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Friction-Induced Tactile Pleasantness on Surfaces with Systematically Varied Roughness

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***Abstract*— The touch of certain materials can evoke the affective perception of pleasantness. Previous research has attributed a high pleasantness of touch to the smoothness of surfaces and to low friction against the exploring fingertip. We have studied the effects of friction and roughness on the pleasantness of touch not between materials, but between samples of the same material where friction is modulated by the variation of roughness. The psychophysical experiments have been implemented for two distinct everyday materials, namely metal and rubber. For rubber, participants report higher pleasantness of touch for lower friction, which is realized by increasing roughness starting from very smooth high-friction surfaces. Lower friction thus outweighs lower roughness in eliciting the perception of pleasantness. The situation is more complex for aluminum, where increasing roughness initially lowers fingertip friction leading to greater pleasantness. Above a certain roughness threshold, friction increases again due to the deformation of skin by high surface asperities. This increase of friction reduces again pleasantness. Thus, pleasantness decreases with increasing friction within each of the two friction regimes. Our findings across the two materials thus suggest that perceived pleasantness monotonously follows lower friction for monotonous friction-roughness regimes.**

Keywords—fingertip friction, roughness, pleasantness

I. Introduction

Tactile experiences are typically characterized by two components: a discriminative and an affective aspect. The discriminative part of touch involves the ability to assess the physical properties of a material, such as roughness, compliance, or temperature, which are often categorized as components of tactile dimensions [1]. The affective aspect on the other hand, encompasses the emotional responses or valence, resulting from touch, such as the perceived pleasantness or unpleasantness of touch. While tactile discrimination can be directly related to the measured physical attributes of a material, for example, to the roughness, which is derived from the measured topography of the surface, the quantification of affective sensations is more challenging. Nevertheless, it is possible to arrive at a pleasantness scale for the touch of different materials using Rasch analysis [2].

Pleasant sensations may be linked to discriminative aspects of touch and the underlying physical parameters, in particular, roughness. Some authors have reported that the preference [3] or pleasantness [4] of materials has a positive correlation to smoothness of the surface. Gwosdow et al. [5] reported that increased skin moisture during fabric sliding on the forearm led to higher skin friction, which enhanced texture perception but reduced tactile pleasantness. For compliant materials, the felt pleasantness is strongly correlated to the perception of softness [6]. Klöcker et al. [7] studied the tangential force (f_T), and the coefficient of friction (μ) of the sliding fingerpad on different materials and found significant correlations to the pleasantness responses of the participants. Materials eliciting low f_T and μ with the finger have been rated as more pleasant to touch.

The work of Klöcker et al. [7] reports a ranking of pleasant touch by physical factors of different materials. Here, we want to investigate the hypothesis that pleasantness of touch is correlated with lower friction also between samples of one material, when friction is varied by changing the surface roughness. Friction is high on very smooth surfaces, where the real contact area is large between skin and sample. Friction is reduced with increasing microscale roughness [8], [9], [10], when the real area of contact is reduced to roughness asperities. However, friction is expected to increase again for large roughness when higher asperities interact with finger ridges and deform the skin [11]. This expected non-monotonic dependence of friction on roughness may open the opportunity to disentangle contributions of friction and roughness to the perception of pleasantness. We chose two commonly used classes of materials for our study, metal and rubber, and produced samples each with the same range of surface roughness. These materials were not only selected for their prevalence in applications but also for their different frictional interactions with human skin, resulting in distinct tactile sensations. Metals are rigid, and offer elastic contact with the finger, whereas rubber is soft and compliant to even small forces during touch. We aimed to check both the validity, and the generality of the hypothesis by testing it on two different materials.

We present our findings in the following order: first, we demonstrate that the relationship between the coefficient of friction (μ) and roughness is non-monotonic for aluminum as metal, whereas it is monotonic for the rubber polydimethylsiloxane (PDMS). Next, we analyze pleasantness

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judgements in relation to individually measured friction for both materials. Finally, we compare the role of roughness and friction in the tactile perception of pleasantness for each material.

II. Materials and Methods

A. Sample preparation

We prepared nine aluminum and PDMS samples sized 50 x 50 mm^2. The roughness of the aluminum surfaces was varied from smooth to rough by polishing with diamond paste (particles sized 3 μm and 1 μm), and by sandblasting with glass beads (d = 40-70 μm, and 150-250 μm) and (or) fused alumina particles (d = 250-355 μm) for different exposure times. The glass beads were spherical and the fused alumina particles were irregular in their geometry, both were obtained from Wiwox GmbH Surface Systems. The PDMS surfaces were fabricated using a replica molding technique, which consisted of two steps: first, the preparation of a negative mold for each aluminum surface and second, molding PDMS from the negative templates to replicate the exact surface topographies. In the first step, the two components A and B of SYLGARD™ 184 Silicone Elastomer were mixed in the ratio 10:1 (A:B) by weight and poured on the aluminum surface until it was fully covered. The mixture was placed in the oven at 90°C for 3 hours to accelerate the curing process. In the second step, liquid PDMS (Smooth-Sil 960) was prepared by mixing the parts A and B in the ratio 10:1 by weight and poured into the silane-treated negative mold prepared in the first step. Air bubbles were removed by placing the mixture in a vacuum chamber prior to curing. Following the curing process, the solidified PDMS sample was carefully demolded. The pre-treatment with silane facilitated the demolding process, by reducing adhesion of the PDMS to the negative mold. The demolded samples exhibited a precise replication of the aluminum surfaces´ topography and are expected to have a modulus of 1.9 MPa at 100% elongation. To limit the experimentation time to approximately 90 minutes per participant, we selected seven aluminum and seven PDMS samples from the original set of nine, with five pairs of identical topography. The selection of the aluminum samples was guided by results of a pilot study, which indicated that the average friction coefficient μ exhibited non-monotonic behavior with increasing roughness. In the selection of PDMS samples, we omitted the one with lowest roughness since it was the only sample that exhibited stick-slip phenomena during tactile exploration.

B. Sample roughness

The roughness values for the aluminum samples were measured by a stylus tip (Accretech GmbH) with tip size r_{tip} = 2 μm, conical shaped, for scan length of 4 mm using a cut-off wavelength of 0.8 mm. The root-mean square slopes (Rdq) of the samples were estimated using a web-based tool (contact.engineering [12]), values ranged from 0.03 to 0.6 that corresponded to an average roughness (Ra) ranging from ~ 0.02 μm to ~ 7 μm. For our samples, Rdq and Ra are strongly correlated with each other (r = 0.95). We note that the parameter Rdq correlates better with the real contact area against the elastic skin rather than conventional roughness parameters such as Ra or Rq [13].

C. Psychophysical study

We invited 34 healthy participants (age 20 to 37, median age 27) with no known skin or neurological impairments. They were unaware of the objectives of this psychophysical study. Forty-two pairs of samples, two times twenty-one unique pairs formed by the seven samples of each material, were presented to them in a randomized order. Our goal was to investigate the role of roughness-modulated friction in the perception of pleasantness, and hence we did not present pairs of samples from two different materials. For every sample pair, the participants were asked to explore one after the other starting from the left one in about five circular movements with the pad of the straight index-finger and answer the forced-choice question: *Which of the two samples is more pleasant for you to touch?* They were allowed to switch between the samples multiple times until they decided for the more pleasant one. The participants wore noise-cancelling headphones to eliminate any bias in responding to the psychophysical question. Visual access to the samples was blurred by an optically diffusive screen to allow for finger positioning while blocking visual information about the samples' roughness.

D. Friction measurements and data analysis

The samples were placed on a 3-axis force sensor (K3D120 with GSV-8 amplifier, ME-Messysteme, Germany) that allowed for the recording of forces at a frequency of 120 Hz. For each trial, we calculated the median friction force (f_T), normal force (f_N), and coefficient of friction (μ) for both the surfaces explored. The coefficient of friction μ was calculated using Amontons´ law: $\mu = f_T/f_N$ for all values of f_N greater than 0.1 N. Participants provided written consent before participating in this study. The study was approved by the local university ethics committee (Antrag 21-06 "'Taktiles Weiß' für die Fingerspitze - Materialstrukturierung für niedrige Reibung"). Significance testing was performed using the Wilcoxon test for cases where the data did not follow a normal distribution, as determined by the Shapiro-Wilk test.

III. Results

A. Roughness vs friction

Before we report the analysis of pleasantness judgements, we introduce the relationship between the average friction coefficient μ and the surface roughness Rdq for both materials.

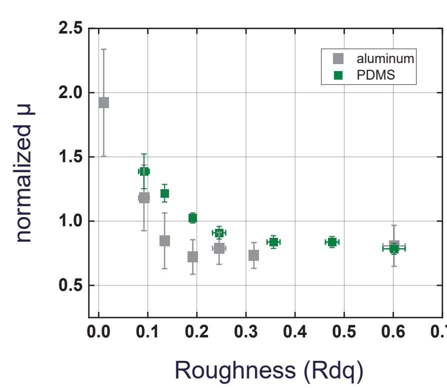

Fig. 1. Variation of normalized friction μ with roughness Rdq. Each data point indicates the mean normalized μ of a particular sample. Error bars indicate the standard deviation from the mean.

To account for individual variations across samples, the μ values for each trial were normalized by the mean μ over all trials for each participant. This normalization approach allowed for the comparison of the average variations in μ between samples, as shown in Fig. 1. For aluminum, μ exhibits a strong decay from the smoothest sample up to Rdq $\approx$ 0.2, followed by a slight increase. We note here that while the roughness range of our samples are still within the definition of 'fine roughness' [14], we denote the samples with Rdq < 0.2 as 'smooth' and Rdq > 0.2 as 'fine' roughness. For PDMS, there is a slower decay in μ spanning the entire range of Rdq with no increase.

To verify if the relation between friction and roughness for both materials is also observed for each participant, individual Spearman rank correlations were performed between Rdq and μ, as well as f_T for both the materials, and we report the mean correlation statistics. For PDMS, we observed a significant decrease in μ (ρ = -0.97, p = 0.001) and a near-significant decrease in f_T (ρ = -0.71, p = 0.094) with Rdq. In contrast, for aluminum, the correlations for μ (ρ = -0.57, p = 0.23), as well as f_T (ρ = -0.34, p = 0.47) with Rdq were not significant.

B. *Perceived pleasantness and measured parameters*

We analyzed a total of 712 decisions for aluminum and 713 for PDMS. Two trials with aluminum and one with PDMS surfaces were not considered for the analysis, due to technical failures in the data recording. Fig. 2 shows the fraction of decisions for the more pleasant sample that coincided with a lower value of each of the four parameters, μ, f_T, f_N, and Rdq.

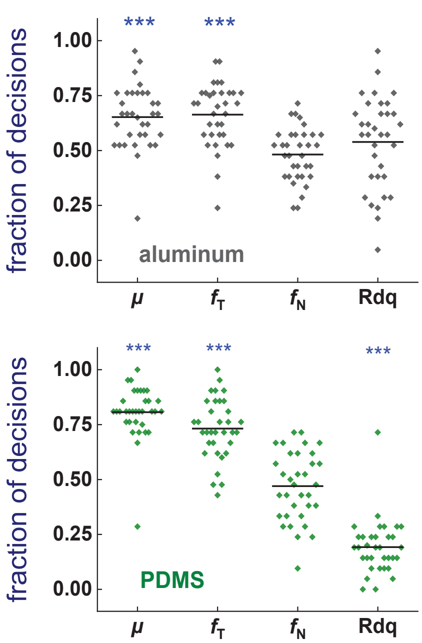

Fig. 2. Fraction of pleasantness decisions for the sample which exhibited the lower value in each trial for each of the parameters μ, f_T, f_N, and Rdq. Each data point represents the fraction of decisions of one participant, with mean fraction value for each parameter indicated by a horizontal line. The deviation of fraction of decisions from chance decisions (0.5) was tested by independent t-test (*** indicates a p < 0.001).

Pleasantness decisions significantly (p < 0.001) went with lower friction (μ and f_T) for both materials, and higher Rdq for PDMS, computed against chance using independent t-tests across participants. The difference in the fraction of decisions for higher plesantness in agreement with samples with a lower μ is significantly higher for PDMS than for aluminum (Wilcoxon test, z = 27.5, p < 0.001). A similar approach was applied to the decisions for higher pleasantness in agreement with samples with a lower f_T and we obtained again a significantly higher difference for PDMS (paired t-test, $t(33)$ = -2.337, p = 0.026). The pleasantness decisions for the sample on which a lower f_N was applied were not significantly different from chance. As a first conclusion, we observe that participants found samples with lower friction more pleasant to touch. This relation is stronger for PDMS than for aluminum.

We want to analyze our results with respect to our working hypothesis, i.e. we investigate if the observation by Klöcker et al. [7] on the correlation of pleasant touch with low friction also holds between samples of one material where friction is modulated through variable roughness. Therefore, we analyzed our data following their approach (see Table. I and II). First, repeated measures analysis of variance (RM-ANOVA) tests were performed to determine if the friction variables μ and f_T, and the normal force f_N varied significantly between each of the seven surfaces of both the materials across participants (Table I).

TABLE I. Analysis of Significant Differences Between Samples (RM-Anova) for Forces and Friction Coefficient and Comparison with Results Reported by Klöcker et al. [7]

Material	Parameter	RM-Anova	p	Agreement with [7]
aluminum	μ	F(6,198) = 90.15	< 0.001	yes
	f_T	F(6,198) = 37.82	< 0.001	yes
	f_N	F(6,198) = 5.45	< 0.001	no
PDMS	μ	F(6,198) = 241.85	< 0.001	yes
	f_T	F(6,198) = 31.90	< 0.001	yes
	f_N	F(6,198) = 2.17	< 0.05	no

TABLE II. Correlation with Perceived Pleasantness for Mean Forces and Friction Coefficient and Comparison with Results Reported by Klöcker et al. [7]

Material	Parameter	Spearman correlation ρ (n = 7)	p	Agreement with [7]
aluminum	μ	-0.36	0.43	no
	f_T	-0.71	0.07	no
	f_N	-0.11	0.81	yes
PDMS	μ	-0.94	< 0.001	yes
	f_T	-0.99	< 0.001	yes
	f_N	0.85	0.016	no

For each RM-ANOVA test, the surfaces were treated as 'within-subject' factors, with the dependent variables- μ, f_T, or f_N. The tests showed that μ, f_T and f_N varied significantly between at least two of the surfaces. Spearman rank correlations were conducted to check the monotonicity in the relationship between the percentage of pleasantness votes for each sample and the mean values of the variables μ, f_T and f_N, as detailed in Table II.

The results indicate a general trend of decreasing pleasantness with increase in friction for both materials. While this relationship was strongly significant for PDMS, this was not the case for aluminum. Similarly, a significant correlation was found between pleasantness and normal force (f_N) for PDMS, but not for aluminum. The positive correlation for PDMS indicates that participants consistently rated samples as more pleasant when they applied a higher force f_N.

The experimental protocol that we followed enabled the participants to explore surfaces at a f_N of their choice. In Fig. 2, we observed that the fraction of pleasantness decisions did not significantly favor a lower or higher f_N. We analyzed in more detail if the participants varied f_N with the measured μ, by plotting the applied f_N against $1/\mu$ [15], as shown in Fig. 3.

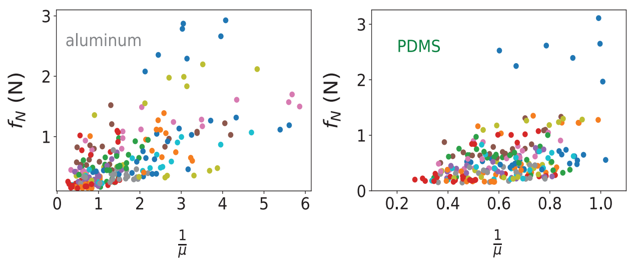

Fig. 3. Variation of normal force f_N with $1/\mu$ for both aluminum and PDMS. A linear positive correlation would indicate that a participant kept the friction force f_T constant between sample with different coefficient of friction μ. Colors represent results for different participants.

We observed that in general, f_N increased with $1/\mu$, meaning a tendency to apply higher f_N on surfaces with a lower μ. A Spearman correlation test was conducted to check if this behaviour was consistent across all the participants. The test resulted in a mean correlation value of 0.5 for aluminum and 0.24 for PDMS. The correlation was significant for only 9 participants for aluminum and 10 participants for PDMS. We conclude that only some participants changed the applied normal force f_N between samples to keep the friction force f_T constant, while others tended to keep the applied normal force f_N constant.

C. *Psychometric analysis for pleasantness decisions with friction (μ)*

In Figs. 4(a) and 4(b), we show a psychometric analysis for the decisions that favoured surfaces with a lower μ for both materials. A psychometric plot is commonly used to find the just noticeable difference (JND) of the stimulus being tested, usually based on a forced-choice task. While we did not directly ask the participants for the perception of friction, we used the psychometric analysis to extract a threshold that indicates the minimum relative difference in μ above which a majority of the pleasantness decisions were for the sample with a lower μ.

For each trial, we count the choice as 1 when it favoured the sample with lower μ and 0 otherwise. Trials were then sorted by increasing relative differences in μ and grouped into bins, for which average decision counts and average relative differences in μ were calculated. A sigmoidal curve was fitted

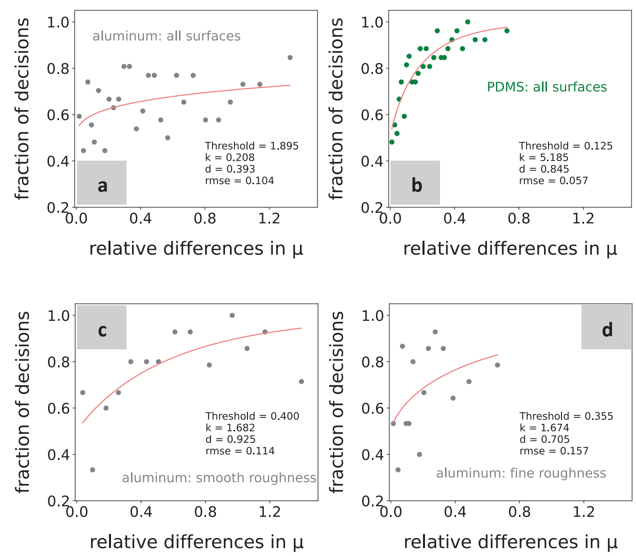

Fig. 4. Psychometric analysis of the fraction of pleasantness decisions for samples with lower coefficient of friction μ as a function of relative differences in friction. The curve fitted to the mean of histogram bins (n = 27) for both materials is defined by the sigmoidal function $1 - 0.5 * e^{-(k*\Delta\mu)^d}$, where k and d are fit parameters that describe the shape of the curve and can be used to determine the threshold, $\Delta\mu$ is the relative difference in the stimulus μ, for each pair in the trial and is calculated using $\Delta\mu = |\mu_1 - \mu_2|/mean\,(\mu_1, \mu_2)$. The 'threshold' refers to $\Delta\mu$ at which the psychometric curve intersects 0.75, which we take as the majority of the fraction of decisions.

to the data points, where the curve was constrained to 0.5 to account for chance choices at zero relative difference, and to 1 for very large relative differences. In Fig. 4(b), we observe that this psychometric analysis is an adequate model for the PDMS results. The threshold for a majority of pleasantness decisions for the sample with a lower μ is at a relative difference of 0.125. Results for aluminum, as presented in Fig. 4(a), exhibit large scatter, such that the psychometric fit is barely a better model than a constant value. We note that average fraction of pleasantness decisions for the sample with lower μ is mostly above 0.5, but that there is a rather weak increase with increasing friction differences. If one accepts the sigmoidal fit as model, the threshold for $\Delta\mu$ would be 1.89. The lower threshold in friction differences for PDMS may be interpreted as indication that friction is a stronger predictor for the perception of pleasantness in PDMS than in aluminum.

D. *Roughness as a predictor for pleasantness*

We checked if there had been contributions to pleasantness from physical parameters other than friction. The investigation into surface roughness Rdq is crucial since friction was controlled by varying Rdq. A Spearman correlation test (two-sided) was conducted to check if there is a consistent decrease or increase in pleasantness votes with Rdq for both materials. The test resulted in a significant correlation (ρ = 0.937, p = 0.002) for PDMS but not for aluminum (ρ = -0.285, p = 0.534).

In the analysis presented so far, we observed that for PDMS both friction and Rdq were significantly correlated with pleasantness votes. For aluminum, neither Rdq nor friction (Table II) were significantly correlated to the pleasantness votes. However, we observed in Fig. 2 that the fraction of responses that favoured lower friction samples (μ and f_T) were significantly above chance for both materials in pairwise comparison. We speculated that the apparent contradiction for aluminum originates from the distinct friction-roughness relationship, a sharp decay followed by a slight increase in μ with increasing roughness. To compare the influence of friction on pleasantness perception in each regime of friction-roughness characteristics, we split the set of aluminum samples into two groups. The smooth-roughness group comprises the four surfaces for which friction decreases with roughness similarly to PDMS. The fine-roughness group contains the four samples for which friction increases with increasing roughness. For each group, we examined how strongly μ influenced the perceived pleasantness.

First, we present the psychometric analysis for the two groups in Fig. 4(c) and 4(d). The threshold in $\Delta\mu$ was reduced from 1.89 to 0.40 for the smooth-roughness group and to 0.35 for the fine-roughness group. Second, the average fraction of decisions where the choice for the more pleasant sample coincided with a lower μ (cf. Fig. 2) increased to 0.76 for the smooth-roughness group and to 0.67 for the fine-roughness group. Interestingly, the percentage of pleasantness decisions in agreement with a lower μ for the smooth-roughness group did not differ significantly from those for PDMS (Wilcoxon test, $z = 292.5$, $p = 0.932$) anymore. We obtained a similar result for pleasantness decisions in agreement with lower f_T between the smooth-roughness group and PDMS ($z = 214$, $p = 0.157$). For the fine-roughness group, the fraction of decisions in agreement with a lower μ significantly differed from those for PDMS ($z = 121.5$, $p = 0.004$), but not significantly for those with a lower f_T ($z = 180$, $p = 0.072$).

IV. Discussion

In this work, we examined the validity of our hypothesis-*surfaces eliciting lower friction are perceived as more pleasant* on samples of aluminum and PDMS when friction is modulated by roughness variations. We produced samples with the same range of roughness from both materials and observed that they had distinct friction characteristics. With increasing roughness, aluminum showed a strong initial decay in μ and a further increase, while PDMS showed a weaker decay across the entire range of roughness. The observed decrease in the friction coefficient μ for both materials can be explained as reduction in adhesive friction of the finger, corresponding to a systematic decrease in the real contact area. However, when for higher roughness the surface asperities increase in height, they deform the fingertip skin during sliding, leading to dissipation and an increase in μ. This increase in μ at high roughness is observed for aluminum but not for PDMS. The distinct friction-roughness characteristics reflect differences in the elastic nature of contact between the finger and the two materials. Qualitatively, the weaker decay in contact area for PDMS can be understood by an elastic flattening of the asperities. The absence of an increase in friction at high roughness may be explained by a reduced skin deformation by the compliant PDMS asperities, as compared to aluminum.

The working hypothesis was confirmed for PDMS, by the correlation in Table. II and by the characteristic psychometric curve in Fig. 4(b). Friction on PDMS decreases monotonously with increasing roughness and their negative correlation is significant. This important result indicates that the key to pleasant touch of rubber is lower friction, realized here by increasing roughness. The threshold value for the relative difference in friction, above which the majority of pleasantness decisions fall for the sample with lower friction, is 12.5 %. This value is close to the threshold reported for the just noticeable difference in transient changes in friction [16], and on micro-structured rubber surfaces [17]. If the just noticeable difference in friction is enough to elicit the perception of pleasantness on rubber, we conclude that friction is the dominant stimulus for assessing pleasantness on rubber surfaces.

The relations are more complex for the aluminum samples with the minimum in friction as a function of roughness. The correlations of pleasantness ratings to measured friction values were not significant (Table. II) when all aluminum surfaces were analyzed together. However, a significant number of pleasantness decisions favoured lower values for the friction variables in pairwise comparisons (Fig. 2). We addressed this apparent contradiction by showing that the fraction of pleasantness decisions favoring lower μ or f_T increased when analyzing aluminum samples separately in groups, that we denote as 'smooth' and 'fine' roughness. Each group corresponds to a monotonic friction-roughness regime. Such analysis within separate groups also led to lower thresholds in relative friction difference for a majority of pleasantness ratings to favor the lower friction samples, as shown in Figs. 4(c) and 4(d). The results for the smooth-roughness group resemble those for PDMS. Increasing roughness leads to lower adhesive friction and to higher perceived pleasantness in touch. For the fine-roughness group, the decrease in friction also leads to higher perceived pleasantness, however for decreasing roughness. We note that pleasantness decisions for pairs consisting of one smooth-roughness and one fine-roughness sample did not correlate significantly with friction difference. The two friction mechanisms, adhesion and deformation, may differ as stimulus so that friction as predictor for tactile pleasantness fails when one is compared with the other.

The results for PDMS and for the smooth-roughness group of aluminum samples are in contrast to the notion that smoother surfaces are more pleasant to touch. Such notion has been supported by psychophysical studies which suggested that the perception of pleasant touch is negatively correlated with surface roughness [3], [4]. Verillo et al. [4] tested grades of sandpaper with particle-size ranging from 16 μm to 905 μm. The average roughness Ra of the samples we used for our study ranged from 0.02 μm to 7 μm. These numbers imply that Verillo's investigation addressed solely the fine and coarseroughness regimes where friction increases with roughness, and that the negative correlation thus aligns with our observations. We suggest that there is a smoothness with pleasing touch, which can be defined as a very low roughness where neither larger roughness asperities nor the large contact area with a perfectly polished sample cause enhanced deformation or adhesion friction.

Tactile pleasantness has also been shown to be strongly correlated to the perceived softness of the object [6]. We emphasize that our comparisons were limited to surfaces of the same material so that no variations of material compliance could contribute to the pleasantness decisions.

Our participants tended to apply a higher force f_N on samples with a lower coefficient of friction μ (Fig. 3). This was not observed in previous studies which compared samples of different materials [7], [18]. We propose that our approach of comparing samples, where only the roughness was varied, invited participants to keep the friction forces constant by lowering f_N on samples with higher coefficient of friction. Perceived pleasantness was positively correlated to the applied force f_N for PDMS surfaces, albeit this was not significant for aluminum surfaces (Table. II). We consider this weak correlation to be a secondary effect of the stronger correlation between higher pleasantness and lower friction coefficients, in combination with the tendency to apply higher force on samples with lower friction coefficients.

Our results are in overall good agreement with the hypothesis that surfaces eliciting lower friction for the sliding fingertip are perceived as more pleasant. While our findings for samples with varied roughness of one material corroborate the conclusions of Klöcker et al. [7] for surfaces of different materials, our parametrized study revealed details of the relation between pleasantness and roughness-controlled friction. For example, we show that very smooth, polished surfaces can generate very high fingertip friction - up to three times the minimum friction at intermediate roughness - which leads to an unpleasant tactile experience.

V. Summary

Friction and roughness are critical dimensions in the tactile discrimination of materials but also determine how pleasant a material feels. We presented a parametrized study where friction is modulated by varying the roughness of samples of one material. Lower friction then has a stronger correlation with perceived pleasantness than lower roughness. For the rubber material PDMS, friction decreases monotonously with increasing roughness, leading to higher perceived pleasantness. For the metal aluminum, friction exhibits a minimum as function of roughness. In a regime of very low smooth roughness on aluminum samples, the relations between friction, roughness, and perceived pleasantness are the same as for the rubber PDMS. For fine roughness, the interaction of surface asperities with the skin leads to higher friction with increasing roughness, resulting in a less pleasant touch. Our results indicate that the notion of a correlation between smoothness and pleasant touch is valid only for the fine roughness regime, where friction decreases with decreasing roughness. We demonstrate an opposite effect for a smooth roughness regime, where very low roughness causes high friction values, resulting in an unpleasant tactile experience. For stiff materials such as metals, one can find a roughness which is optimized for the pleasantness of touch by minimizing fingertip friction.

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