Effects of surface textures and shapes on perceived softness of hard materials

Qingyu SUN *, Junliang GUO **, Shogo OKAMOTO **

** Graduate School of Engineering, Nagoya University, Furo-Cho, Chikusa-ku, Nagoya-shi, Aichi 464-8603, Japan*
sun.qingyu@c.mbox.nagoya-u.ac.jp
*** Tokyo Metropolitan University, 6-6 Asahigaoka, Hino-shi, Tokyo 191-0065, Japan*
okamotos@tmu.ac.jp

Abstract: This study investigated the influence of multiple surface features on the perceived surface softness during rubbing motion. Participants rubbed and ranked 13 types of 3D-printed rigid specimens with different macroscopic shapes and microscopic grains. A regression analysis revealed that the amplitude of the surface sinusoidal shape and the diameter of microscopic grains positively and negatively affected the signal-to-noise ratio calculated by the softness ranks, respectively. Smooth surfaces featuring a sinusoidal macroscopic shape with an amplitude of 0.5 mm felt softer than flat, smooth surfaces. By contrast, surfaces featuring grains with a diameter of 1 mm felt harder than the flat, smooth surfaces. These findings can help design soft-feeling product surfaces.

Keywords: *Softness, Texture, Microscopic grains, Surface shape*

1. INTRODUCTION

The softness perceived from surfaces is deeply related to the luxury experienced while touching and using products. Interestingly, perceived softness is not the inverse of physical hardness. Surface patterns and friction mediate perceived softness. For example, plastic surfaces with grains can feel softer than flat surfaces. In one study [1], [2], the effective radii of the grains were reported to be approximately 30 μm or 1 mm. Inoue et al. [3] demonstrated that finger-sized concave and convex shapes cause the surfaces to feel softer and harder, respectively, when pushed by fingertips. Furthermore, a reduction in the surface friction causes surfaces to feel softer when they are rubbed with fingers [4]. Hence, by manipulating the macroscopic and microscopic features of the surfaces, perceived softness can be altered even when the surfaces are made of hard materials that cannot be deformed by human fingers.

Thus far, the effects of macroscopic surface shapes on the perceived softness have not been investigated for the rubbing motion, although their effects on pushing motion have been reported [3]. The objective of this study is to investigate whether sinusoidal surface height patterns with large wavelengths contribute to the softness experienced while rubbing surfaces. Additionally, we investigated the influence of microscopic grains, having radii and heights of hundreds of micrometers, on softness perception, because such influences were not quantitatively reported in [1] or [2]. We created 3D-printed hard specimens with macroscopic height variations and micrograins. The participants rubbed these surfaces to rank them in terms of their perceived softness. The influential factors were statistically analyzed and discussed.

2. METHOD

2.1 Stimuli: 3D-printed surface textures

We created 13 3D-printed specimens. The 3D printer used was Form 3 (Formlabs, MA), with a nominal

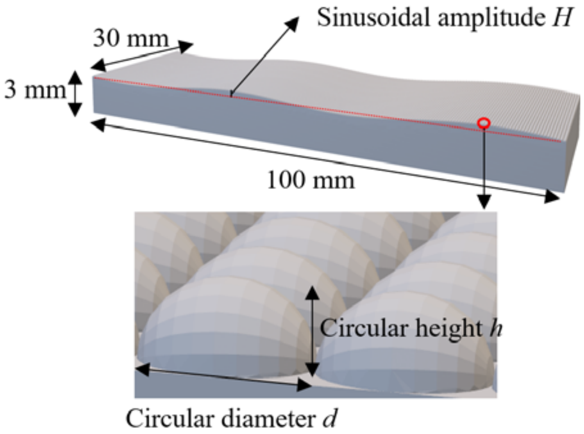

Figure 1: Physical size of specimens and the three parameters

Table 1: Stimuli parameter values

H (mm)	d (mm)	h (mm)	Stimulus
0	0	0	A
0	0.50	0.50	B
0	0.75	0.25	C
0	1.00	0.75	D
0.5	0	0	E
0.5	0.50	0.25	F
0.5	0.75	0.50	G
0.5	0.75	0.75	H
0.5	1.00	0.50	I
0.75	0	0	J
0.75	0.50	0.75	K
0.75	0.75	0.50	L
0.75	1.00	0.25	M

resolution of 25 μm and the Young's ratio of the plastic was 2.8 GPa. The physical dimensions of the specimens were $100 \times 30 \times 5$ mm, as shown in Fig. 1. There are two main surface features: macroscopic and microscopic. The macroscopic feature was a sinusoidal wave with a wavelength of 50 mm, and its amplitude (H) was a free parameter ranging from 0 to 0.75 mm. The microscopic spherical or hemispherical grains had diameter (d) ranging from 0 to 1 mm and height (h) ranging from 0.25–0.75 mm, as listed in Table 1.

These parameters were determined using an orthogonal table to decrease the number and redundancy of the specimens. In the orthogonal table, multiple parameters are altered among the specimens. However, a similar primary effect can be achieved using exhaustive specimens, without considering the interaction between the factors. The levels of parameters H, d, and h were 3, 4, and 4, respectively.

2.2 Tasks

The participants rubbed the randomly arranged specimens using their index finger to explore the softness. They wore a pair of glasses with translucent tapes such that they could not see the detailed shapes of the specimens. They then ranked the specimens according to their perceived softness. A higher rank referred to a harder specimen. Tied ranks were allowed.

2.3 Participants

Eight university students in their twenties participated in this experiment after providing their written informed consents. The objectives of the study were not explained to the participants prior to the experiments.

2.4 Analysis

Table 2: Experimental result. Mean softness ranks and their SN ratio.

Stimulus	SN ratio (dB)	Mean softness rank
A	−15.23	4.9
B	−18.17	7.4
C	−17.51	6.9
D	−22.28	13.0
E	−4.39	1.5
F	−14.43	5.0
G	−18.74	8.5
H	−19.77	9.6
I	−18.55	8.1
J	−3.98	1.5
K	−16.10	6.3
L	−19.89	9.5
M	−18.55	8.1

We used the signal-to-noise (SN) ratio employed in the Taguchi method to assess the softness of the specimens. The participants ranked the softness of the specimens, i.e., where smaller ranks were softer. Smaller-the-better features were then used for the obtaining of the SN ratio for specimen j:

$$SN_j = -10 \log \left(\frac{\sum_i^n y_{ji}^2}{n} \right) \tag{1}$$

where y_{ji} indicates the softness ranks assigned by each participant, and n is the number of participants, i.e., 8. i is the index of participants ($i = 1, \ldots, 8$). The SN ratio considers both the mean rank and its variability among participants. When the mean rank and its variability were small, the SN ratio was high.

We then conducted a multiple regression analysis with three physical parameters, H, h, and d as explanatory variables and the SN ratio of the specimens as objective variable.

3. RESULTS

Table 2 lists the average softness ranks and SN ratios for all the specimens. The softest specimens were stimuli E ($H = 0.5$ mm, $d = 0$, $h = 0$) and J ($H = 0.75$ mm, $d = 0$, $h = 0$), while the least soft specimen was D ($H = 0$, $d = 1$ mm, $h = 0.75$ mm).

Table 3: Coefficients of three parameters for linear regression analysis

Parameter	Coefficient	p-value
H (Amplitude of macro-shape)	5.28	0.060
d (Diameter of micrograins)	−9.18	0.010
h (Height of micrograins)	−6.48	0.118

The results indicate that surfaces with a low-frequency sinusoidal wave may present a softer texture than flat surfaces with micrograins. We also conducted a Wilcoxon signed-rank test to compare stimuli A ($H = 0$, $d = 0$, $h = 0$), i.e., a flat and smooth surface and J ($H = 0.75$ mm, $d = 0$, $h = 0$), for which the SN ratio was the largest among all surfaces. We found a significant difference between A and J ($p = 0.0078$), indicating that stimulus J was judged to be softer than stimulus A. Furthermore, the flat and smooth surface (Stimulus A) and the flat surface with relatively large micrograins (Stimulus D) were also significantly different ($p = 0.0078$) in terms of their ranks. Stimulus D was judged to be harder than stimulus A.

Table 3 shows the regression coefficients of the linear regression analysis, where H, d, and h are explanatory variables. The amplitude of low-frequency sinusoidal waves (H) exhibited a positive trend ($p = 0.060$), whereas the diameter (d) of microscopic grains exhibited a significantly negative effect on the perceived softness. The three parameters explained the SN ratio of softness with the correlation coefficient and adjusted $\hat{R}^2$ values being 0.92 and 0.78, respectively.

4. DISCUSSION

The experimental results and analyses indicated that smooth surfaces with a macroscopic shape felt softer than flat and smooth surfaces, or surfaces with micrograins. Note that all the specimens were composed of the same hard plastic resin; however, their surface softness felt different when they were rubbed, owing to their macroscopic and microscopic surface patterns. The effect of microscopic patterns was also reported in [1] and [2], where micrograins caused surfaces to feel softer. Hence, the results obtained in [1] and [2], and those of the present study differ in terms of the effects of micrograins. This difference may be caused by the difference in the materials used in [1], [2], and the present study.

Although the cause of the abovementioned phenomenon due to macroscopic shapes remains unknown, there are a few reports related to the demonstration of softness on hard touch panels [5], [6]. They presented low-frequency friction changes on the panel based on the pressing force and velocity of the finger. The softness perception in our experiment could possibly be due to changes in the finger pressing force, or friction during the rubbing motion. The tangential frictional force changes with changes in the surface gradient [7]. The low-frequency changes in friction may induce perceived softness [5], [6].

The conducted research has its limitations, viz., the variation of specimens and the number of participants. This potentially caused weak statistical significance for some parameters. Therefore, we intend to expand this research in the future. Optimization of the sinusoidal amplitude H and microscopic grain diameter d can also be considered to maximize the perception of softness.

5. Conclusion

In this study, we examined the influence of sinusoidal waves with large wavelengths and microscopic grains on the perceived softness of hard materials during the rubbing motion. The participants explored and ranked 13 types of 3D-printed specimens having macroscopic and microscopic surface features designed using a cross table. Regression analysis revealed that the SN ratio of softness ranks increased in the presence of macroscopic sinusoidal waves. To the best of our knowledge, this is the first report on this phenomenon. Although further studies are required to optimize the surface features, our findings make a positive addition in the literature for creating a perceived softness for materials used in product packaging, car interiors, and other such real-world consumer applications.

ACKNOWLEDGMENTS

This work was in part supported by MEXT Kakenhi #21H05819 and #20H04263.

REFERENCES

[1] Akane Ban et al., Vehicle interior parts, Patent JP5 253 103, 11 17, 2008.

[2] Akane Ban, Soft feel grain for hard plastic, Journal of the Robotics Society of Japan, vol. 30, no. 5, 494-495, 2012.

[3] Koki Inoue, Shogo Okamoto, Yasuhiro Akiyama, and Yoji Yamada, Surfaces with finger-sized concave feel softer, IEEE Transactions on Haptics, vol. 15, DOI: 10.1109/TOH.2021.3138640, 2022.

[4] Naomi Arakawa and Shogo Okamoto, Less frictional skin-like materials are felt softer in a physically inconsistent manner, Proceedings in IEEE World Haptics Conference, WPI.10, 2019.

[5] Ken Ito, Shogo Okamoto, Hatem Elfekey, Hiroyuki Kajimoto, and Yoji Yamada, Feeling softness on a hard touch panel using an electrostatic tactile texture display, Proceedings of IEEE Global Conference on Consumer Electronics, pp. 282-283, 2017.

[6] Giryeon Kim, Shogo Okamoto, Yasuhiro Akiyama, and Yoji Yamada, Softness presentation via friction force control on electrostatic tactile panel display, Proceedings of IEEE Global Conference on Life

Sciences and Technologies, pp. 219-221, 2020.

[7] Yohei Fujii, Shogo Okamoto, and Yoji Yamada, Friction model of fingertip sliding over wavy surface for friction-variable tactile feedback panel, Advanced Robotics, vol. 30, no. 20, pp. 1341-1353, 2016.