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RESEARCH ARTICLE

Designing Macroscopic Surface Features Perceived as Soft During Finger Sliding

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ABSTRACT Humans evaluate material softness not only by pressing but also through stroking or rubbing motions. While previous studies have primarily focused on pressing to investigate compliance-related softness perception, the present study investigates softness perception during sliding, focusing on the "curved surface softness illusion," in which slightly wavy surfaces feel softer than flat ones during fingertip sliding, despite being made of the same material. The objective of this study is to identify the surface features of sinusoidal surfaces that enhance the softness perceived in this illusion, using an optimal designing approach. A set of hard plastic specimens with varying wavelengths and amplitudes was manufactured based on a central composite design. Then, their perceived softness was evaluated in an experiment involving 32 participants. Results showed that perceived softness during sliding exhibited an inverted U-shaped function of both macroscopic sinusoidal wavelength and amplitude. A response surface method was then used to determine the design parameters that would maximize perceived softness. In a post-hoc experiment, the optimally designed specimen was rated as soft as the softest specimen in the initial experiment. The specimen judged as softest exhibited the surface wavelength of approximately 70 mm and amplitude of 0.40 mm. The findings of this study will enable the manipulation of softness perception through surface design, which will potentially be applied to consumer products. However, the mechanism of this perceptual phenomenon remains unknown and should be further investigated.

INDEX TERMS Haptics, softness perception, optimal design, surface response methodology.

I. INTRODUCTION

Softness is a crucial psychophysical dimension of tactile perception [1], [2], [3], and it plays a significant role in the perceived quality and user preferences of consumer products such as clothing fabrics and packaging. Hence, understanding the relationship between the sense of softness and physical properties of surfaces in different tactile exploration patterns has practical implications. Previous studies have predominantly associated the physical counterpart of softness with compliance, that is, the ease of deformation of objects when being pressed [4], [5], [6], [7]. Thus, most of the experimental research on softness perception have focused on compliant surfaces pressed or pinched [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15].

However, softness is more diverse, encompassing not only compliance but also factors such as viscosity, granularity, and furriness [16]. These factors are associated with different exploratory procedures when individuals engage with soft materials in everyday life. For instance, when exploring surfaces such as textiles [16], [17], [18], [19] and facial skin [20], lateral stroking and rubbing are commonly employed in addition to pressing. Research has further highlighted that physical properties such as friction and fine roughness of tissue papers contribute to the softness perception [21], [22]. Among them, our study concentrates

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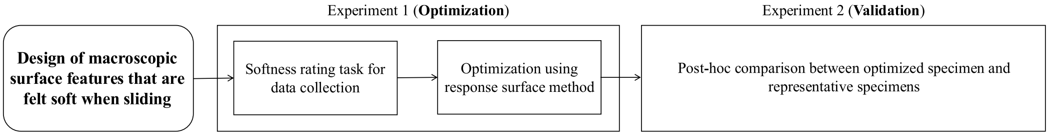

FIGURE 1. Research flow of the present study.

on surface friction, which relates to macroscopic surface topology during the rubbing motion.

From a tribological perspective, when fingers slide across a surface with a low elastic modulus, the adhesion friction between the fingertip and the surface tends to be high [23], [24], [25]. However, experiments trying to manipulate surface lubrication have shown paradoxical outcomes, where surfaces with lower friction are perceived as softer [26]. Our previous research supports this finding: microscopically roughened hard resin surfaces (with higher friction) were perceived as harder than smooth surfaces during lateral finger movement [27], [28].

Dynamic changes in friction have also been linked to perceived softness. Studies using electrostatic frictional tactile displays have shown that low-frequency frictional variations (10–20 Hz) evoke the sense of softness [29], [30]. During lateral sliding motions, frictional forces also change accordingly when fingers slide over physical surfaces with varying slopes [31], [32]. This change in slope-related friction may relate to the phenomenon that gently wavy hard resin surfaces are perceived as softer compared to perfectly flat surfaces [27], [33].

In summary, previous research has reported examples in which both direct (lubrication) and indirect alterations (e.g., through surface shape manipulations) of friction can influence perceived softness during lateral sliding motions. Building on our earlier works [27], [33], the present study aims to optimize the physical parameters of surfaces with sinusoidally wavy shapes, based on the perceived softness during lateral finger movements. To date, there have been no reports on the optimization of surface profiles that feel soft when slid over by fingers.

To optimize the surfaces with macroscopic sinusoidal waveforms to evoke softness, we employ the response surface methodology [34], [35], [36], a technique commonly used in quality engineering. Given that the optimization of tactile perception involves prototype development and user evaluation of physical samples, experimental costs are a primary concern. Thus, the central composite design (CCD) [36], [37], frequently used for parameter design in the response surface method, is employed as a cost-effective approach that avoids exhaustive searches across the parameter space. The results of this study are expected to provide valuable insights into tactile design for product packaging and other applicable surfaces. Although the primary focus of this study is the design of surfaces perceived as soft during sliding, it also sheds light on the reasons why waved surfaces elicit such soft sensations.

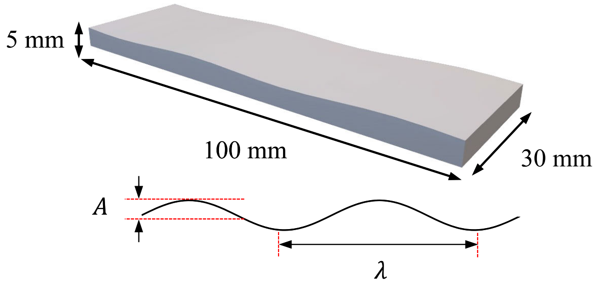

FIGURE 2. Dimensions of plastic specimens with sinusoidal waves. ***A*** **and** λ **are the amplitude and wavelength of the sinusoidal wave, respectively.**

Fig. 1 illustrates the overall research flow. In Experiment 1, data for optimization were collected through a user study in which participants slid their fingers over surfaces with various macroscopic profiles and rated the perceived softness. The optimal surface design was then determined based on the response surface method. In Experiment 2, as a follow-up to Experiment 1, another user study was conducted to validate the perceived softness of the optimized design.

II. METHODS

A. TEXTURE SPECIMENS BY CENTRAL COMPOSITE DESIGN

Twelve types of macroscopically wavy and smooth surfaces were prepared. As shown in Fig. 2, the dimensions of each specimen were 100 × 30 × 5 mm. The physical parameters A and λ represent the designed amplitudes and wavelengths of the macroscopic sinusoidal surface features, respectively. All specimens were manufactured using a 3D printer (Form 3, Formlabs Inc., CA) with Clear resin (Formlabs Inc., CA; Young's Modulus = 2.8 GPa). The material is rigid enough not to be deformed by finger forces.

As shown in Fig. 3, the specimen parameters were designed using the CCD. The CCD is an experimental design method aimed at fitting second-order models to response surfaces, allowing for an efficient reduction in the required number of experiments and specimens. After the central point and boundaries were determined, the combinations of the two parameters were calculated within the circular symmetry.

We prepared a sample set through two CCDs. Initially, we referred to our previous research [27], [33] to establish the range for λ between 18.8 and 61.2 mm, and for A between 0.44 and 0.86 mm for the first CCD, centered at $\lambda = 40$ mm and $A = 0.65$ mm. The ranges were ± 21.2 mm for λ (x-axis) and ± 0.21 mm for A (y-axis). In total, nine specimens were designed for the first CCD, as shown in black in Fig. 3.

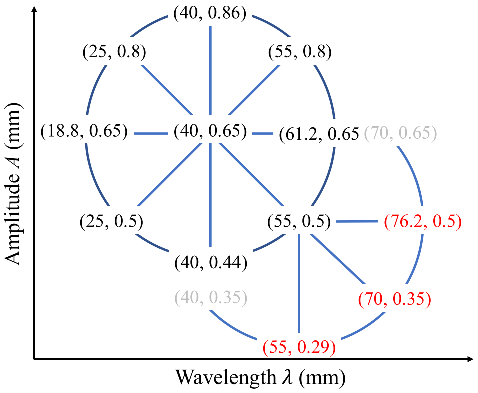

FIGURE 3. Loci of 12 specimens on a plane of sinusoidal wavelength λ and amplitude A determined by two central composite designs. Specimens in gray fonts were not employed in the study.

TABLE 1. Physical parameters of texture specimens. Surface roughness: mean and standard deviation among three measurements.

Symbol	Wavelength λ(mm)	Amplitude A (mm)	Surface roughness R_a (μm)
A	18.8	0.65	1.00 ± 0.10
B	25	0.5	0.95 ± 0.09
C	25	0.8	0.82 ± 0.11
D	40	0.44	0.89 ± 0.07
E	40	0.65	0.72 ± 0.08
F	40	0.86	0.90 ± 0.10
G	55	0.29	0.85 ± 0.09
H	55	0.5	0.71 ± 0.06
I	55	0.8	0.88 ± 0.07
J	61.2	0.65	0.89 ± 0.07
K	70	0.35	0.70 ± 0.10
L	76.2	0.5	0.83 ± 0.06

Subsequently, based on the results from a pilot study involving six participants, we expanded the parameter space by applying an additional CCD with $(\lambda, A) = (55, 0.5)$ being the center by using the same parameter ranges (λ : ± 21.2 mm, A : ± 0.212 mm). This led to the design of three additional specimens, as indicated by the red fonts in Fig. 3. The two gray-shaded specimens were omitted because of their proximity to the parameters already covered in the first CCD. Table 1 lists the detailed physical parameters designed for all the specimens. Overall, the sinusoidal wavelength was in the range of 18.8–76.2 mm, and the amplitude ranged 0.29–0.86 mm.

After printing the specimens, their surfaces were polished with #1200 sandpaper to remove unintended fine surface irregularities. To examine the average surface roughness at three distinct points in the central part of the smooth specimens, we used a contact-type profilometer (SJ-310, Mitsutoyo Co. Ltd., Japan). The average roughness values of the smoothened specimens ranged $R_a = 0.70$–1.10 μm.

B. EXPERIMENT 1: EVALUATION OF SUBJECTIVE SOFTNESS BY A VISUAL ANALOG SCALE

1) EXPERIMENTAL TASK

Each participant used the index finger of their dominant hand to slide over 12 randomly presented specimens and arranged them based on perceived softness along a 1-meter-long visual analog scale. The distance between two specimens indicated the degree of difference in their perceived softness. Once, all the specimens were arranged on the desktop, the participant could freely examine them to determine their final positions. As the concept of softness, they referred to deformable softness, which is the degree of ease of deformation of the material. This concept was first provided in English and then in the participants' native languages, either Japanese or Chinese.

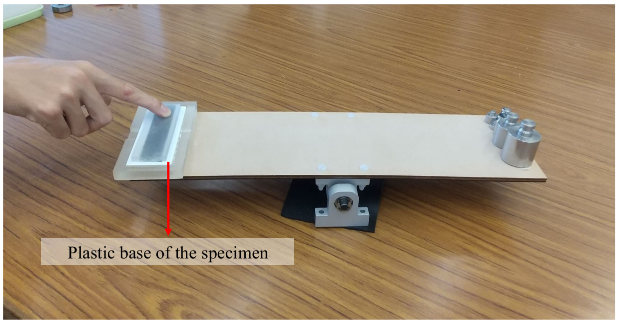

FIGURE 4. Experimental setup for softness evaluation test. The participants slid their finger on a specimen using a balance and arranged them on the desktop in the order of perceived softness.

During the practice phase, the experimenter visually monitored the participants' finger movements to ensure their sliding speed remained within an appropriate range (between 50 mm/s and 200 mm/s). Participants were then encouraged to determine their own optimal exploratory speed for perceiving surface profiles and softness, and to maintain a consistent motion throughout the main session. During the main task, their exploratory behavior was also monitored, and corrective instructions were given when necessary.

As shown in Fig. 4, a balance was used to control the pressing force at 230 gf. The authors and their colleagues selected this pressing force from their preliminary experiments and they agreed that the difference of softness was well perceived under this condition. Participants slid their fingers over the specimens while ensuring that the end of the balance did not contact the desktop, thereby maintaining a consistent normal force.

Each specimen was glued to a plastic base (white plate in Fig. 4). The participants were instructed to hold this base while picking the specimen up from the table or the balance to prevent them from perceiving the mechanical hardness of the specimens through direct touch. They wore glasses with lenses blurred by opaque tape to prevent them from seeing the detailed shapes of the specimens. The evaluation task was performed with three repetitions for each participant. The typical duration of the entire experiment was one hour, which included a 15-minute softness evaluation task and a 5-minute rest period for each repetition.

2) PARTICIPANTS

Thirty-two university students (10 females and 22 males, mean age of 23.5 years) participated in this experiment after providing their written informed consent. They should not have wounds on their fingers or have difficulty in tactile perception. They were unaware of the objectives of the study before the experiments and were paid 1500 JPY per hour.

3) ANALYSIS

Although participants were encouraged to make full use of the 1-meter visual analog scale, we observed that some participants provided responses within a relatively limited range (six participants used less than 70% of the available range). Thus, we applied min-max normalization to each participant's perceived softness ratings across specimens, scaling the response range to between 0 and 1.

Next, the geometric mean of each participant's three repeated trials was computed for each specimen. To detect outlier participants, we calculated the correlation coefficient between each participant's responses and the average responses of the other 31 participants. If a participant's correlation coefficient was not significantly different from 0 at $p < 0.05$ or if the coefficient was negative, that participant was considered an outlier, and all his/her responses were excluded.

As a result, nine participants were excluded, yielding a final sample size of 276 (23 participants × 12 specimens). Among the nine outliers, two exhibited significantly negative correlation coefficients of -0.883 and -0.640. The other seven outliers exhibited no self-consistency, and had an insignificant correlation with the average responses of the other participants. In other words, their answers appeared to be random, suggesting that the softness illusion was not experienced by them. As discussed later, the inclusion of all the participants do not substantially influence the optimization results.

Subsequently, we performed a regression analysis using a quadratic linear model equation, with the explanatory variables being λ (wavelength), A (amplitude), their interaction, and quadratic terms. In the response surface methodology [34], [35], [36], [38], quadratic models are typically used to estimate the optimal parameter set that maximizes the response variable—in this case, perceived softness. The model was computed using the 276 samples described above. Finally, based on the regression coefficients of the explanatory variables, we computed the response surface and determined the values of λ and A that maximized perceived softness.

C. EXPERIMENT 2: POST-HOC COMPARISON BETWEEN OPTIMIZED SPECIMEN AND REPRESENTATIVE SPECIMENS

1) SELECTED SPECIMENS

This task focused on comparing the optimal specimen, Specimen K (judged as the softest in Experiment 1), with a flat specimen, which was not included in Experiment 1. To serve as control or dummy stimuli and to obscure the objective of the task from participants, we included two additional specimens: Specimen A, judged as the hardest among the 12 specimens in Experiment 1, and Specimen D, the median sample in terms of rated softness among the 12 specimens. In total, five specimens were tested in Experiment 2.

For the optimal specimen, a new sample was manufactured using the parameter combination ($\lambda = 69.7$ mm, $A = 0.40$ mm), which was optimized for perceived softness through the response surface methodology in Experiment 1. The details of this optimization process are provided in Section III-A.

2) EXPERIMENTAL TASK

The experimental task was identical to that described in Experiment 1. Participants were asked to arrange the five samples along a 1-meter-long visual analog scale, positioning them from left (soft) to right (hard) based on their perceived softness. Each participant performed a single trial per experiment, as the small sample set likely enabled them to remember their answers, rendering multiple repetitions unnecessary. The duration of each experiment ranged from 5 to 10 minutes.

In addition, to investigate the effect of applied force on softness judgment, we performed the experimental task under two different applied forces (30 gf and 230 gf). In the preliminary experiments, a pressing force below 30 gf made it difficult to maintain a stable sliding motion, while a force above 230 gf caused participants' fingers to fatigue easily. These two force levels were tested by individuals in a counterbalanced manner.

3) PARTICIPANTS

Fifteen university students (six females and nine males, mean age of 23.4 years) participated in this experiment after providing their written informed consent. Five of the participants—one of whom exhibited a significantly negative correlation with the average trend in Experiment 1—had previously been identified as outliers in that experiment. All participants were unaware of the objectives of the study before the experiments.

4) ANALYSIS

We conducted paired t-tests (two-tailed) to examine the significance of the differences among the three specimens: the optimized sample, the softest sample from Experiment 1 (Specimen K: $\lambda = 70$ mm, $A = 0.35$ mm), and the flat surface sample with the Holm adjustment of p-values. The other two samples were not involved in the comparison because they were used as control stimuli.

III. RESULTS

A. EXPERIMENT 1: EVALUATION OF SUBJECTIVE SOFTNESS OF ALL STIMULI BY A VISUAL ANALOG SCALE

Fig. 5 shows the mean perceived softness and standard errors for all specimens (where a higher value indicates a softer perception). λ and A represents the sinusoidal wavelength

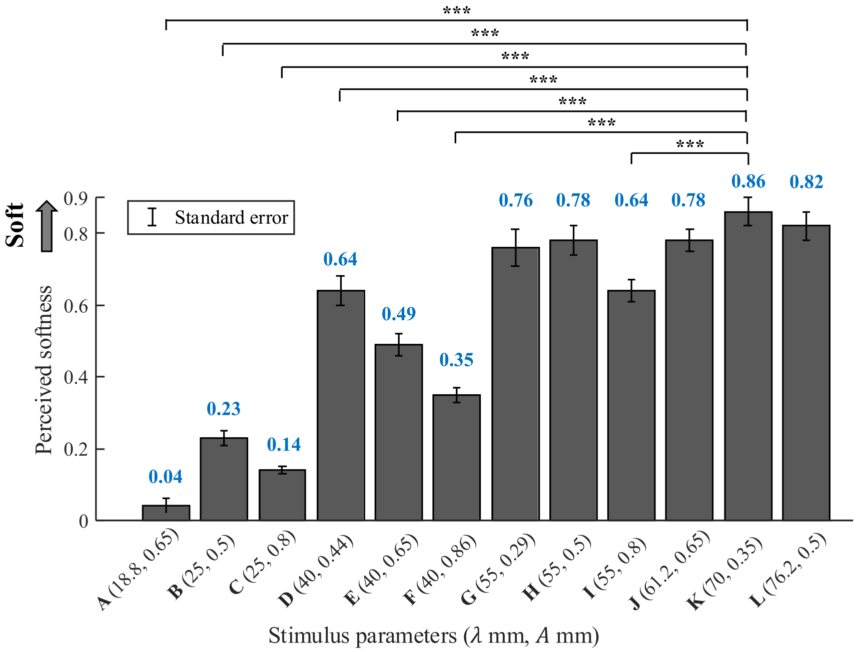

FIGURE 5. Bar plot of the perceived softness values for the specimens. Mean values are shown in blue, and error bars represent the standard errors among participants. *** indicates $p < 0.001$.

TABLE 2. Linear regression analysis of perceived softness using λ, *A*, their interaction, and quadratic terms as explanatory variables.

Parameter	Coefficient	95% conf. int.	deg. freedom	t-value	p-value
Wavelength (λ)	0.042	0.014	270	5.85	1.4×10^{-8}
Amplitude (A)	1.020	1.552	270	1.31	0.190
$\lambda \times A$	-0.002	0.013	270	-0.27	0.790
λ^2	-2.99×10^{-4}	9.21×10^{-5}	270	-6.48	4.2×10^{-10}
A^2	-1.124	0.933	270	-2.41	0.017

* The sample size is 276 and the adjusted R^2 is 0.75.

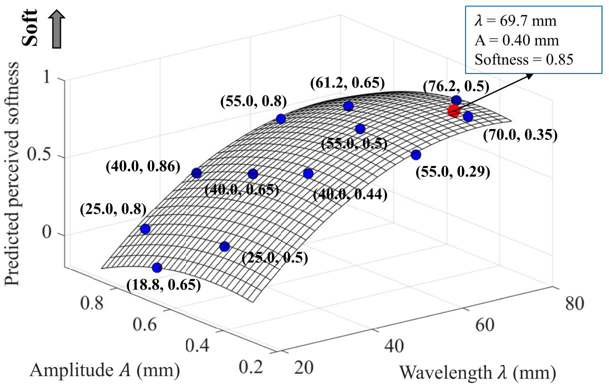

FIGURE 6. Response surface plotted from (1) by referring to the coefficients of explanatory variables in Table 2.The blue points are the mean softness across the participants.The red point shows the predicted softest value.

and amplitude of the specimen's surface profile, respectively. Specimen A ($\lambda = 18.8$ mm, $A = 0.65$ mm) was rated hardest with the lowest mean score of 0.04. Specimen K ($\lambda = 70$ mm, $A = 0.35$ mm) was rated softest with the mean score of 0.86, followed by Specimen L (0.82, $\lambda = 76.2$ mm, $A = 0.50$ mm). In a post-hoc manner, we conducted paired t-tests between the perceived softness of Specimen K and all other 11 specimens. As shown in Fig. 5, Specimen K was evaluated significantly softer than Specimens A, B, C, D, E, F, and I ($p < 0.001$). The p-values were adjusted by the Holm method.

Table 2 shows the result of regression analysis for perceived softness using λ, A, their interaction and quadratic terms as explanatory variables. The coefficients for λ ($p = 1.4 \times 10^{-8}$), λ^2 ($p = 4.2 \times 10^{-10}$), and A^2 ($p = 0.017$) were found to be significant, while those of A and the interaction term $\lambda \times A$ were not. Based on the coefficients in Table 2, the response surface formula was as follows:

$$S = 0.042\lambda + 1.020A - 0.002\lambda \times A - 0.00029\lambda^2 - 1.124A^2 + 1.825, \quad (1)$$

where S represents the perceived softness. The adjusted R^2 for this regression model was 0.75. The coefficients of λ^2 and A^2 were negative, indicating that as λ and A increase,

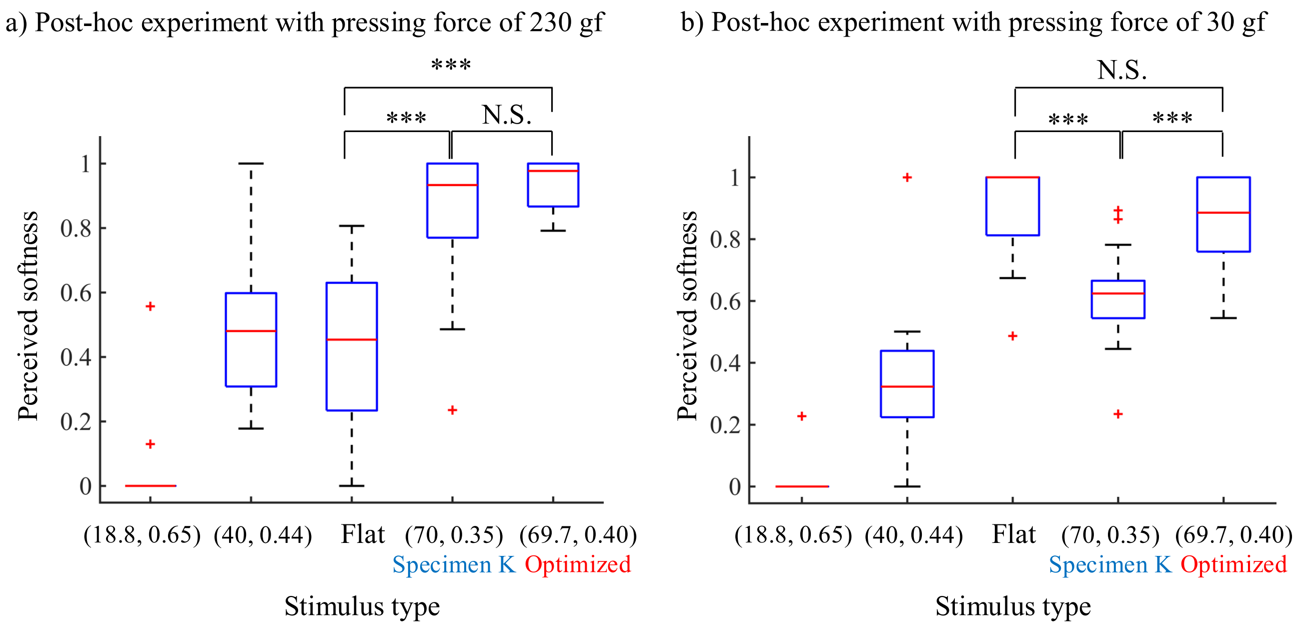

FIGURE 7. Boxplots of five representative specimens in the post-hoc experiment.The specimen parameters in x-axis were written as (λ, A) in millimeter.*** indicates $p < 0.001$ with Holm correction of factor 3.

perceived softness initially increases and then decreases with a quadratic trend.

We calculated the global maximum of S by solving the partial derivatives of S with respect to both A and λ equal to zero:

$$\frac{\partial S}{\partial \lambda} = \frac{\partial S}{\partial A} = 0. \tag{2}$$

The calculated global maximum of the response surface was 0.85 with $\lambda = 69.7$ mm and $A = 0.40$ mm as shown in Fig. 6. These parameter values fall within the range of initial parameter set with $\lambda = 18.8$–76.2 mm and $A = 0.29$–0.86 mm. The optimized parameters are close to those of Specimen K ($\lambda = 70$ mm, $A = 0.35$ mm), which exhibited the highest perceived softness value of 0.86 as shown in Fig. 5.

B. EXPERIMENT 2: POST-HOC COMPARISON BETWEEN THE OPTIMIZED SPECIMEN AND REPRESENTATIVE SPECIMENS

Fig. 7 shows the result of the post-hoc experiment including the optimally designed specimen, three representative specimens (Specimen A, D, and K) used in Experiment 1, and the flat surface. Therefore, five specimens in total were evaluated. Fig. 7(a) shows the results when the net normal force was 230 gf, which is identical to Experiment 1. There was no significant difference in perceived softness between the optimized sample and Specimen K, which was judged softest in Experiment 1. Both the optimized specimen and specimen K were significantly softer than the flat surface sample ($t(14) = 7.00$, $p = 5.9 \times 10^{-7}$ and $t(14) = 4.32$, $p = 6 \times 10^{-4}$, respectively). We did not compare the other two specimens since they were control stimuli.

To investigate the influence of pressing force on perceived softness during lateral sliding motion, we varied the weight of the counterbalance to achieve a net force of 30 gf, and the results are shown in Fig. 7(b). Because we used visual analog scale and normalized distance as perceived softness within each force condition, it is not meaningful to compare Fig. 7(a) and Fig. 7(b). While using a smaller pressing force, there was no significant difference in perceived softness between the flat surface sample and the optimized sample. However, both flat and the optimized sample were significantly softer than Specimen K ($t(14) = 4.43, p = 4.5 \times 10^{-4}$ and $t(14) = 4.11$, $p = 9.5 \times 10^{-4}$, respectively).

IV. DISCUSSION

This study successfully demonstrated the optimization of surface parameters to evoke a perception of softness during sliding with fingers. The analysis through the surface response method revealed that the sinusoidally curved surface was perceived softest when λ is approximately 70 mm. As aforementioned in the introduction section, friction and its variation have been reported to affect perceived softness [26], [27], [28], [29], [30], [33]. When a finger slides over a convex surface, the change in the gradient of the surface varies the tangential resistance [31], [32], [39]. On surfaces with smaller wavelengths, the change in the gradient is larger, which leads to a greater change in the friction. On the other hand, for surfaces with larger wavelengths, the surface friction slowly changes while being slid by a finger. The presence of the optimal λ value suggests that there exists an optimal change in the surface friction to induce softness perception. Such λ value is nearly 70 mm; however, we do not come up with rational explanations for this value.

One possibility is the temporal frequency of the frictional fluctuation. According to studies using a friction-variable surface texture display, the frequency range of 10–20 Hz is effective to evoke the sense of softness on a flat touch panel [29], [30]. This frequency range is considerably higher than what applies in our setup. In our case, when a person slides their finger over a surface with $\lambda = 70$ mm at 100 mm/s—which falls near the midpoint of typical finger sliding speeds during surface exploration [40]—the resulting temporal frequency of frictional changes is approximately 1.4 Hz. Further, although some researchers demonstrated that softness is felt via vibrotactile stimuli to finger pad [41], [42], the effective frequencies were approximately 5 Hz, which is still high compared with 1.4 Hz. Hence, we cannot explain the optimal λ value from the viewpoint of the temporal frequency on the basis of earlier studies.

The amplitude A exhibited an inverted U-shaped trend, similar to the wavelength λ. Small values of A do not produce substantial effects to evoke the sense of softness. Conversely, large values of A make the surface bumps more distinctly felt, diminishing the effect of inducing softness. Similar to λ, there exists an optimal value for A, suggesting that moderate yet clearly perceptible frictional variations generated as a finger slides over bumped surfaces are effective in delivering the perception of softness.

One possible explanation for the "curved surface softness illusion" is a potential link between perceived softness and pleasantness. In the post-experiment interviews, most participants reported that the specimens they rated as soft during sliding felt comfortable or pleasant. Similar results have been reported in previous studies. For example, when pressing materials that are harder than human skin, pleasantness and perceived softness showed a high correlation [9], [43]. In another experiment, where participants slid their fingers over various surface materials and rated the pleasantness, smooth and soft items were rated as more pleasant than rough and frictional materials [44]. Picard et al. [45] found that softness and pleasantness were grouped together in their similarity rating task of automotive seat materials. Hence, we consider that the "curved surface softness illusion" observed in the present study is partially related to tactile pleasantness.

The optimized surface, with $\lambda = 69.7$ mm and $A = 0.40$ mm, had parameters similar to Specimen K ($\lambda = 70$ mm, $A = 0.35$ mm), which was rated as the softest in Experiment 1. As shown in Fig. 7(a), both the optimized specimen and Specimen K were rated as softer than the flat specimen, with no significant difference between their softness ratings. The optimal solution identified using the set of specimens was coincidentally close to one of the existing specimens. This occurrence is common in quality engineering when the parameter space is relatively small. While this does not imply that the optimization process is meaningless, the similarity in parameters limits the potential for significant improvements.

However, in the results shown in Fig. 7(b), where a 30 gf force was applied, a significant difference was observed between the optimized specimen and Specimen K, despite their similar geometric parameters. The optimized specimen was rated as nearly as soft as the flat specimen. The reason for this difference is unclear; however, it is evident that the perceived softness during sliding depends on the applied pressing force. Even without controlling the pressing force, the "curved surface softness illusion" is still expected to occur [33].

We excluded nine outliers from the 32 participants for the optimization. The outliers were determined based on a statistically valid method; however, the number of outliers was unexpectedly high for the authors. For seven out of the nine outliers, their responses were not significantly correlated with the mean responses, suggesting that they did not substantially perceive the differences in the softness of specimens. The other two outliers answered oppositely, suggesting that they probably perceived softness differently from the majority of the participants. Therefore, we derive the optimal parameters, including the results of all 32 participants. In a regression analysis identical to Experiment 1, the coefficients for each explanatory variable were as follows: λ: 0.030 ($p = 0.005$), A: 0.50 ($p = 0.66$), $\lambda \times A$: 0.0083 ($p = 0.36$), λ^2: -2.7×10^{-4} ($p = 5.5 \times 10^{-5}$), and A^2: -0.83 ($p = 0.22$). The response surface derived from these coefficients yielded an optimized parameter set of $(\lambda, A) = (63.6, 0.62)$, which is close to Specimen J, ranked third in softness in Experiment 1. The softness ratings between Specimens J and K are not significantly different ($t(22) = 2.02$, $p = 0.11$); hence, we speculate that the outliers did not substantially affect the optimization. Nonetheless, we need to investigate the reasons why several participants' responses did not align with the mean responses. A key point may lie in individual differences in the definition of softness, which inherently includes a variety of concepts [16], as well as the difference in the exploratory speeds among the participants.

The sinusoidal function may not be the only surface profile capable of evoking the curved surface softness illusion. Other functions, such as the Gaussian function—hich is often used to represent bumps in the field of haptics [31], [39]—may also be effective. Similarly, surface shapes that exhibit low-frequency variations in slope may induce the illusion. Furthermore, the surface profile does not necessarily need to be regular; for instance, chaotic or random surfaces could potentially produce similar effects, provided they are primarily composed of low-frequency components.

An even more challenging topic is the optimization of surface functions, although the present study focused solely on sinusoidal profiles. This challenge arises primarily for two reasons. First, widely used optimization methods are generally suited for parameter tuning but are limited when it comes to optimizing functional shapes. Second, in human-involved experimental optimization, the process must be conducted with minimal cost, which restricts the dimensionality of the search space and makes exhaustive exploration of complex surface functions impractical.

There are several aspects of this study that could be improved in future work. First, because we did not control the sliding speed or measure the horizontal resistance with a force sensor during the experiment, we were unable to quantitatively analyze the effect of dynamic tangential resistance on perceived softness. Future work should include measurements of these physical quantities or employ passive touch experiments to better control such variables. On the other hand, the fact that 9 out of 32 participants, especially two of them who had opposite answers, provided responses that significantly differed from the others highlights a substantial degree of individual variability. This variability may stem from participants' difficulty in adopting a unified definition of softness when sliding their fingers over the surfaces. Therefore, future research should aim to improve the experimental procedures, including a clearer definition of softness, as surface textures or smoothness are often semantically involved [16], [46], [47].

V. CONCLUSION

Previous studies have reported the "curved surface softness illusion," in which surfaces with slight undulations feel softer than flat surfaces when stroked laterally. However, those studies did not attempt to determine an optimal surface design. In the present study, we employed a CCD to systematically vary the wavelength (λ) and amplitude (A) of sinusoidal surface undulations, and applied response surface methodology to identify the optimal parameters.

This study yielded the following key findings:

- The optimized specimen ($\lambda = 69.7$ mm and $A = 0.40$ mm) was perceived to be as soft as the softest among the 12 samples evaluated in the experiment.
- Perceived softness followed an inverted U-shaped function with respect to both wavelength (λ) and amplitude (A).

We hypothesize that the second finding is associated with low-frequency variations in tangential resistance during stroking.

We believe these findings contribute to a deeper understanding of softness perception and may inform the design of tactile surfaces in applications such as consumer product packaging.

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