Surfaces with finger-sized concave feel softer

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***Abstract*—The judgment of elastic softness is determined not only by mechanical parameters related to hardness, such as the elastic modulus and stiffness, but also by macroscopic surface features. This study experimentally demonstrates that objects with a finger-sized concave with a depth of 1—3 mm feel softer than flat surfaces made of the same materials when they are pushed by a finger. In Experiment 1, participants judged the surfaces of a rigid material with thumb-sized concaves to be softer than the flat and convex surfaces. Experiment 2 used rubbers of various elastic moduli, and the softness of a concave object with a Young's modulus of 0.55 MPa was subjectively equal to that of a flat object with an average Young's modulus of 0.23 MPa. Furthermore, the softness of a convex object was subjectively equal to that of a 1.68 MPa flat object. The contact phenomena between a finger pad and concave or convex objects are different from those between a finger pad and flat objects, and they influence the softness judgment. Such phenomena include the relationship between the pressing force and contact area. These results provide insights into surface design and improve comprehension of the perceptual principles of softness.**

Fig. 1: Experimental scenario; pushing flat and hard plates with a concave or convex at the center.

I. INTRODUCTION

When humans touch an object, their fingertips and the object surface deform; based on this, the object's softness is judged [1], [2]. The various definitions of softness include elastic or deformable softness [3], and the perception of elastic softness is formed by multiple principles. One principle is based on the relationship between the object's surface displacement and the pressing force [4], [5], [6]. The surface displacement is primarily judged by proprioceptive cues; however, tactile cues may also mediate it [7]. Another hypothetical principle is based on the coupling of the finger pressing force and the contact area [8]. The curves of the pressing force and contact area are considered to determine the perceived softness of objects [8], [9]. The pressure distribution in the contact area may also affect the softness judgement. When the object is soft and includes a large deformation and contact area, the pressure is widely distributed, and its maximum value is relatively small. This principle, based on the force and contact area, has been leveraged to develop tactile softness displays [10], [11]. These various principles function simultaneously [2], [12], [13]. Along with these studies, in recent years, softness perception has been intensively studied, including exploratory strategies [14], [15], pleasantness [16], softness of complex objects [5], and individuality [17], [18].

The interaction between the pressing force and surface deformation, including the contact area, underlies softness perception; therefore, macro- and mesoscopic surface topological features that influence finger deformation may change the perceived softness when touching surfaces of hard materials. For example, in [19], [20], car interior surface grains were designed to induce soft impressions. Their study claimed that to enhance these effects, the preferred depth and radius of curvature of microscopic and mesoscopic grains were in the ranges of 60–350 μm and 0.5–2.0 mm, respectively; however, they did not exhibit experimental data on how softness perception was affected by these grains. Furthermore, earlier studies mostly employed flat surfaces in studying the perception of elastic softness whereas non-flat objects such as fruits [5], spheres [21] and tumors (e.g. [22]) were used in other studies. The present study investigates the perceived effects of concaves as large as finger pads, which are approximately 10–100 times larger than those investigated in [19], [20]. The contact between a finger pad and such a finger-sized concave leads to a contact area greater than that made by a flat surface, which may affect the perceived softness.

This study includes two experiments. In Experiment 1, we prepared hard plastic plates with a finger-sized concave or convex. The sizes of the concaves were designed to resemble the average human first, third, and fifth finger pads. Participants pushed the center of these concaves and convexes to rank them on the basis of their perceived softness. We expected that the surface with concaves, into which the finger pads fit, would feel softer than a flat surface. In contrast, a convex surface would feel harder than a flat surface, considering a hypothetical principle based on the relationship between the pressing force and contact area [8]. In Experiment 2, the softness perceived by touching a concave or convex elastic surface was matched with the softness of flat surfaces made of materials with different elastic moduli. The results of this study will help with surface design and provide insights into the comprehension of softness perception.

II. METHODS

This study was approved by the Institutional Review Board of the School of Engineering, Nagoya University (#20-17).

A. Experiment 1: Ranking task of concave and convex hard surfaces

1) Stimuli: We used 16 types of specimens made of hard plastic. They were made by a 3D printer (Form3, Formlabs Inc., MA, USA) using a hard plastic resin (nominal Young's modulus: 1.6 GPa). The specimens were cylindrical, as shown in Figs. 1 and 2. Nine specimens had an ellipsoidal concave in the center (Samples 1–9). The concaves on Samples 1–3, 4–6, and 7–9 resembled the sizes of the fifth, third, and first fingers, respectively, with respect to hand data of Japanese people [23]. Three specimens had a spherical concave in the center (Samples 10–12), and three specimens had an ellipsoidal convex in the center (Samples 13–15). Furthermore, one specimen was flat with no concave or convex (Sample 16). The designed values

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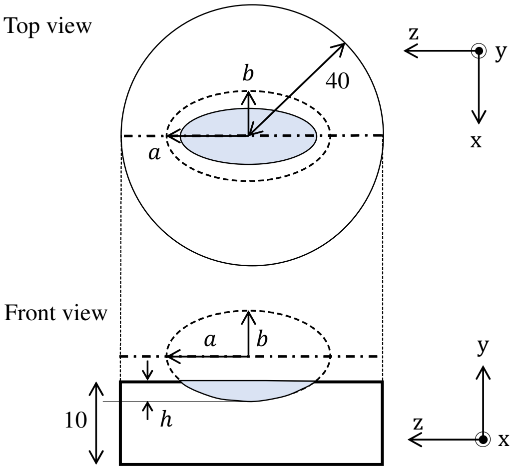


Fig. 2: Specimen parameters manipulated in the experiment. The upper figure shows the top view, and the lower figure, the front view. The unit of length is in millimeters.

TABLE I: Parameters of surface shapes used in the experiment. The unit of measurement is in millimeters. Samples 1–12 were concave surfaces, Samples 13–15 were convex surfaces, and Sample 16 was flat.

Sample no.	1	2	3	4	5	6
a	11.9	11.9	11.9	14.5	14.5	14.5
b	5.6	5.6	5.6	6.8	6.8	6.8
h	1	2	3	1	2	3
Sample no.	7	8	9	10	11	12
a	15.2	15.2	15.2	7.5	7.5	7.5
b	8.3	8.3	8.3	7.5	7.5	7.5
h	1	2	3	1	2	3
Sample no.	13	14	15	16		
a	11.9	14.5	15.2	0		
b	5.6	6.8	8.3	0		
h	-2	-2	-2	0		

of the variable parameters shown in Fig. 2 are listed in Table I. The height and axes of the 3D-printed objects used in the experiment were close to these values with an average relative error of 0.4%.

2) Tasks: The participants pushed all 16 specimens, which were randomly arranged on the desk by the experiment facilitator, and ranked them based on their perceived softness, as shown in Fig. 1. They could freely compare the specimens before completing the task. No time limit was set, and the specimens could be touched many times before completing the ranking task. In a single trial, only one of the first, third, and fifth fingers were used. The participants touched the flat surface and the centers of the concave and convex with their finger pads such that their fingernails did not touch the specimens. Furthermore, they pushed the surface without sliding motions. Softness typically describes a deformable characteristic of materials or objects; however, we used solid plastic that could not be deformed by finger forces. Nonetheless, the participants conducted the tasks without any questions about the softness. No instructions were given about the force used for pressing. The participants were allowed to assign tied ranks to more than one specimen when their softness was perceived as equal.

The experiment facilitator provided instructions on which finger would be used in the task in a randomized order. Only one task was conducted using two of the three fingers; however, two tasks were performed with the remaining finger, which was also randomly selected. These two tasks tested using the same finger were used for participant screening purposes, as mentioned in Section II-A4. The screening task, which used the finger used in the first task, was conducted after the other three normal tasks. There was a break of a few minutes after each task. During the experiment, the participants wore smoke sunglasses; however, they were not fully blinded and could locate the specimens.

3) Participants: Twenty university students in their 20s (mean and standard deviation: 23.2 ± 1.2 years old, 4 females) participated in the study after providing written informed consent. They were not aware of the objectives of the study.

4) Data Analysis: To screen the participants, Spearman's rank-correlation coefficient was calculated between the results of two ranking tasks conducted by an individual using the same finger. The correlation coefficients were significant at a level of 0.05 for all participants, and the values ranged between 0.54–0.98 with a median of 0.88. Hence, we did not screen out any participants and used the results of the first trial of the two tested using the same finger for the latter analysis.

We tested the differences in the ranks assigned to the 16 types of specimens using the Friedman test. If the differences had a significance level of 0.05, as post-hoc tests, we then applied a pairwise Wilcoxon signed-rank test for the pairs between the specimen that was ranked as softest and the other 15 types of specimens. For these post-hoc tests, the significance level was adjusted using Bonferroni's method with a factor of 15.

In contrast to our expectations, effects of the concave depth h were not clearly observed. As a post-hoc test, we grouped the same type of concaves, irrespective of the h values, and compared them. The specimens resembling the fifth finger, i.e., Samples 1–3, those resembling the third finger, i.e., Samples 4–6, and those resembling the first finger, i.e., Samples 7–9, were grouped together. Furthermore, spherical concaves, i.e., Samples 10–12, and convexes, i.e., Samples 13–15, were also combined into two groups. The flat specimen (Sample 16) was not merged with any other groups. The ranks of these six groups were compared using the Friedman test and post-hoc Wilcoxon signed-rank tests, similar to the process described above. For the post-hoc comparison, the significance level was adjusted by a factor of 5.

B. Experiment 2: Softness matching task using rubber specimens

Participants compared a rubber object that had a concave or convex surface with flat objects made of rubber with different hardness values. They then selected a flat object whose softness was subjectively equal to that of the concave or convex object.

1) Rubber specimen stimuli: Fourteen flat rubber cylinders with different hardness values were used as comparison stimuli. The cylinders were 10 cm in diameter and 5 cm in height. These cylinders were made by blending two of the five types of commercial silicone rubber (KE-1415, KE-1417, KE-26, Shin-Etsu Chemical Co., Ltd., Japan; ELASTOSIL M8520, ELASTOSIL M4470, Wacker Asahikasei Silicone Co., Ltd., Germany). The hardness of the cylinders was tested using a Shore A durometer (GS-719N Teclock Co., Ltd., Japan) and the results were transformed to Young's moduli following [24]. The results ranged between 0.20–3.00 MPa, as listed in Table II.

We used a cylinder with a concave as a concave reference stimulus; the size of the concave was the same as that of Sample 8 in Table I. A cylinder with a convex was used as a convex reference stimulus; the convex size was identical to that of Sample 15. These reference stimuli were made of rubber G in Table II, with a Young's modulus of 0.55 MPa. The molded rubber concave and convex were slightly smaller than their original designs by 4.0% on average.

TABLE II: Elastic moduli of all samples in Experiment 2.

Sample name	A	B	C	D	E
Elastic modulus (MPa)	0.20	0.23	0.27	0.33	0.39
Sample name	F	G	H	I	J
Elastic modulus (MPa)	0.47	0.55	0.61	0.73	0.94
Sample name	K	L	M	N	
Elastic modulus (MPa)	1.23	1.50	1.95	3.00	

2) Tasks: Participants compared one of the two reference stimuli, i.e., concave or convex objects, and 14 comparative stimuli, i.e., flat objects, using the index finger of their dominant hand. Nine of the participants tested the concave object and then the convex object after a break of a few minutes. The other half tested the reference stimuli in the reverse order. The comparative stimuli were randomly arranged on the desk, not in the order of physical hardness. The participants were instructed to push the center of the stimuli using a finger pad to investigate their softness. Sliding was not allowed. They then selected a comparative stimulus whose material softness felt most similar to that of the reference stimulus. There was no time limit set for the task; however, most participants finished the task within 2–3 min, during which they could touch the stimuli at any time. Participants wore smoke glasses so that they could barely see the cylindrical stimuli to touch. The participants conducted these matching tasks only once for each reference stimulus.

3) Participants: Seventeen university students (mean and standard deviation: 23.0 ± 1.3 years old, 3 females) participated in Experiment 2 after providing written informed consent. Twelve among them also participated in Experiment 1.

4) Data analysis: We used the t-test to compare the Young's modulus of the reference stimuli (0.55 MPa) with the Young's moduli of flat objects that the participants selected as having subjectively equal softness to the references. This comparison was separately conducted for each of the two reference stimuli.

III. RESULTS

A. Results of Experiment 1: Ranking tasks

Fig. 3 shows the results of the ranking tasks where 16 types of samples were tested with the first, third, or fifth finger of the participant. The vertical axes show the softness ranks, and the samples with lower ranks were judged to be comparatively softer. Similarly, Fig. 4 shows the ranks after the same types of surfaces were merged, irrespective of depth h.

As shown in Fig. 3 (a), the samples tested using the first finger exhibited differences in their ranks ($\chi^2 = 112.9$, $df = 15$, $p = 4.47 \times 10^{-17}$). Sample 8, which had a concave resembling the first finger pad, was judged to be the softest, and its ranks were significantly lower than those of the concave samples resembling the fifth finger (Samples 1–3), the convex samples (Samples 14–16), and the flat sample (Sample 16). Furthermore, as shown in Fig. 4 (a), the sample groups exhibited differences in their ranks ($\chi^2 = 132.2$, $df = 5$, $p = 8.20 \times 10^{-27}$). The concave group (Samples 7–9) with sizes similar to that of the first finger pad exhibited the lowest ranks.

As shown in Fig. 3 (b), the softness ranks of the 16 samples were not equal ($\chi^2 = 120.4$, $df = 15$, $p = 1.58 \times 10^{-18}$) when tested using the third finger. Sample 9, which is a concave surface corresponding to the first finger pad, was judged to be the softest, and it exhibited statistically lower ranks than the spherical concave (Samples 10–12), convex (Samples 13–15), and flat objects (Sample 16). As shown in Fig. 4 (b), the six sample groups also differed in terms of their ranks ($\chi^2 = 137.8$, $df = 5$, $p = 5.15 \times 10^{-28}$), and the group corresponding to the first finger was judged to be the softest. This group was judged to be statistically softer than the groups of the spherical concave (Samples 10–12), convex (Samples 13–15), and flat (Sample 16) samples.

As shown in Fig. 3 (c), the softness ranks of all the samples were not equal ($\chi^2 = 129.1$, $df = 15$, $p = 3.16 \times 10^{-20}$) when they were tested by the fifth finger. Sample 8, which is a concave shape corresponding to the first finger pad, was ranked softest and judged statistically softer than two concave resembling the fifth finger (Samples 1 and 2), two spherical concave (Samples 11 and 12), convex (Samples 13–15), and flat samples (Sample 16). As shown in Fig. 4 (c), the ranks of the six sample groups were not equal ($\chi^2 = 146.4$, $df = 5$, $p = 7.83 \times 10^{-30}$). The concaves corresponding to the size of the first finger (Samples 7–9) were softer than the concaves resembling the fifth finger (Samples 1–3), spherical concaves (Samples 10–12), convexes (Samples 13–15), and flat object (Sample 16).

B. Experiment 2: Matching tasks

Fig. 5 shows the mean and standard error values of the Young's moduli of the flat objects that the participants selected as having subjectively equal material softness to the concave and convex surfaces. Note that the Young's modulus of the rubber that was used for the concave and convex surfaces is 0.55 MPa. As the left bar shows, the concave surface of 0.55 MPa was matched with a flat surface with a rubber hardness of 0.23 ± 0.035 MPa (mean and standard error). These subjectively equal Young's moduli were significantly smaller than that of the concave object, i.e., 0.55 MPa ($t(16) = 9.06$, $p = 1.07 \times 10^{-7}$, two-tailed t-test), which indicates that the concave surface felt softer than a flat surface with an equal Young's modulus. In contrast, as the right bar shows, the softness of the convex object was matched with that of a flat object of 1.68 ± 0.17 MPa, which is greater than 0.55 MPa ($t(16) = 6.65$, $p = 5.61 \times 10^{-6}$, two-tailed t-test). This indicates that the convex surface felt harder than a flat surface.

IV. DISCUSSION

In Experiment 1, we expected that the concave objects, the sizes of which were most similar to those of the finger pads, would be judged as the softest by the participants. This is because the contact area is magnified when the finger pad just fits into the concave, provided that the contact area is a major determinant of softness perception. However, regardless of the fingers, i.e., first, third, and fifth fingers, the largest concaves, the sizes of which were similar to that of the first finger, were judged to be the softest. We consider this to still be inconclusive because the participants may have failed to fit their finger pads into the appropriately matched concaves, which may have produced results that we did not anticipate. Furthermore, individual differences in finger dimensions and shapes may have affected the results. Note that we adopted ellipsoidal and spherical concaves, and their dimensions were determined on the basis of mean finger dimensions; however, the shapes and sizes of finger pads are individually different. For more controlled studies, we need to prepare tailor-made concaves for individuals and ensure that their finger pads exactly fit into the concaves. However, the results of Experiment 1 indicate that concaves that are slightly larger than finger pads are effective in causing perceived softness. The participants' answers regarding the spherical concaves fluctuated heavily, as shown in Figs. 3 and 4. This may be because of the shape mismatch between the individual finger pads and concaves. When the finger pad is pushed on a concave that is differently shaped or smaller than the finger pad, the finger pad contacts the edge between the flat surface and the concave, which may disperse the effect of concaves on softness

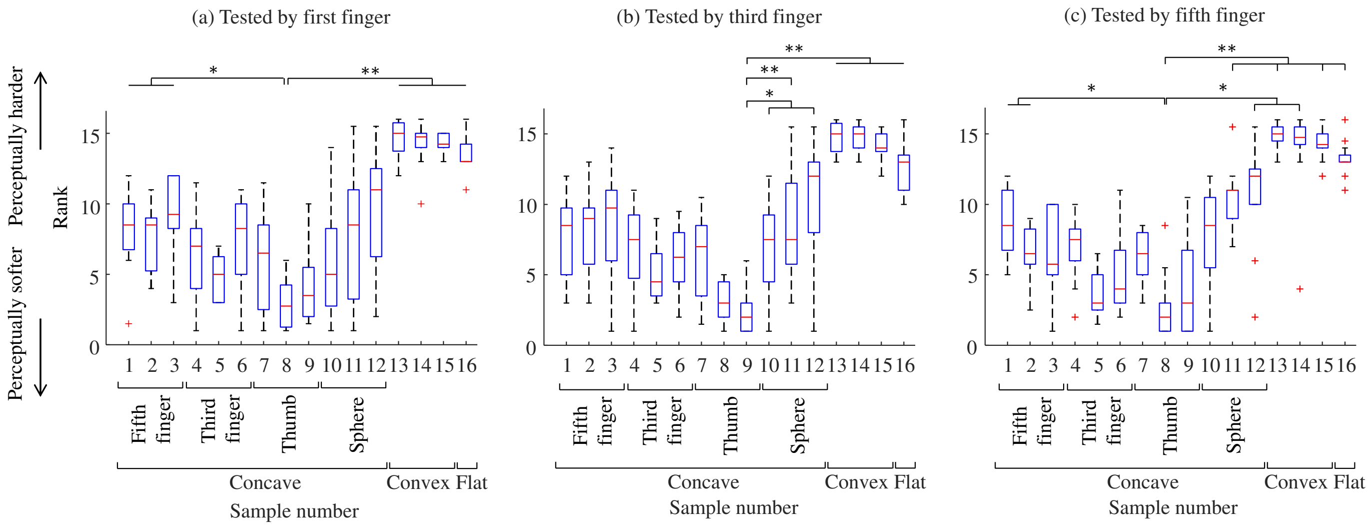


Fig. 3: Box plots of the ranks of all samples. The left, middle, and right columns represent the results when touched by the thumb, third finger, and fifth finger, respectively. Samples with low/high ranks were judged soft/hard. Samples 1–3, 4–6, and 7–9 had ellipsoidal concaves resembling the sizes of the fifth, third, and first fingers. Samples 10–12 had spherical concaves. Samples 13–15 had ellipsoidal convexes. Sample 16 had a flat surface. * and ** indicate the statistical differences in the ranks between two samples at $p < 0.05$ and $p < 0.01$, respectively.

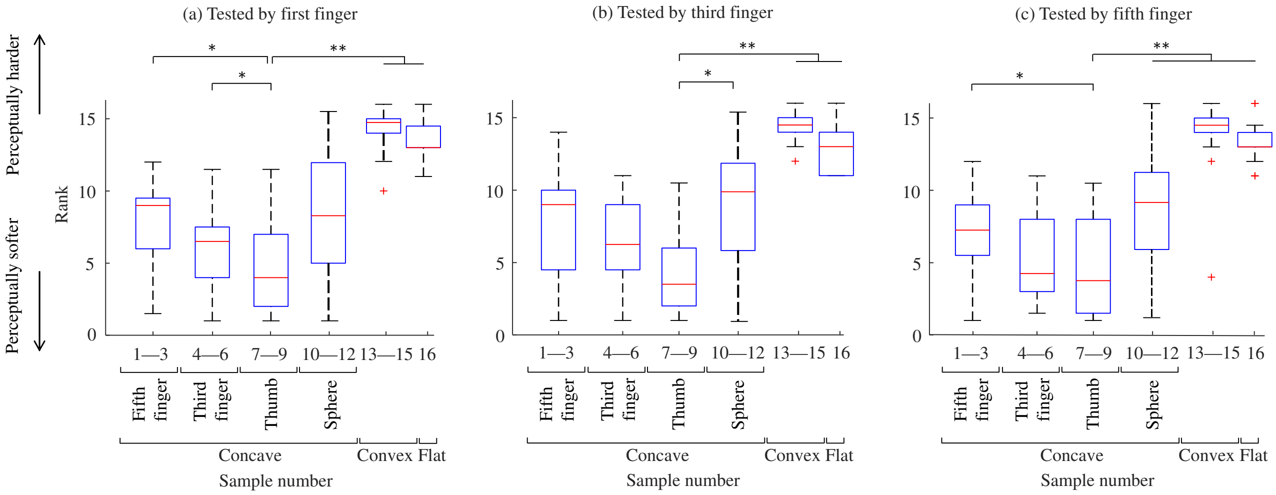


Fig. 4: Box plots of the ranks of all sample groups. The left, middle, and right columns represent the results obtained when the samples were touched by the thumb, third finger, and fifth finger, respectively. Samples were grouped based on the size of the concaves or the surface shapes. * and ** indicate the statistical differences in the ranks between two groups at $p < 0.05$ and $p < 0.01$, respectively.

perception. In contrast, the participants' answers regarding the thumb-sized concaves did not fluctuate as much as those regarding the spherical ones. The thumb-sized concaves were larger than or nearly equal to the pads of all participants' fingers, and stable effects on softness perception may be expected.

The primary interest of this study is why finger-sized concaves and convexes affect our softness perception of objects. It would be reasonable to discuss the softness perception of elastic objects from the viewpoint of stiffness and the elastic modulus [2]. We discuss the relationship between the contact force, contact area, and displacement at contact based on the Hertz contact theory, which does not accurately hold for finger pads; however, it is still meaningful to comprehend the general trends [25]. According to the theory [26], when two spheres are in contact with a normal force F, the radius a of the circular contact area is approximated as

$$a = \left(\frac{3F}{4} \frac{R^*}{E^*} \right)^{\frac{1}{3}}, \tag{1}$$

where R^* is the equivalent radius determined by the radii of the two spheres, R_1 and R_2:

$$\frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2}. \tag{2}$$

E^* is the equivalent elastic modulus determined by Young's moduli (E_1 and E_2) and the Poisson ratios (ν_1 and ν_2) of the two materials:

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}. \tag{3}$$

Let E_1, R_1, and ν_1 denote the parameters of the human fingers, referring to [23], [27], we set $E_1 = 0.1$ MPa, $R_1 = 6.8$ mm, and $\nu_1 = 0.48$. For a concave object, $R_2 = 8.3$ mm, and $E_2 = 0.55$ MPa.

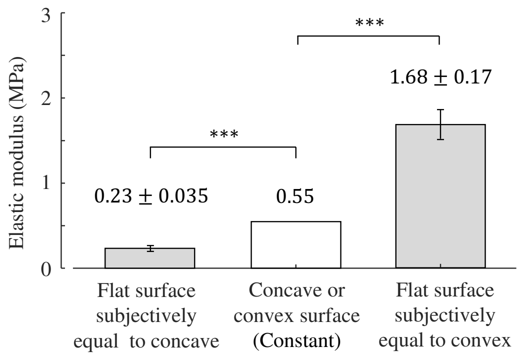
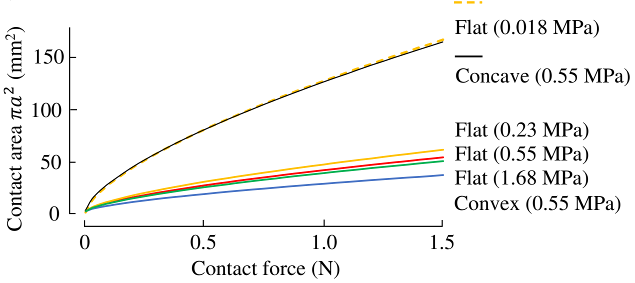


Fig. 5: Mean and standard error values of the Young's moduli of flat materials selected by the participants as subjectively equal to the concave or convex object. Left: Young's moduli subjectively equal to the concave surface made of rubber (0.55 MPa). Center: Young's modulus of the rubber used for the concave and convex surfaces. Right: Young's moduli of the materials that were subjectively equal to the convex surface made of rubber (0.55 MPa). *** indicates statistical significance level of $p < 0.001$.

(a) Force-area curve



(b) Force-displacement curve

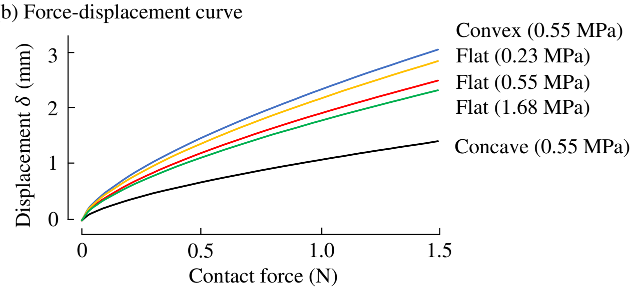


Fig. 6: Curves simulated by Hertz contact theory. (a) Force-area curve, (b) force-displacement curve.

For a flat object, R_2 is infinity. E_2 is either 0.23 MPa, 0.55 MPa, or 1.68 MPa. For a convex object, R_2 is -8.3 mm, and $E_2 = 0.55$ MPa. For the R_1 and R_2 values, we used the short axes of the third finger (6.8 mm) and thumb-sized concave and convex (8.3 mm). ν_2 was set to 0.48 considering the rubber material used in this study. Fig. 6 (a) shows the curves between the force and contact area when this spherical finger is in contact with concave, flat, and convex objects. Fig. 6 (b) shows the curves between the force and displacement, from which the stiffness or spring constant can be calculated. The displacement is the change in the distance between the centers of the two objects, computed as follows:

$$\delta = \frac{a^2}{R^*}. \tag{4}$$

Fig. 6 (a) shows that the contact area is smallest for the convex object (blue curve), and its apparent hardness or elastic modulus is the largest. The contact area is largest for the concave object (black curve), and its apparent hardness is the smallest. These curves are very different from those of the flat object with the same hardness (red curve), which indicates that the concave and convex shapes change the force-area curves and apparent hardness. Based on the force-displacement curve shown in Fig. 6 (b), the convex object (blue) appears less hard than the flat object of equal Young's modulus (red). The apparent stiffness or spring constant of the convex object is smaller than that of the flat object. Hence, a convex increases the apparent Young's modulus and decreases the apparent spring constant. Furthermore, the concave decreases the apparent Young's modulus and increases the apparent spring constant. These two types of quantities, i.e., spring constant and Young's modulus, affect the softness judgment simultaneously; however, the role of Young's modulus may be more important [2] for the object hardness used in the present study. The changes in the apparent Young's moduli caused by convex and concave shapes may perceptually surpass those in the apparent spring constants.

TABLE III: Apparent Young's moduli and spring constants of three objects with an actual Young's modulus of 0.55 MPa. Apparent Young's moduli were computed from the force-area curves, assuming that the stimuli were flat. Apparent spring constants were defined within 0.5–1.5 N.

	Perceived Young's modulus	Perceived spring constant
Concave	0.018 MPa	1369 N/m
Convex	-	634 N/m
Flat	0.55 MPa	774 N/m

Table III lists the nominal or apparent Young's moduli and spring constants of concave, convex, and flat objects of the same actual Young's modulus: 0.55 MPa. The apparent Young's modulus of the concave was determined using the least squares method such that the force-area curve of the flat surface best fitted that of the concave. The apparent spring constant was computed using the force-displacement curve between 0.5–1.5 N. The apparent Young's modulus of the concave object is 0.018 MPa, although its nominal material hardness is 0.55 MPa. This means that the force-area curve of the concave object is close to that of a flat object of 0.018 MPa (dotted yellow curve in Fig. 6 (a)). The apparent spring constant of the concave object is 1369 N/m, which is greater than that of a flat object of 0.55 MPa. The apparent Young's modulus of the convex object does not exist because no flat object can achieve similar curves, even with infinite hardness. The apparent spring constant of the convex object is 634 N/m, which is smaller than that of the flat object.

According to the above analyses, in this setting, it was suggested that the force-area curves or Young's moduli more dominantly affected the perceived softness than the force-displacement curves or spring constants. Earlier studies also agreed that the contact area or Young's moduli are highly significant for softness perception [2], [8], [10], [11], [13]. In contrast, a study by Xu et al. [5] is inconsistent with the present study. They investigated the softness perception of plums that are largely spherical and similar to our convex stimuli. In terms of the shape of the stimuli, [5] and the present study should be compared, whereas most of the earlier studies employed flat surfaces. In [5], no evidence was found suggesting that contact areas were used for judging the softness of plums. They concluded that the force-displacement curve and the composite spring constant derived from the curve were good predictors for the perceived softness. Although the present study and [5] used spherical convexes as stimuli, their conclusions are very different. We speculate that the irregular variation of natural plums decreased the reliability of contact area cues in the experiments of [5] and influenced the softness judgment of the assessors in [5]. The differences in the conclusions about the role of contact areas between the present study and [5] indicate that further studies are necessary to comprehend the softness perception of non-flat objects.

One concern of the present study may be in the experimental methods used for the ranking (Experiment 1) and matching tasks (Experiment 2). In particular, the task in Experiment 1 suggested to the participants that the stimuli should differ in terms of perceived softness. The method of constant stimuli may provide more convincing conclusions in the scenario where the pair of a concave or convex object and flat object was compared in terms of softness. Owing to the restrictions placed under the COVID-19 pandemic, we avoided the method of constant stimuli because it requires a long task duration. However, the effects of the convex and concave shapes observed in this study are substantial. For the reference stimulus of $\sim$1 MPa, the Weber ratio was approximately 15% [2]. In our results, the softness of a concave object with a Young's modulus of 0.55 MPa was judged to be close to that of a flat object of 0.23 MPa. This difference in Young's moduli is greater than that calculated using the Weber ratio, and is considered meaningful.

We also note the potential cognitive biases of the surface shapes. Round shapes are linked to feelings of softness in a synesthetic manner [28]. The participants could have visually recognized the rounded concaves or convexes before or after touching them, which could have biased their judgment of softness. If so, the perceived softness of both the concaves and convexes would be expected to be similarly influenced, whereas opposite effects were found in the experiments; the concaves felt softer and the convexes felt harder. It is thus reasonable to conclude that the synesthetic biases of round shapes were less significant than the effects of tactile interaction between the finger pad and surface shapes.

V. CONCLUSION

Physical hardness, such as the elastic moduli, and perceived hardness are different. An earlier hypothesis that the finger contact area is a major cue for softness perception suggests that macroscopic surface shapes influence perceived softness. We tested this possibility in Experiment 1 and compared the material softness of objects with finger-sized concaves, convexes, and flat surfaces. The objects with concaves, the sizes of which were similar to that of the average first finger, were judged to be softer than the others. Furthermore, the objects with convexes were judged to be harder than the others. In Experiment 2, the material softness of the concave and convex objects was matched with flat objects with different Young's moduli. The concave object of 0.55 MPa corresponded to a flat object of 0.23 MPa. The convex object of 0.55 MPa corresponded to a flat object of 1.68 MPa. These experiments demonstrated that finger-sized concaves and convexes influenced the softness experienced when pushing these surfaces with the finger pads. The findings of this study will assist in surface design and provide some insights into the principles of softness perception. In future work, these findings should be combined with detailed measurements of contact statuses.

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