Hardness Perceived When Sliding Over Roughened Surfaces

Qingyu Sun, Shogo Okamoto, *Member, IEEE*, and Hongbo Wang

***Abstract*—The objective of this study was to investigate the influence of roughened surface features on the perceived hardness of various materials. Thirteen participants used a visual analog scale to evaluate the hardness of ten 3D-printed specimens by sliding a fingertip on them. The specimens had two types of surface features: flat and smooth, or with microscopic rectangular gratings. They were fabricated from two types of plastic with different Young's moduli—2.46 and 9.35 MPa. We found that both surface pattern and mechanical hardness significantly contributed to the perceived hardness of a material individually and without interaction. The roughened surfaces with rectangular gratings were judged to be harder than the flat and smooth surfaces of the same material. Among the parameters of the rectangular gratings, the groove width or periodic surface wavelength significantly contributed to the perceived hardness. Although the root cause of this phenomenon is unknown, friction caused by surface roughness is considered a potential mediator that influences the perceived hardness. The findings of this study can facilitate the manipulation of softness perception through surface design.**

***Index Terms*—Haptic interfaces, hardness perception, visual analog.**

I. Introduction

Hardness or softness is an important tactile feature of products and a significant factor in consumer satisfaction. Therefore, elucidating the mechanisms behind softness perception is crucial. Softness can be classified as furry, granular, viscoelastic, or deformable [1]. Previous studies concentrated on deformable softness with pressing motions using elastic surfaces [2], [3], [4], [5], [6], [7], [8], [9], [10], [11]. For example, the ability of humans to estimate the softness of silicone rubber specimens with various compliance levels was studied under active and passive contact conditions [2]. In addition, psychophysical experiments have been conducted using silicone rubber stimuli of various thicknesses and compliances [3]. These studies indicated that softness perception is achieved through the simultaneous use of tactile and kinesthetic cues. Tactile cues are primarily responsible for the perception of surface deformation. When a finger presses an object, the direction of the reaction force is mainly normal to the surface, which with tactile cues, including the contact area, collectively contribute to the judgement of object hardness [3], [9], [12], [13]. Meanwhile, kinesthetic cues are responsible for the perception of the force–displacement ratio [2], [3], [4], [6].

Although, in most studies, researchers have focused on pressing motions, hardness or softness is also perceived through sliding motions [1], [14], [15], [16], [17]. For example, the hardness of various materials is perceived when a finger is placed on a contact force-controlled rotating drum with an attached textured surface [14]. Under such conditions, a cue for the force–displacement ratio is not readily available. Skin lubricated with frictional powder is perceived harder than that lubricated with frictionless powder when rubbed with bare fingers [17]. Furthermore, humans adopt pressing and sliding motions equally when determining the softness of their skin [18], [19]. It is reasonable to consider that humans can judge an object's hardness while sliding a finger over it because the elastic modulus of an object influences its surface friction [20], which is a major component in determining tactile feeling.

Linkages between surface friction and the determination of hardness have recently been demonstrated using force display devices [21], [22], and a frictional surface was reported to feel harder. Therefore, we hypothesized that surface textures affecting friction would influence the perceived hardness while rubbing. This hypothesis was supported by our preliminary study [16], in which plastic surfaces with fine dotted patterns were perceived as harder, during rubbing motions, than flat and smooth surfaces made of the same resin.

To the best of our knowledge, this study is the first to investigate the perceived hardness when rubbing distinctively patterned surfaces made of materials with the same or different mechanical stiffness. Our previous study used only one type of material for 3D-printed specimens [16]; in contrast, we used two types of materials with different mechanical hardnesses in the present study. Thus, we sought to determine whether the influence of surface patterns on hardness perception was interchangeable with that of mechanical hardness. We controlled the normal contact force of the rubbing motion using a balance such that the softness judgment based on the pushing motion or force–displacement cues was largely inhibited. In a previous study [16], the participants examined the surface freely without a designated force; therefore, individual differences and active variations in force might have influenced the experimental results.

II. Methods

A. Texture Specimens

Two types of 3D-printed surface patterns were prepared for the experiment: flat and smooth specimens and microscopically roughened specimens, as shown in Fig. 1. The dimensions of each specimen were $100 \times 30 \times 5$ mm. As shown in Table I, each surface pattern was assigned a symbol and classified into one of two groups: F (flat and smooth) or R (microscopically roughened gratings). Symbols 1 and 2 represent Young's moduli of 2.46 and 9.35 MPa, respectively. Two types of specimens, flat (F1, F2) and microscopically roughened gratings (R1A, R2A, R1B, R2B, R1C, R2C, R1D, and R2D), were

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TABLE I
PHYSICAL PARAMETERS OF TEXTURE SPECIMENS

Surface type	Symbol	Ridge width/ Groove width GW (mm)	Groove height h (mm)	Measured height (mm)	Young's modulus (MPa)	R_a (μm)
Flat and smooth	F1	-	-	-	2.46	0.63
	F2	-	-	-	9.35	0.50
Roughened surfaces with rectangular gratings	R1A	0.5	0.25	0.23	2.46	0.72
	R2A	0.5	0.25	0.24	9.35	0.81
	R1B	0.5	0.75	0.70	2.46	0.76
	R2B	0.5	0.75	0.67	9.35	0.71
	R1C	0.75	0.25	0.22	2.46	0.69
	R2C	0.75	0.25	0.24	9.35	0.77
	R1D	0.75	0.75	0.68	2.46	0.80
	R2D	0.75	0.75	0.73	9.35	0.65

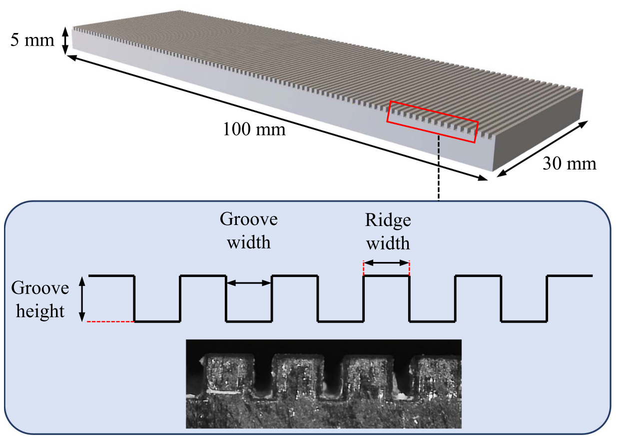

Fig. 1. Dimensions of specimens with rectangular gratings. The groove and ridge widths were set equal. A close-up photo is also shown.

fabricated from each of the two types of resins with different mechanical hardnesses. F1, R1A, R1B, R1C, and R1D were made from 2.46-MPa resin (Elastic 50 A, Formlabs, USA; Shore A hardness: 50). F2, R2A, R2B, R2C, and R2D were made from 9.35-MPa resin (Flexible 80 A, Formlabs, USA; Shore A hardness: 80). Young's moduli for Elastic 50 A and Flexible 80 A were calculated using the formula in [23].

The rectangular gratings had three microscopic physical parameters: groove width, ridge width, and groove height. We varied these parameters for acquiring knowledge of surface design and for investigating the sensitivities of parameters toward perceived softness. The groove width was set equal to the ridge width and was 0.5 mm or 0.75 mm; the groove height was 0.25 mm or 0.75 mm, as listed in Table I. These two parameters were chosen as close as possible to the parameters of the stimulus with microscopic-hemisphere grains that felt hardest among 13 specimens in [16], so that a similar effect would be expected. Therefore, there were two variable parameters with two levels. Because 3D printers do not precisely render the microsurface patterns, we employed parameter values that could be reproduced nearly as designed. In total, ten specimens were prepared for the analysis described in Section II-D to compare the effects of mechanical hardness and surface features on the perception of hardness.

After printing the specimens, their surfaces were polished with #1200 sandpaper to remove unintended fine surface irregularities. The actual groove heights of the specimens with microscopically roughened gratings were measured using a digital camera (Alpha 7, Sony, Japan), as shown in Table I. The errors in the groove heights were less than 10% of the set value. To examine the average surface roughness R_a

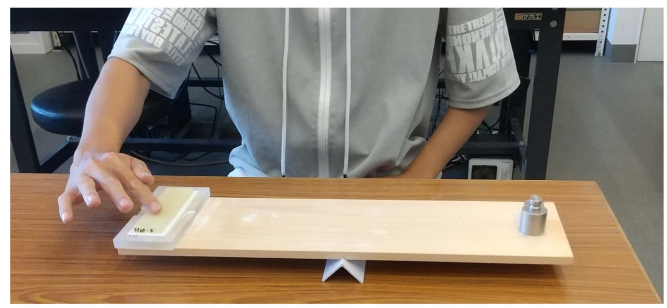

Fig. 2. Experimental setup for softness judgment test. Each participant slid a finger on a specimen using a balance and arranged them on the desktop along a visual analog scale.

of the three distinct points in the central part of the flat specimens, we used a contact-type profilometer (SJ-310, Mitsutoyo Co. Ltd., Japan). The average roughness values of the flat specimens were $R_a = 0.50$–0.63 μm for both types of resins. The probe of the profilometer was stuck on grooves on specimens and could not overcome the grating ridges. Instead of the sliding direction, we measured the R_a values of the ridges along their longitudinal directions.

B. Participants

Thirteen university students (two female and 11 male; six Chinese and seven Japanese; mean age: 23 years old) participated in the experiment after providing written informed consent. They were unaware of the objectives of the study before the experiments and were paid 1090 JPY per hour.

C. Task: Evaluation Test of Subjective Softness by Visual Analog Scale

Each participant slid the index finger of their dominant hand on each of the 10 randomly presented specimens and arranged them based on perceived softness along a visual analog scale [24]. A balance was used to control the pressing force at 30 gf, as shown in Fig. 2. This value was determined after confirming that there were no substantial differences in softness perception with a controlled pressing force of 20–100 gf. The participants were asked to sustain their balance as much as possible so that the pressing force was better controlled.

The participants arranged the specimens along a 1-m-long scale according to perceived softness. The experimenters explained that softer specimens would be located close to the right extremity, and the distance between the two specimens indicated the degree of difference in their perceived softness. Furthermore, participants were encouraged to use the full range of the 1-m scale. The participants were instructed to refer to the deformable softness, that is, the degree of ease of deformation of the material. The concept of softness was first presented in English and then in the participants' native languages, that is, Japanese or Chinese.

Each specimen was glued to a plastic base. During the task, the participants were instructed to hold this base while picking it up from the table or the balance such that they were unaware of the exact mechanical hardness of the specimens. They wore a pair of glasses whose lenses were blurred by opaque tape so that they could not see the detailed shapes of the specimens. To minimize the influence of the different adhesions between the two types of resins, talcum powder was applied using a spatula to lubricate the surfaces prior to the experiments.

In a preliminary experiment involving five participants who did not participate in the main experiment, the variability of the results within individuals was small, with the correlation coefficient of the specimen distances from the left end of the 1-m scale being 0.91 between two different trials of the same participant. Hence, the evaluation task was performed only once for individual participants, with a final confirmation step in which the participants were encouraged to check their classifications again after a 15-min rest. Therefore, the typical duration for the entire experiment was 1 h, including the 30-min softness evaluation task and 15-min confirmation step.

D. Data Analysis

The distance between the left edge of the 1-m-long scale and each specimen was measured as perceived softness. For example, if one specimen was located at the center of the scale, its softness score was 0.5. The minimum and maximum softness scores were 0 and 1, respectively. For each specimen, we removed potential outliers using the criterion of the mean plus or minus twice the standard deviation. Based on this criterion, eight judgments were excluded in the subsequent analysis. Seven of the eight judgements excluded were the scores for the roughened specimens (R2A, R1B, R2B, R1C, R2C, R1D, R2D), and they were distributed widely among the specimens.

We conducted two separate analyses of variance (ANOVA) for the different specimen ranges. First, we performed a two-way ANOVA for all ten specimens to compare the influences of both the surface patterns (smooth and flat or microscopically roughened) and stiffness of the resins (Young's modulus of 2.46 MPa or 9.35 MPa) on perceived softness. Their interactions were also investigated. The second analysis was a two-way ANOVA for the roughened specimens featuring rectangular gratings to explore the influence of the physical parameters, namely, groove width (ridge width) and groove height, on the perceived softness. The two independent factors were groove width (0.5 mm or 0.75 mm) and groove height (0.25 mm or 0.75 mm). The *anovan* function in MATLAB (2021b, Mathworks Inc., USA) was used for these analyses.

III. Results

The perceived softness and corresponding standard error values of the ten specimens are shown in Table II and Fig. 3. The specimen perceived as the softest was F1 (flat and smooth surface: 2.46 MPa) and the specimen perceived as hardest was R1D (groove width: 0.75 mm, groove height: 0.75 mm, 2.46 MPa).

Table III summarizes the ANOVA results for all specimens. Both the surface patterns (flat or roughened surface) and mechanical hardness (Young's modulus) significantly influenced the perceived softness ($p < 0.001$ and $p = 0.006$, respectively). Furthermore, the two factors did not interact with each other. These results suggest that differences in Young's moduli were recognized during the sliding motions, and specimens with microscopically roughened gratings felt harder than the flat specimens. When outliers were included in the dataset for the analysis, these conclusions did not change, and the mechanical hardness ($F(1, 126) = 4.46$, $p = 0.036$) and surface pattern ($F(1, 126) = 18.95$, $p < 0.001$) were the main effects with no interaction ($F(1, 126) = 0.70$, $p = 0.403$).

Table IV presents the results of the two-way ANOVA on eight microscopically roughened specimens, with the groove width and height as factors. The groove width significantly influenced the perceived softness ($p < 0.001$), whereas neither the groove height nor its interaction with groove width showed any significant influence. This conclusion held true even when outliers were included in the dataset. Specifically, the influence of groove width was pronounced ($F(1, 100) = 11.73$,

TABLE II
Perceived Softness of All Texture specimens*

Surface type	Symbol	Mean perceived softness	Standard error
Flat and smooth	F1	0.68	0.05
	F2	0.50	0.08
Roughened surfaces with rectangular gratings	R1A	0.40	0.06
	R2A	0.39	0.04
	R1B	0.44	0.07
	R2B	0.34	0.07
	R1C	0.33	0.06
	R2C	0.21	0.05
	R1D	0.19	0.03
	R2D	0.21	0.04

* The sample size is 122.

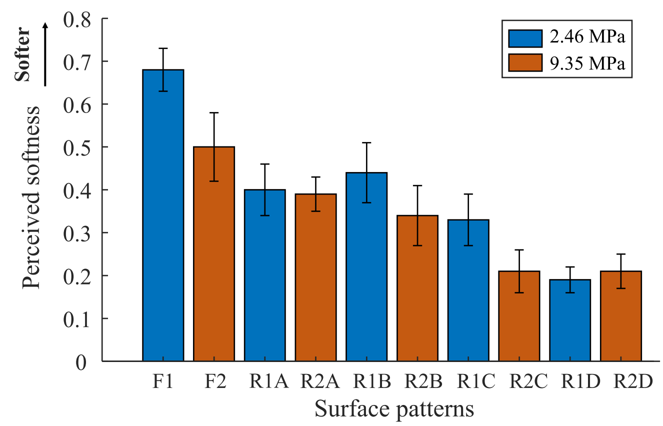

Fig. 3. Bar plot of the perceived softness values for specimens. Error bars are the standard errors among participants. F: Flat and smooth. R: Roughened with rectangular gratings. 1 and 2: Resins of 2.46 and 9.35 MPa, respectively. Letters A, B, C, and D stand for different surface patterns of microscopically roughened specimens, as described in Table I and Section II-A.

TABLE III
Results of Two-Way ANOVA Using All the Specimens

	Sum of squares	df	F	p-value
Mechanical hardness	0.345	1	7.96	0.006
Surface pattern	1.484	1	34.27	< 0.001
Interaction	0.064	1	1.47	0.227
Error	5.108	118		

TABLE IV
RESULTS OF TWO-WAY ANOVA FOR PHYSICAL PARAMETERS OF RECTANGULAR GRATINGS

	Sum of squares	df	F	p-value
Groove width	0.584	1	16.34	< 0.001
Groove height	0.035	1	0.97	0.327
Interaction	0.025	1	0.71	0.401
Error	3.326	93		

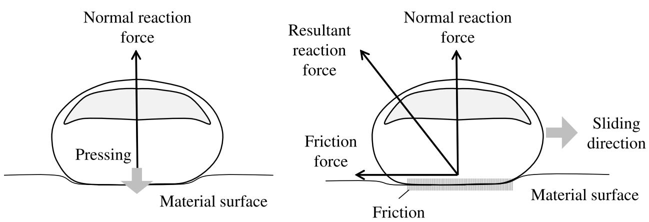

Fig. 4. Reaction forces during pressing and sliding motions. During sliding, friction forces may influence hardness judgement.

$p = 0.0009$), while the effects of groove height ($F(1, 100) = 0.69$, $p = 0.410$) and their interaction ($F(1, 100) = 1.40, p = 0.239$) were not statistically significant.

IV. DISCUSSION

In this section, we review the results and discuss the effects of surface patterns on the perception of hardness and softness. Microscopically roughened surfaces with rectangular gratings significantly decreased the perceived softness compared with the flat and smooth surfaces, as shown in Table III and Fig. 3. This result is consistent with our hypothesis that surface textures affecting surface friction patterns influence the perceived hardness of a material during sliding. The finger skin penetrates the grooves during the sliding motion, which increases friction because additional tangential forces are required for the penetrated skin surface to deform while sliding [25]. Therefore, the larger groove width results in larger friction force or variation under a dry contact condition and natural exploratory speeds. Note that larger spatial wavelengths of grating scales cause lesser friction when the wavelength of the grating scale is as small as 100 μm or smaller and adhesion is a major determinant of friction [26]. In our experiment, the specimens with the largest groove width (namely, R2C, R1D, and R2D), which might produce the largest friction or the largest variation in instantaneous friction according to [25], tended to be felt harder than the others. Some studies also reported that surface friction influences softness judgment [17], [21], [22], [27]. In summary, the results of this study suggest that microscopically rougher surfaces with rectangular gratings feel harder than flat surfaces; however, the reason for this remains unknown.

One potential mechanism to explain the results of this study was proposed by Arakawa et al. [17]. As shown in Fig. 4, only the normal reaction force is involved in a pressing motion. However, both frictional and normal reaction forces are generated during a sliding motion. Arakawa et al. suggested that the normal force is overestimated, because the part of the friction force is perceptually mixed up with the normal force. Given that the ratio of the contact area to the normal force is a cue to judge object softness [9], [12], the overestimated normal force may make the object to be perceived harder. The hypothesis in [17] is consistent with the results of our experiments. In our experiment, the friction caused by surface roughness might have resulted in additional perceived hardness.

The groove width influenced the perception of softness, as shown in Table IV. Previous studies agree that the groove width of gratings is the main factor that affects roughness perception and increases the subjective roughness as it increases [28], [29], [30]. In our study, when the groove width of the rectangular gratings increased from 0.5 mm to 0.75 mm, the perceived softness scores decreased by 38% on average, as shown in Fig. 3. Consequently, the rougher surface appeared to be harder during the sliding motion in our experiment. Additionally, the groove height has a positive effect on the perceived roughness, particularly when it is small enough for the finger skin to reach the bottom of the groove [31]. Hence, we expected some influence of groove height on softness; however, no significant effects were found. We speculate that the finger skin of the participants could not reach the bottom of the grooves because of the small groove width and pressing force (30 gf) for all groove height levels in our experiment, that is, 0.25 mm and 0.75 mm, considering the height of the epidermal ridges being approximately 60 μm [32]. Therefore, the specimens with different groove heights could not be largely differentiated in terms of the perceived roughness, and the groove height rarely contributed to the perception of softness. In the future, different groove heights, for example, 0.05 mm and 0.75 mm, should be used to investigate their effects.

Notably, the effect of Young's modulus was substantial for the flat specimens; however, the effect was moderate for the microscopically roughened specimens, as shown in Fig. 3. The roughened specimens with different Young's moduli did not differ significantly in terms of perceived softness; this suggests a potential interaction between the mechanical hardness and surface pattern. However, this tendency was not confirmed by the result of the two-way ANOVA as shown in Table III. A recent demonstration [22] agrees with this result and provides some clues for this phenomenon. Using a commercial force display, they simulated virtual surfaces with two levels of stiffness, 400 and 500 N/m, and kinetic friction coefficients of 0 and 0.5. Participants stroked the surface using a stylus and determined which virtual surface was softer. Consequently, the participants' judgment of softness was less accurate with greater kinetic friction during a sliding motion, suggesting that the existence of friction may affect the softness judgement under this situation. In our experiment, the microscopically roughened specimens with rectangular gratings had more frictional surfaces owing to the skin penetrating the grooves of specimens [25]. Consequently, the surface roughness may have obscured the differences in the perceived hardness between specimens with various Young's moduli.

The artifact or linguistic confusion caused by the experimental design is a concern. Some participants might have been inclined to judge the specimens with microscopic gratings as "hard" because of artifacts when they did not actually feel so. "Soft" and "smooth" or "slippery" may conceptually overlap in some cultures [33], [34]. An English dictionary also describes "soft" as including the concept of surface smoothness [35]. Therefore, the concepts of hardness and roughness can be confused with haptic perception [34]. In particular, when harder stimuli tend to be rougher in a stimulus set, experimental results may show a link between hardness and roughness. However, the same specimen sets were manufactured using both hard and soft resins in our experiment. Hence, the surface shapes and resin hardness were independent, such that an accidental correlation between perceived hardness and roughness could be avoided in the experiment. Furthermore, as in the analysis shown in Table III, the participants could differentiate the two types of resins of different mechanical stiffnesses in a physically congruent manner ($p = 0.006$); mechanically harder resins were judged to be harder. Additionally, the definition of softness provided to the participants before the experiment had no connection with surface roughness. Hence, the participants reasonably distinguished the material hardness in the experiments without any suggested relationships between surface patterns and softness. Nonetheless, it is still an open question how conceptual confusion between softness and roughness can be measured or avoided.

Some aspects of the present study could be improved in the future. Owing to the limitations of the 3D printer and polishing process using sandpaper, the control of the surface patterns was imperfect. Regarding the experimental protocol, tactile sensory words with similar lexical meanings in different languages can potentially lead to differences in the responses for tactile perception [36]. Therefore, differences in responses to softness perception among various cultural backgrounds should be further investigated. The vertical movement was not perfectly controlled by the balancer and might have caused the exact normal force to vary from 30 gf, which may potentially affect the hardness perception in an unknown manner. Hence, a better control method is required. Moreover, variations in the surface patterns and mechanical hardness of the resins were limited, and we may not be able to assert the generality of the effect of roughness on softness perception. If we investigate a variety of surface patterns and parameters, we may recognize their interactive effects and further optimize the surface design accordingly. Properties other than Young's modulus, such as hydrophobicity, may potentially influence softness perception in unknown ways, although we attempted to reduce such effects via lubrication using talcum powder.

V. Conclusion

Our previous study reported that during sliding motion, surfaces with fine dotted patterns were perceived as harder than flat and smooth surfaces made of the same resin [16]. However, only one type of plastic material was used in our previous study. To further investigate this phenomenon in the present study, we examined the influence of microscopic roughness on the perceived hardness of specimens with two different types of materials for promoting the generality of the effects. Softness evaluation tasks were conducted using a visual analog scale during sliding motions. The results show that the microscopically roughened surfaces with rectangular gratings felt hard during sliding motions, and as the groove width of the gratings increased, the specimens felt harder. Although the real cause remains unknown, we speculate that friction may contribute to this phenomenon; a more frictional surface would feel harder during sliding. We believe that our findings contribute positively to the literature on creating perceived softness in consumer applications.

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