa) were fabricated for each dimension. Dome-shaped samples were fabricated by casting a monomer resin into stainless steel molds, followed by UV curing. The molds were precision-machined to have specific diameters and heights. Commercial hard-type and soft-type UV resins were cast, respectively, onto a flat stainless steel

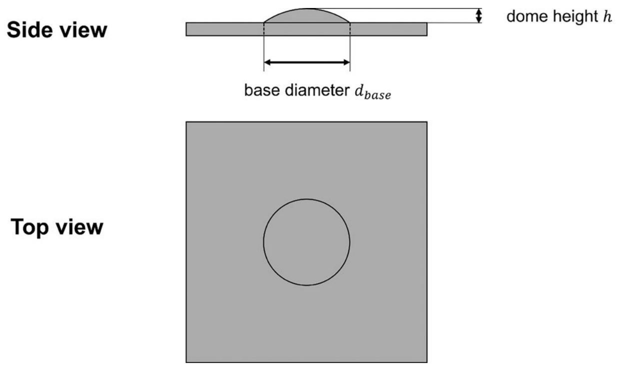

Fig. 1. Layout of a 2.5D tactile sample for the experiments.

d_{base} (mm)	h_{ref} (μm)
1.4	50
	100
	200
	400
2.8	100
	200
	400
	800
5.6	200
	400
	800
	1,600

Table 1. Heights h of 2.5D samples by the base diameter d_{base}.

plate featuring a 200 μm-thick polyimide spacer using a doctor blading process. The cast resins were then solidified into films via photo-crosslinking by exposure to UV light (wavelength: 360 nm) for 5 minutes. Finally, the resulting films were detached from the stainless steel plate.

For each reference sample, a total of five test samples were fabricated whose heights were

$$h_{test} = (1 + \epsilon)\, h_{ref}, \tag{1}$$

where ϵ were 0.05, 0.1, 0.2, 0.3, and 0.5. The values for ϵ was decided to include the result of a previous study by Goodwin et al.[8]. In their study, the difference threshold for curvature perception at the fingerpad was approximately 0.1. Given the limits of our mould fabrication resolution, the smallest feasible value for ϵ in sample fabrication was 0.05. The height of each sample was measured using an optical 3D profiler (VR-3200, Keyence Corporation, Japan), and only those with a deviation of less than 5% from the target height were selected for the experiment.

Apparatus
For this experiment, we built an apparatus that can present two 2.5D feature samples to a participant as requested by a computer program made in Visual Studio C++, using OpenGL. The apparatus consists of a rotating disk mechanism inside a box that visually blocks the 2.5D samples from a participant. The disk has a diameter of 29 cm, where up to sixteen samples can be installed as shown in Fig. 2. On the disk, the reference and test samples are alternately arranged. During an experiment, the apparatus was enveloped by a box where only two samples, i.e., one reference and one test sample, were exposed to the participant for each trial. A cloth was attached to the opening to block a possible visual cue from the apparatus. The position of the rotating disk is controlled with a Dynamixel smart actuator (XC430-W15Q-T, Robotis Inc., Korea), so that the computer program can select a test sample and decide whether to position the test sample to the left or to the right. The command to position the samples on the disk is sent via serial communication, bypassed with a microcontroller (Arduino Uno, Italy).

Procedure
The experimental procedure was implemented following the experimental paradigm of the method of limits[27]. Before the experiment, a participant signed a consent form, and an experimenter instructed him/her about the purpose of the experiment and the procedure. After that, the participant was seated in front of a desk where the

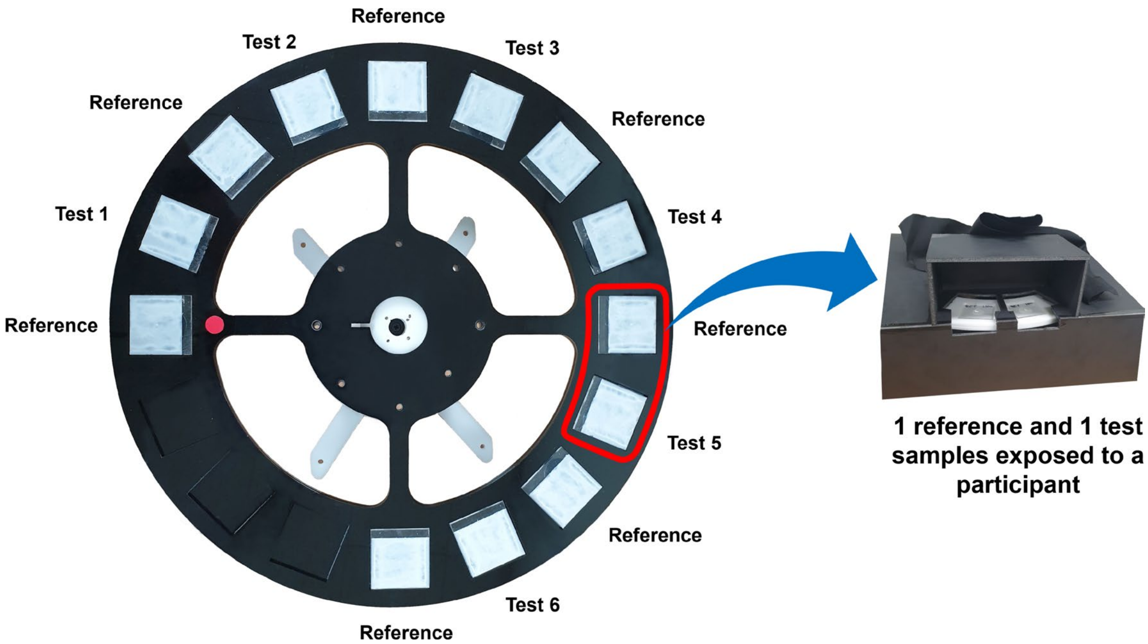

Fig. 2. Experimental apparatus. The test and reference samples are alternately placed on an experimental disk, and only one test sample and one reference sample are exposed to a user during the experiment. A cloth is attached to the opening to cover a participant's hand, blocking visual cues from the apparatus.

experimental apparatus was set up, and was asked to wear noise-cancelling headphones. When s/he was ready, the participant launched the experimental program, which asked him/her to type the ID that could hide his/her identity. The experiment started with the tallest 2.5D test sample, which was randomly located on the left or right. In the method of limits, both ascending and descending series are employed to mitigate response bias[28]. Implementing the ascending series requires fabricating multiple samples near h_{ref} with micrometer-scale step increments, which led to substantial size deviations in the final fabricated samples. For this reason, we decided to employ only the descending series for the experiment. Nonetheless, the potential limitations associated with using a descending-only procedure should be acknowledged. In another slot, the reference stimulus was located. The participant could freely feel the two stimuli with his/her index fingertip without time limit. Then, the participant typed the answer to a question asking whether s/he felt the height difference between the two samples by typing either with "Y" (yes) or "N" (no). When the answer was "yes", the experimental disk rotated to present the tallest test sample among the ones smaller than the previous test sample. When the answer was "no", the experimental program terminated. The experiment was repeated four times for one reference height h_{ref}. Thus, the experiment consisted of 4 (number of repetitions) $\times$ 12 (number of reference sizes) $\times$ 2 (number of compliance) = 96 experimental blocks. There was a five-minute break for every two experimental blocks. It took 2 hours for a participant to complete the experiment on average.

Data analysis
The experimental results evaluated the difference threshold as the averaged height of two samples, the last sample with the answer "yes" and the sample with the answer "no", which is typical for a method of limits[27]. The difference thresholds for the four repetitions were averaged for each h_{ref}. Then, the averaged difference threshold was converted to a Weber fraction by dividing it by h_{ref}. Next, given a base diameter d_{base}, the Weber fractions were averaged across different d_{base} values. For the mean Weber fractions, we analyzed the effect of the diameter d_{base} and the sample compliance using repeated measures ANOVAs. Additionally, we analyzed the Weber fractions by h_{ref}/d_{base} since the reference height range was decided to be proportional to d_{base}.

Results
Figure 3 shows the results of Experiment 1. We examined the main effect for the three surface feature variables. For the Weber fractions of 2.5D surface feature height, we applied a two-way repeated measures ANOVA with the factors, d_{base}, and sample compliance. The results indicate a significant effect of diameter $(\mathrm{F}(2, 28) = 12.315, \mathrm{p} < 0.001, \eta_p^2 = 0.468)$ on the Weber fraction, i.e., the perception of 2.5D sample height perception. Sample compliance did not have a significant effect on Weber fraction of 2.5D surface features ($F(1, 14) = 0.822$, $p = 0.38$, $\eta_p^2 = 0.055$). We represented the mean Weber fractions with d_{base} by sample compliance in Fig. 3(a). In a subsequent Bonferroni post-hoc analysis following the ANOVA on the Weber fraction for 2.5D sample height perception, significant differences in the Weber fraction were found for the pairs d_{base}=1.4 and 2.8 mm (p=0.004), and d_{base}=1.4 and 5.6 mm (p=0.002). It means a generally decreasing trend of the Weber fraction with an increase of d_{base}.

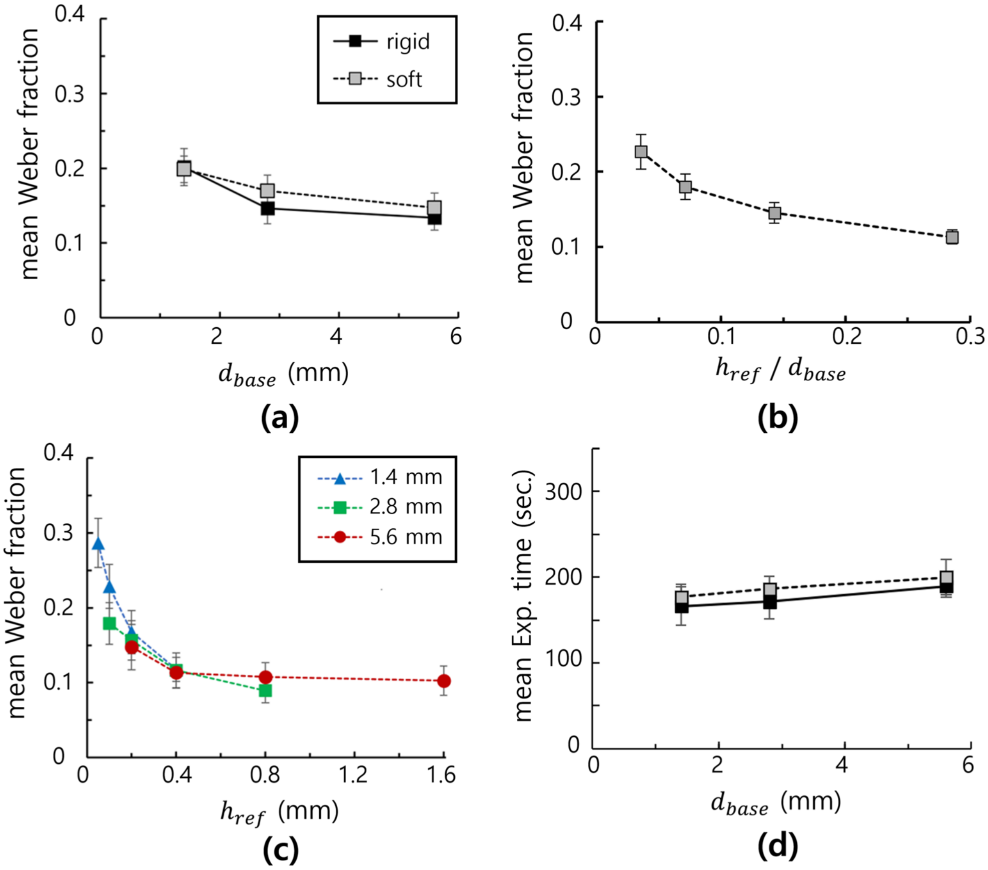

Fig. 3. Results of Experiment 1. (a) Mean Weber fractions of 2.5D surface feature height by sample base diameter d_{base} and sample compliance; (b) Mean Weber fractions by h_{ref}/d_{base}; (c) Mean Weber fractions versus h_{ref} by d_{base}; (d) Mean experiment time by sample base diameter d_{base}. Error bars indicate standard errors.

Additionally, we analyzed the effect of the slope of surface feature, expressed with h_{ref}/d_{base}, on the Weber fraction, which was reportedly to affect haptic shape perception (Fig. 3 (b)). When a repeated measures one-way ANOVA was applied to the Weber fraction with the factor h_{ref}/d_{base}, a significant effect was observed (F(3, 42) = 20.396, p < 0.001, η_p^2=0.593). A following Bonferroni post-hoc analysis showed that significant differences between all slope pairs (p=0.001 between h_{ref}/d_{base} = 0.05/1.4 and 0.1/1.4; p=0.003 between h_{ref}/d_{base} = 0.05/1.4 and 0.2/1.4; p=0.021 between h_{ref}/d_{base} = 0.05/1.4 and 0.4/1.4; p=0.007 between h_{ref}/d_{base} = 0.1/1.4 and 0.4/1.4; p=0.044 between h_{ref}/d_{base} = 0.2/1.4 and 0.4/1.4;) except for the slope pair, h_{ref}/d_{base}=0.1/1.4 and 0.2/1.4 (p=0.095). The results show a generally decreasing trend in the Weber fraction with an increase of the surface feature slope h_{ref}/d_{base}.

Figure 3 (c) shows the mean Weber fraction by h_{ref} for the three d_{base} values. Because the range of h_{ref} varied with d_{base}, we plotted the Weber fraction for each (d_{base}, h_{ref}) pair by dividing the corresponding difference threshold by h_{ref}. The Weber fraction monotonically decreased with the height of surface feature, h_{ref}, approaching 0.1 at the higher end of the tested range.

Additionally, we analyzed the effect of d_{base} and sample compliance on the experiment time for each condition (Fig. 3 (d)). When a two-way repeated measures ANOVA was applied with the factors d_{base} and sample compliance, no significant effect was found for either factor (F(2, 28) = 1.846, p = 0.177, η_p^2 = 0.116 for d_{base}; F(1, 14) = 0.515, p = 0.485, η_p^2 = 0.035 for sample compliance).

The results of Experiment 1 indicate that the Weber fraction decreased as the base diameter increased for shapes with a smaller reference height-to-diameter ratio, but tended to converge for a larger reference height-to-diameter ratio. The effect of sample compliance did not affect haptic discrimination of 2.5D surface feature height.

Experiment 2: haptic absolute threshold of 2.5D surface feature height

This experiment measured the absolute threshold of 2.5D dome shape feature height for samples with three base diameters, 1.4, 2.8, and 5.6 mm. As was the case for Experiment 1, the method of limits was selected as an experimental paradigm.

Methods

Participants

Fifteen participants (nine males and six females; 20–26 years old, mean±SD = 23.47±1.41 yrs) were newly recruited for the experiment. The participants had no known sensory disorders by self-report and were compensated for the experiment. Informed consent was obtained from all participants.

Stimuli

The result of Experiment 1 indicated no significant effect of sample compliance on the haptic perception of 2.5D surface feature height. Thus, this experiment was conducted with only rigid samples. Sample layout is the same as Experiment 1 (Fig. 1). The base diameters, d_{base} were 1.4, 2.8, and 5.6 mm, the same as Experiment 1. The sample heights for test samples were 1.25, 2.5, 5, 10, 20, 40, 80, and 160 μm. The molds for fabricating samples with heights of 1.25–5 μm were produced on a quartz wafer via a laser lithography process, which is similar to the method in LaMotte et al's study[4], as mechanical machining was not feasible due to precision limitations. In contrast, the molds for heights of 10–160 μm were created by the precision-machining of stainless steel, identical to those used for the difference threshold sample fabrication. The samples were fabricated by casting a monomer resin into the molds, followed by UV curing. Subsequently, the height of each sample was measured using a 3D optical profiler (PLu neox, Sensofar, Spain), and only those with a height deviation within 5% (10–160 μm) or 10% (1.25–5 μm) of the target value were selected for the experiments.

Apparatus

The same rotating unit as Experiment 1 was used for Experiment 2. On each experimental disk, eight test samples whose height ranged from 1.25 to 160 μm were alternately located along with flat-surfaced samples (Fig. 4). As was the case for Experiment 1, only two samples, one flat and one test sample, were exposed to a user.

Procedure

The experimental procedure was designed according to the absolute threshold measurement for the method of limits[27]. Pre-experimental procedures were the same as Experiment 1. The measurement was conducted for a descending series, which means the stimulus height decreased as the experiment proceeded. As in Experiment 1, the method of limits typically employs both ascending and descending series to estimate absolute thresholds. However, implementing the ascending series would require fabricating numerous sub-threshold samples at finely spaced levels, demanding high mould-resolution and resulting in substantial dimensional errors. Therefore, only the descending series was used in this experiment. The potential bias associated with this approach is acknowledged. The experiment started with the tallest test sample, whose height was 160 μm (Fig. 4). On each trial, a participant felt two samples, one flat sample and one test sample. Whether the test sample was on the left or not was randomized by the experimental program. Then, the experimental program asked whether the heights of the two samples were equal or not. If the answer was "no", the experiment continued, and the test sample's height was increased by rotating the experimental disk. The experimental block terminated when the answer was "yes". For each participant, the experiment was repeated four times for each diameter and descending series (Fig. 5).

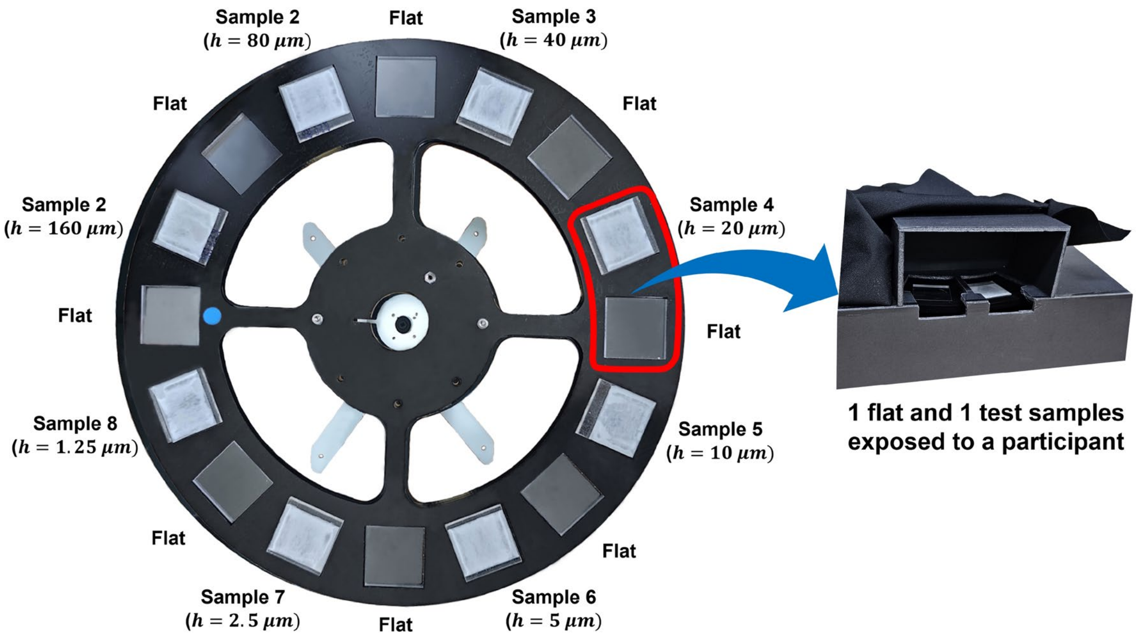

Fig. 4. An experimental disk for Experiment 2. The test and flat samples are alternately placed on an experimental disk, and only one flat sample and one test sample are exposed to a user during the experiment.

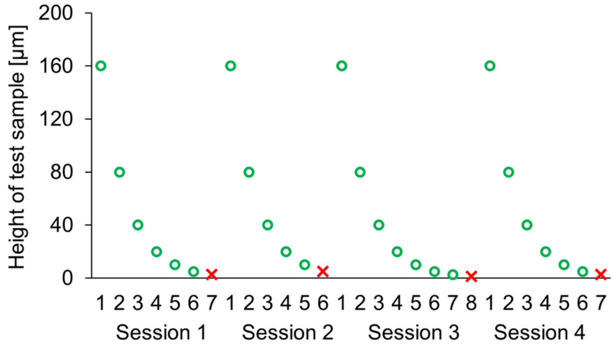

Fig. 5. An example of experimental results. The participants repeated four descending series of test stimulus for a reference condition. A series continued until the participant felt the heights of two samples were "not equal" and terminated when the answer changed to "equal".

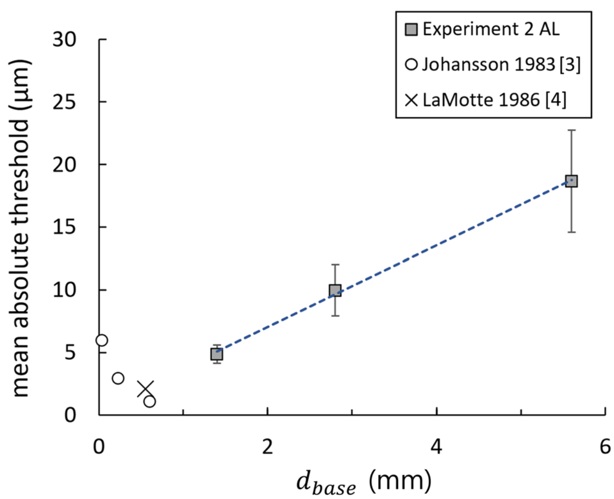

Fig. 6. Mean absolute threshold of 2.5D surface feature height by sample base diameter d_{base} with a blue trend line ($AL = 3.258 \cdot d_{base} + 0.526$, $R^2 = 0.998$). Error bars indicate standard errors. Circular and 'X' markers indicate the absolute thresholds reported in the previous works by Johansson & Lamotte (1983)[3] and LaMotte & Whitehouse (1986)[4], respectively.

Data analysis
For each experimental block, a transition point for two different answers, "yes" and "no", was taken as an estimate for an absolute threshold. Then, the four measurements were averaged as the absolute threshold for a base diameter d_{base}.

The effects of d_{base} on the absolute threshold of 2.5D surface feature height and experiment time were evaluated with one-way repeated measures ANOVAs.

Results

Figure 6 shows the result of Experiment 2, the mean absolute threshold of 2.5D surface feature height and mean experiment time by same base diameter. A one-way repeated measures ANOVA was conducted on the mean absolute thresholds with a factor sample base diameter d_{base}, and the result indicates a significant effect of d_{base} on the mean absolute threshold ($F(2, 28) = 6.173$, $p = 0.006$, $\eta_p^2 = 0.306$). When a Bonferroni post-hoc analysis was conducted, significant differences were found between h_{base} = 1.4 mm and 2.8 mm and between h_{base} = 2.8 mm and 5.6 mm. When a one-way repeated measures ANOVA was conducted on the mean experiment time with a factor d_{base}, no significant effect was found ($F(2, 28) = 0.111$, $p = 0.895$, $\eta_p^2 = 0.008$). The thresholds measured in three levels of d_{base} exhibited a strong linear trend with a high coefficient of determination (R^2 = 0.998). This finding is consistent with the 2.1 ± 0.3 μm threshold reported for a single 550 μm-diameter raised dot on a smooth plate in a previous study by LaMotte and Whitehouse (1986)[4]. When compared with the findings of Johansson and Lamotte (1983)[3], the present results exhibit an opposite trend: in their study, absolute thresholds decreased as the reference diameter increased, suggesting that a different perceptual mechanism or strategy may operate for smaller features. (Nonetheless, the experimental procedures for the aforementioned previous research employed different experimental paradigms than the present study. Both of the previous studies used a two-alternative forced-choice procedure for the threshold measurement, whose response bias could be different from that obtained from the method of limits.) The implications of these divergent patterns are discussed in the following section.

Overall, the result of Experiment 2 indicates a significant effect of d_{base} on the absolute threshold for 2.5D surface feature height perception. Moreover, the absolute threshold tended to linearly increase as d_{base} was increased.

Discussion

The present study investigated human perception of 2.5D surface feature height by measuring difference and absolute thresholds. The results of Experiment 1 indicated that the Weber fraction decreased as the sample base diameter increased and converged to approximately 0.1 when the ratio between the height of a shape and the base diameter was close to 0.3. The effect of surface compliance on perception was found to be less significant. The result of Experiment 2 indicated a significant effect of sample base diameter on the absolute threshold of 2.5D surface feature height perception. The absolute threshold increased with the sample base diameter. The experiment time was measured for both experiments, but no significant effect of sample base diameter or surface compliance on the results was observed. The significant effect of d_{base} on the perception of 2.5D surface-feature height in Experiment 1 provides the design criteria for a surface-morphing display to maintain high position resolution when the unit shape size is increased. Meanwhile, the increase in absolute thresholds for larger d_{base} observed in Experiment 2 offers reference values for determining the minimum renderable height for surface features of varying sizes.

A notable feature of Experiment 1 is the significant effect of sample base diameter d_{base} on the haptic discrimination of 2.5D surface feature height. To avoid the possible effect of slope change by d_{base}, we kept the ratio of the h_{ref} to d_{base} constant for different d_{base} considering the effect of slope/edge information on the shape discrimination reported in a previous study[11]. The experimental results indicate that an increase in the sample base diameter, or sample size, improved the height discrimination of the 2.5D surface feature. Additionally, the effect of the slope, h_{ref}/d_{base} on the haptic height discrimination of 2.5D surface feature was found to be significant. To see the interaction between the slope h_{ref}/d_{base} and d_{base} for the difference threshold, there was a significant interaction between them ($F(6, 84) = 3.324$, $p = 0.007$, $\eta^2 = 0.192$). When the slope was low, i.e, h_{ref}/d_{base} was smaller, but the effect of d_{base} on the discrimination threshold was significant but it was insignificant for a larger slope. It means that a larger contact area or a longer fingertip travel provided additional information on the 2.5D shape feature perception, but the effect became insignificant as the slope, i.e., h_{ref}/d_{base}, was increased. A possible explanation can be found in a smaller h_{ref} for a smaller d_{base} whose change can be less perceivable for smaller 2.5D feature heights. Meanwhile, samples with a larger d_{base} are supposed to have larger h_{ref}, which would provide less noisy sample feature height information. For larger slopes, the sample feature height was supposed to be large enough, even for the samples with a smaller d_{base}, which would have resulted in an insignificant effect of d_{base} on the height discrimination.

Another feature of Experiment 1's result is an insignificant effect of surface compliance on the 2.5D surface feature shape perception. Multiple previous studies demonstrated significant effects of surface compliance on surface shape, which is contrary to the result of the present study[15–18]. An apparent difference between our study and the other studies is that the stimuli for the previous studies were virtual haptic stimuli mostly rendered by kinesthetic haptic feedback interfaces. Then, the participants of the previous studies would have compressed the virtual surface, and the final fingertip trajectory would have depended on the compliance, affecting the perceived surface shape. On the contrary, the participants of the present study had cutaneous information available from which they could have compensated for the discrepancy in the surface geometry due to surface compliance.

The perception thresholds in Experiment 1 can be seen in an opposite aspect, i.e., in comparison to larger features than the ones used in the present study. In this regards, Kapper's work provides a guideline for expecting the surface feature perception for a larger scale shape[29]. She conducted an extensive review on human curvature perception studies and summarized them in terms of zeroth-order information (height differences), first-order information (height and attitude), and second order information (height, attitude, and curvature). She provided an extensive review of human curvature-perception studies by classifying the relevant cues into zeroth-order (height), first-order (height and attitude), and second-order information (height, attitude, and curvature). The literature indicates that zeroth-order cues contribute minimally[30] and that removing second-order information does not elevate discrimination thresholds[31]; thus, first-order information is the primary determinant of curvature perception[32]. In the context of the present study, zeroth-order information corresponds to h_{ref} and h_{ref}/d_{base}. As shown in Figs. 3 (b) and (c), the effects of h_{ref} and h_{ref}/d_{base} are evident at smaller values but the perception thresholds plateau at larger values, consistent with prior findings. This pattern suggests that the perceptual mechanism for small surface features may differ from that involved in perceiving larger object shapes, raising an important question for future research.

The results of Experiment 2 indicate a linear increase of absolute thresholds with an increase in sample base diameter, which is contrary to the result of Johansson and LaMotte's previous study conducted on smaller shapes than the ones used for the current study[3]. The authors of the previous study explained that the higher threshold for the shapes with a smaller base area is due to their less lateral deformation of a fingertip for a very small shape, around the size of papillary ridges at the fingertip. Meanwhile, the base diameters of 2.5D shapes for the current study are significantly larger than those for the previous study, implying a different mechanism would have affected the height perception. The result of the present study implies that the tactile information to feel a 2.5D surface feature can depend on the contact information during fingertip exploration. A 2.5D surface feature sample with a smaller base diameter has higher slope changes during the same fingertip travel, enabling a participant to perceive the surface feature. It means that the participant may have felt a subtly higher frequency signal/vibration for a surface feature with a smaller diameter, indicating a smaller absolute threshold. An alternative explanation for the contrary trend between the result of Experiment 2 and the previous study by Johansson and LaMotte is to see the absolute threshold as a function of d_{base}. In that case, the "U" shape function may mean a band-pass feature of the absolute threshold. The idea would be substantiated if there is a monotonic relation between d_{base} and the frequency.

Another notable feature of the present study is the opposite trends of the absolute and difference thresholds as a function of d_{base}. In Experiment 1, the difference threshold decreased as d_{base} increased, while the absolute threshold increased as d_{base} increased. A possible explanation can be found in the role of the slope information expressed as h_{ref}/d_{base}. As shown in Fig. 3 (b), the result of Experiment 1 indicates a low Weber fraction, or a higher sensitivity for a larger slope, h_{ref}/d_{base}. Applying this information for the absolute threshold, given a fixed d_{base}, a user would have enough information to perceive a 2.5D surface feature when the slope is high enough. Then, the sample height, equivalent to the absolute threshold, can be translated back to the slope information.

While the present study offers new insights into human perception of 2.5D surface-feature height, several limitations should be noted. First, although we restricted the stimuli to under-fingerpad sizes, future work should examine a broader range of feature sizes - particularly larger d_{base} - to develop a more general understanding of haptic surface-feature perception. Second, the effect of compliance on the absolute threshold of the 2.5D surface feature was not tested in Experiment 2. It was because the effect of compliance was found to be insignificant in Experiment 1. However, if the mechanisms for the difference and absolute threshold are different for 2.5D shape features, the effect of compliance still needs to be tested for the absolute threshold. Next, the findings should be validated under more practical conditions involving actively morphing surfaces. Because the motivation of this work is to provide quantitative perceptual data for features rendered by a surface-morphing display, experiments using a dynamic, display-based setup will be essential for more ecologically valid evaluation.

Overall, the present study investigated human perception of 2.5D surface feature height in terms of absolute and difference thresholds in two experiments. The effect of surface area defined as d_{base} on absolute and difference thresholds was found to be significant in the experiments. The difference threshold tended to decrease as d_{base} increased, while the absolute threshold tended to increase with an increase of d_{base}. Meanwhile, the effect of surface material did not have a significant effect on the 2.5D shape feature height. The findings of this study can inform the specification design of surface-morphing tactile displays[25] and support the development of Braille-like haptic display requirements. In our future work, we plan to further investigate human perception of complex 2.5D shape features rendered with a more practical experimental setup. For example, the effect of 2.5D shape feature arrays on difference thresholds will be studied for a practical extension of the present study. Moreover, the hypothesis suggested in the discussion sections will be experimentally substantiated. We explained that the smaller absolute threshold for a smaller d_{base} was due to variation of the contact frequency. The idea will be tested by measuring the frequency during contact for different d_{base} while controlling the finger movement. Also, the role of the slope information for the absolute and different thresholds will be tested by controlling the shape of the 2.5D surface feature to have uniform slopes.

Data availability

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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Author contributions

I.H., S.Y. and J.P. conceived the experiments, J.P. implemented the experimental setup, I.H. and J.P. conducted the experiments, S.Y. and J.P. analyzed the results. All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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