Perception of Friction in Tactile Exploration of Micro-structured Rubber Samples

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Abstract. Fingertip friction and the related shear of skin are key mechanical mechanisms in tactile perception, but the perception of friction itself is rarely explored except for the flat surfaces of tactile displays. We investigated the perception of friction for tactile exploration of a unique set of samples whose fabric-like surfaces are equipped with regular arrays of flexible micropillars. The measured fingertip friction increases with decreasing bending stiffness, where the latter is controlled by radius (20–75 µm) and aspect ratio of the micropillars. In forced-choice tasks, participants noticed relative differences in friction as small as 0.2, and even smaller when a sample with less than 100 µm distance between pillars is omitted from the analysis. In an affective ranking of samples upon active touch, the perception of pleasantness is anticorrelated with the measured friction. Our results offer insights towards a rational design of materials with well-controlled surface microstructure which elicit a dedicated tactile appeal.

Keywords: Tactile perception · Friction · Materials

1 Introduction

Friction is the force which resists sliding of the fingertip over a sample surface in tactile exploration. Its strength indicates shear deformation in the skin which leads to activation of mechanoreceptors and thus contributes to the process of tactile perception [1]. Friction, often referred to by the word pair sticky/slippery, has been invoked as one of the important dimensions in the tactile perception of surface textures [2, 3] and in the perception of similarity or distinction between materials [4–8]. The perception of fingertip friction also plays a key role in the adjustment of prehensile forces, securing grip when lifting objects [9–11]. Despite the frequent discussion of friction as important channel in tactile perception, there are but few studies on the perception of friction itself. Smith and Scott asked participants to rate their tactile perception on a scale between "most

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slippery" and "most sticky" and found an average correlation of 0.85 with the kinetic friction coefficient in a wide range from 0.4 to 2.8 [12]. Grierson and Carnahan reported significant correlation between perceived slipperiness and the measured friction coefficient only if a tangential motion of the fingertip over the surface was involved, in contrast to static or tapping touch [9]. Little correlation between measured and perceived friction was reported in two studies on surfaces of consumer goods [13, 14].

The perception of friction can be entangled with the perception of surface texture. The mutual influence is manifest in the structure of the perceptual space derived from tactile exploration of materials, where the tactile dimensions of slipperiness and of roughness are correlated [4]. The cross-talk between resistance against lateral motion and roughness perception has been used to render roughness in tactile displays by modulation of lateral forces [15]. The entanglement of friction and roughness perception is also reflected in the finding that subjective roughness estimates decrease upon lubrication of the contact [16].

Tactile displays allow to modulate fingertip friction by imperceptible ultrasonic excitation, where an air cushion effectively lubricates the contact [17]. This technology allows to determine just noticeable differences in friction without changing roughness or surface material. Weber fractions, i.e. just noticeable changes of friction, where found to be around 0.18 for spatial variation [18] and 0.11 for transient changes [19].

Our interest lies in the understanding of role of friction in tactile perception of materials towards a design of materials with a predictable tactile appeal. Here, we focus on the physical basis of friction and the friction perception of well-controlled fabric-like surfaces in contrast to the previously studied smooth or less controlled surfaces. We prepared polymer samples with a surface structure consisting of a regular array of flexible cylindrical pillars with flat top surfaces. These samples represent fibrillar materials like fabrics and papers, however with a well-controlled structure and the option to vary the structural parameters. We asked participants to compare friction and rate pleasantness of samples and measured the forces during their tactile exploration.

2 Experiments

Micro-structured elastomer samples were prepared by replica molding using templates which were themselves replicated from a microfabricated arrays of silicon pillars (Institute of Semiconductors and Microsystems, TU Dresden, Germany). Square samples with a side length of 50 mm carried a hexagonal array of pillars (Fig. 1) with a radius of 20–75 μm and a center-to-center distance of four times the radius, i.e. 80–300 μm (see Fig. 1). In this design, the flat top surfaces of the pillars cover a fraction of $\pi/(8\sqrt{3}) \approx 22.6\%$ of the total area for all samples, i.e. the exposed surface on top of the pillar is constant for different pillar radii. Six arrays with the following radius and height of pillars were used in this study: 20 μm/120 μm, 50 μm/100 μm, 50 μm/200 μm, 50 μm/300 μm, 75 μm/350 μm, 75 μm/450 μm.

Polydimethylsiloxane (PDMS, Elastosil M4601, Wacker Chemie AG, München, Germany) templates were replicated from micropatterned silicon wafers exhibiting a micropillar array of 5 cm × 5 cm (TU Dresden, Germany). The samples were made from the polyurethane 'Neukadur high elastic A50' (Altropol, weight ratio of components

1:1, Young's modulus of 5 MPa at 1 Hz). This elastomer was poured onto the PDMS templates, degassed in a vacuum chamber for 10 min, and baked overnight in an oven at 65 °C to cure the polyurethane.

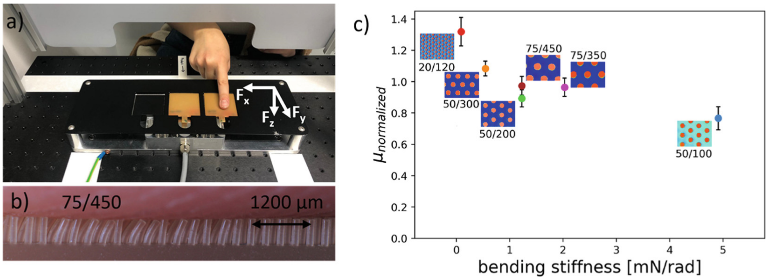

Fig. 1. a) Tactile exploration setup. Samples are mounted to a three-axis force sensor with coordinates as indicated. The visual access is blocked by an opaque screen. b) Close-up of a finger sliding over an array of pillars (75 µm radius, 300 µm distance, 450 µm height). c) Average normalized coefficient of friction as function of the calculated bending stiffness of pillars Eq. (1). Error bars indicate standard deviation across participants Labels next to the data points indicate radius and height of the pillars in µm. The top view images have a size of 550 µm × 750 µm.

For the tactile exploration experiments (Fig. 1), samples were mounted to 3-axis-force sensor (K3D120 with GSV-8 amplifier, ME-Messysteme, Germany). Forces in normal direction (F_N) and friction forces ($F_F = \sqrt{F_x^2 + F_y^2}$) were recorded at a rate of 120 Hz, the friction coefficient was determined as $\mu = F_F/F_N$ and averaged over the time of each trial. Participants were asked to explore the surfaces with the index fingertip of their dominant hand in circular movements with a straight finger. An opaque screen blocked the view of the samples, and a headphone suppressed the sound from the sliding fingertip. Participants were asked to maintain a constant normal force. As visual feedback on their actual normal force, they were shown a bar chart with a marked target range of 0.3 to 0.5 N. The fingertip moisture was recorded with a corneometer (CM 825, Courage + Khazaka electronic GmbH, Germany).

In our psychophysical study, 19 Participants (age 20 to 27, 7 males, 1 left-handed, unpaid volunteer university students of physics, engineering, psychology, and the arts with no known cutaneous or motor impairments) explored the 6 samples described above in three different experiments. The participants were naïve with respect to the goal of the study, they were instructed before the experiments in detail and gave their consent to participation. All experiments were designed to comply with the principles outlined in the Declaration of Helsinki. The study was approved by a university ethics board (proposal "Perception of micro-patterned materials (18–16)").

In Experiment 1, participants explored each of the 15 pairs of 6 samples once in random order for the time they needed, and they were allowed to switch between the two samples of one pair as often as they wanted. In a forced-choice task, they had to decide "for which of the two sample it is more difficult to move the finger over the surface, if you apply the same pressure on the sample." We did not ask directly about friction to avoid a bias in answers which could arise from a different understanding of the technical term friction. Experiment 1 took 16 to 35 min for each participant.

In Experiment 2, scheduled one week after Experiment 1, participants explored by touch all 6 samples lying next to each other on a table behind the opaque screen. They explored the surfaces by circular motion of their index fingertip and then lifted the samples to sort them in the perceived order of pleasantness in touch, typically within 5 min. In the directly following Experiment 3, participants were asked to explore each of the 6 samples once using the same procedure as in Experiment 1. The samples were mounted on the force sensor as in Experiment 1 to repeat friction measurements on the day of Experiment 2. Experiment 3 took participants between 8 and 14 min.

3 Results

In Experiments 1 and 3, mean applied normal forces were between 0.36 and 0.39 N for the participant with most constant forces, and between 0.30 and 0.63 N for the participant with the largest range of mean normal forces applied to different samples. The measured friction coefficients varied between 1.0 and 1.3 for the participant with lowest and between 2.1 and 2.9 for the one with the highest friction. We found no correlation of fingertip moisture with friction coefficients ($r = 0.06$, $p = 0.81$). For the analysis of results, we normalized the friction coefficients by division with the average friction coefficient of each participant to give equal weight to variations between samples for each participant, independent of the absolute value of the friction coefficients. The normalized average coefficient of friction is plotted as a function of the bending stiffness for pillars on each sample in Fig. 1c. While there was no clear relation of friction to either pillar height or pillar radius, we found a correlation ($r = -0.81$, $p = 0.0506$) with the bending stiffness of the pillars. In Fig. 1c, samples are ordered by the bending stiffness, which can be approximated as [20]:

$$\frac{F_{top}}{\theta} = \frac{\pi}{2}\frac{ER^4}{L^2}, \tag{1}$$

F_{top} the lateral force acting on the top of each pillar, θ the bending angle, L the height of the pillars, R their radius, and $E = 5$ MPa the elastic modulus of the material. The normalized coefficient of friction decreases from above 130% of each participant's mean value for most bendable pillars to below 80% for the least bendable pillars. High aspect ratio and small pillar diameter contribute to the bending flexibility of pillars. The photograph in Fig. 1b visualizes the bending. Pillar bending may increase friction by direct contact between the side walls of the pillars with the skin and by interlocking of their edges with the papillary structure of the fingertip skin [21].

The results for friction perception in Experiment 1 are summarized in Fig. 2. The psychometric curves represent the probability that participants have indicated that sample as "more difficult to move the finger", for which the higher friction coefficient was measured. This probability is plotted as function of the relative difference in friction coefficient between the two samples. The relative difference is computed for each trial, i.e. each sample pair and participant. The probability is then calculated for bins of 19 trials, where the relative difference in friction coefficient is the average for all trials in that bin. The probability increases from a value of 0.5, which indicates a choice by chance at small friction differences, to a value of 1 at large difference in friction, where all decisions on perceived higher friction agree with the measurement. In Fig. 2a, the measured forces are analyzed in form of the friction coefficient μ, which can be considered as invariant under different applied normal forces. From the level of 75% probability in the psychometric curve, we can extract a just noticeable difference of $\Delta\mu/\mu = 0.21$ for the perception of relative differences in friction (Weber fraction).

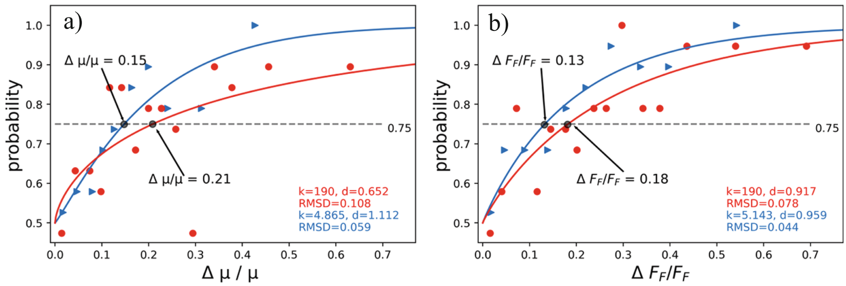

Fig. 2. Probability for indicating the sample with the higher measured friction versus a) the relative difference in friction coefficient between two samples, and b) the relative difference in the measured friction force. Red dots represent analysis of data for all samples, blue triangles analysis of data after omission of trials including the 20 μm/120 μm sample. Each data point represents the probability for a bin of 19 trials with similar relative differences. The solid lines are Weibull sigmoid functions fitted to the data points. The fit parameters and the root mean-square deviation (RMSD) of data points from the fit curves are listed. (Color figure online)

The data point representing one set of 19 trials ($\Delta\mu/\mu = 0.29$) is a peculiar outlier. We noticed that this set of trials includes a high number of samples with smallest pillar radius of 20 μm. Assuming that participants were unsuccessful in comparing friction on this sample with friction of other samples, we also present a psychometric curve for trials with all samples except the 20 μm/120 μm sample. There is no outlier and less scatter of data points with respect to the sigmoid function, reflected in a drop of the root-mean-square deviation (RMSD) from 0.108 to 0.059. The just noticeable difference in friction coefficient for the reduced set of samples decreases to $\Delta\mu/\mu = 0.15$.

We do not know if the perception of "the difficulty to move the finger over the surface" in our task reflects the friction force or the coefficient of friction, i.e. if participants directly compare friction forces or if they implicitly consider the applied normal pressure when judging the friction force. In Fig. 2b we present psychometric curves which are based on relative differences in the measured friction force. These curves follow a similar trend as the curves based on the friction coefficients with lower values for the RMSD. The just noticeable difference in the friction force is lower with 0.18 and with 0.13 after excluding comparisons with the 20 μm/120 μm sample.

The results of Experiment 2, where the six samples were ordered with respect to perceived pleasantness in touch, are analyzed in Fig. 3. The rank in pleasantness of each sample is plotted versus the normalized friction coefficient for all samples and all participants in Fig. 3a. There is a moderate but significant anticorrelation ($r = 0.444$,

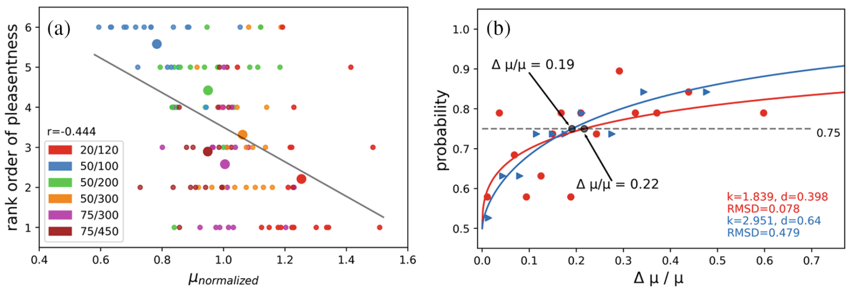

Fig. 3. a) Pleasantness ranking versus friction (Experiment 3). Small dots represent data for all participants, the linear fit indicates the moderate but significant correlation ($r = -0.44$, $p < 0.001$). Large dots represent data averaged over all participants. b) Probability for ranking a sample as less pleasant to touch as function of the relative difference in friction coefficient (Experiment 3) between sample pairs. The red dots represent the analysis of comparison between all samples, the blue dots an analysis excluding comparisons with the 20 μm/120 μm sample. (Color figure online)

$p < 0.0001$) between friction coefficient and perception of pleasantness. The averages over all participants visualize this correlation. When we correlated the rank of perceived pleasantness for each individual participant with the rank of the friction coefficient using Kendall's correlation coefficient, we find negligible correlation for 7 participants, weak or moderate positive correlation for 3 participants, and moderate to very strong negative correlation for 9 participants.

Assuming that large differences in friction cause an unequivocal decision on perceived pleasantness, the data can be analyzed in analogy to the psychometric curves (see Fig. 3b). We plot the probability to rank the sample with the higher measured friction coefficient as less pleasant to touch for all samples pairs as function of the relative difference in friction coefficient. The probability to perceive one sample as less pleasant increases with increasing difference in the friction coefficient and is larger than 75% for relative differences of more than 0.22, i.e. above the just noticeable difference in friction perception. When we exclude comparisons with the 20 μm/120 μm sample from the analysis, the 75% level is reached already at a relative difference in friction of 0.19.

Friction coefficients for all samples and participants were correlated between Experiment 1 and Experiment 3 ($r = 0.67$, $p < 0.001$). A strong correlation ($r = 0.983$, $p < 0.001$) was observed for the normalized averaged friction coefficients of the six samples between Experiment 1 and Experiment 3. We conclude that friction between fingertip and micro-structured rubber samples is consistent over time in participants and samples, with some variation between trials which is probably caused by variations of the portion of the fingertip in contact with the sample and of the angle between knuckle and surface.

4 Conclusion

We created a set of samples from one polymeric material with perceptible differences in fingertip friction by varying only the length scales of a regular array of flexible micropillars on the surface. Friction increases with decreasing bending stiffness of the pillars.

By combining a forced-choice task on friction perception with force measurements on each trial, we report for the first time just noticeable relative differences (JNDs) in the friction coefficient between samples with controlled structural variations. The JNDs are around 0.2 and thus comparable to those reported for spatial friction contrast on tactile displays [18]. They are higher than JNDs reported for transient changes in tactile displays [19], which may be explained by distraction through roughness and compliance differences or by the break when lifting the finger for a switch between samples. Our results also confirm a correlation of lower friction with pleasant touch [22] for a set of manufactured samples which differ not in material but rather in the microscopic surface structure. Psychophysical experiments with well-controlled flexible surface structures thus open new opportunities for systematic differentiation of friction from other tactile dimensions such as roughness or compliance.

We noticed that participants had difficulties judging friction differences when one sample was the one with the smallest microstructures. Similarly, this sample received widely varying rankings in the pleasantness of touch. The values of JNDs in friction dropped by 30% after omitting this sample from the analysis. It is the only one that clearly falls into the small-scale regime of the duplex theory, where different mechanisms of perception are expected [23], for example a perception of slipperiness through the subjective intensity of vibrations which are excited by small structures [24]. It would be interesting to construct a stimulus set of samples from both regimes of the duplex theory, i.e. with structures smaller and larger than 100 μm, to verify if friction differences are perceived correctly in each regime, but not between regimes.

In conclusion, the combination of materials science approaches for a full control of surface structures at the micrometer scale with the elucidation of mechanisms in fingertip friction and with the quantification of friction perception is a step towards a rational design of materials with low friction and a pleasant tactile appeal.

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