Perceptual Constancy in the Speed Dependence of Friction During Active Tactile Exploration

Maja Fehlberg, Eva Monfort, Sairam Saikumar, Knut Drewing, and Roland Bennewitz

***Abstract*—Fingertip friction is a key component of tactile perception. In active tactile exploration, friction forces depend on the applied normal force and on the sliding speed chosen. We have investigated whether humans perceive the speed dependence of friction for textured surfaces of materials, which show either increase or decrease of the friction coefficient with speed. Participants perceived the decrease or increase when the relative difference in friction coefficient between fast and slow sliding speed was more than 20%. The fraction of comparison judgments which were in agreement with the measured difference in friction coefficient did not depend on variations in the applied normal force. The results indicate a perceptual constancy for fingertip friction with respect to self-generated variations of sliding speed and applied normal force.**

***Index Terms*—Fingertip friction, perceptual constancy, speed-dependent friction, tactile perception.**

I. Introduction

FRICTION is one of the five dimensions of human tactile perception, along with fine roughness, compliance, coarseness, and warmness [1]. Friction is, therefore, a key component of our tactile communication with the material world. The sensation of friction arises from shearing forces when materials come into sliding contact with the skin of fingertips. Forces cause skin deformation, especially when touching rough textures. At the same time, tactile exploration on fine textures causes vibrations in the skin. The activation of mechanoreceptors by both stimuli, shear and vibration, lead to complex signals in the somatosensory cortex which are then interpreted as tactile perception [2], [3]. Tactile perception from frictional interactions is involved in many everyday actions, such as choosing the right gripping force to lift objects [4], [5], discriminating materials with smooth surfaces [6], [7], or perceiving similarities between textured materials [8], [9].

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Despite the crucial role of friction in tactile interaction with materials, only few studies have addressed the perception of friction itself. It was shown that participants correctly estimate friction differences between materials [10], perceive transient changes of 11% in friction induced by ultrasonic vibrations [11], and perceive differences in friction coefficient of 15% on differently micro-structured surfaces of the same material [12]. In line with these findings, human tactile perception differentiates variations in surface chemistry down to a single atomic layer, utilizing friction, vibration, and stick-slip [7].

Other tactile dimensions may influence the perception of friction. An entanglement between friction and roughness perception was established in a study which reported a decrease in the subjective estimates of roughness when friction was lowered by lubrication [13]. Friction was also found to play a key role in perception of fine roughness (lateral scale $< 100\,\mu$m), whereas static skin deformation is more important to perceive coarse structures ($> 100\,\mu$m) [14], [15].

In active exploration of materials, participants may vary the direction of finger movement, the sliding speed, or the applied normal force. Decreasing skin friction with increasing speed was observed for several materials, namely nylon, plexiglas, polycarbonate [16], aluminum and fabrics [17], and polypropylene, and rough glass [18]. Lower sliding speed was reported to allow for better friction discrimination [19]. Participants may tend to scan low-friction surfaces faster than higher-friction surfaces, independent of the perceptual task [20].

The sensory system provides us with stable representations of objects and their properties despite our own movements and changing environmental conditions. Examples for this perceptual constancy are the stable location of objects looked at while turning the head or the successful identification of color under changing illumination [21]. An example for constancy in tactile perception is the stable estimation of roughness under varying sliding speed. Roughness perception mostly originates from cutaneous cues that are speed dependent. Roughness constancy has been demonstrated for a large variety of textures [22]. It has been suggested that proprioceptive cues for the finger movement support the constancy in the roughness perception [23].

To investigate the tactile perception of friction and a possible perceptual constancy, this study quantifies how fingertip friction varies with sliding speed for different materials. We are interested whether this variation in friction is perceived by humans in active tactile exploration. To answer this question, we measure friction and applied normal force of all participants while they explore nine textured surfaces with different fingertip speeds and ask for which speed they perceive the resistance to sliding as higher. Positive and negative correlations of friction with speed for different materials provide us with a balanced distribution of stimuli for the forced-choice task.

II. Samples and Methods

Samples for the study were made from three different materials, namely hard polyacrylate, paper, and elastic polyurethane. For each material, we produced samples with different surface structures to broaden the range of frictional response. Each sample measured 50 mm by 50 mm.

The two polyacrylate samples were 3D printed (Original Prusa SL1 3D Printer) using a photo-curable polymer resin (Prusament). Each layer of the resin was cured by 405 nm UV light exposure, with a layer resolution of 25 μm and a spatial resolution of 47 μm. One sample is printed with a randomly rough ("RR") surface topography with an average roughness of $R_a = 25.26\,\mu\mathrm{m}$ and a root-mean square slope of $R_{dq} = 0.19$, the other sample carries a rectangular array of gaussian bumps ("GB") whose widths and heights are 2.1 ± 0.2 mm and $45 \pm 8\,\mu\mathrm{m}$ ($R_a = 4.57\,\mu\mathrm{m}$, $R_{dq} = 0.069$).

As paper samples we chose wrapping paper with glitter particles ("P1", $R_a = 10\,\mu\mathrm{m}$, $R_{dq} = 0.502$), wrapping paper containing synthetic materials ("P2", $R_a = 3.21\,\mu\mathrm{m}$, $R_{dq} = 0.193$), a grey sketch paper ("P3", $R_a = 5.6\,\mu\mathrm{m}$, $R_{dq} = 0.257$) and standard drawing paper ("P4", $R_a = 2.64\,\mu\mathrm{m}$, $R_{dq} = 0.236$). The paper samples were cut into 50 mm by 50 mm pieces and glued to plastic holders of the same dimensions with a double-sided adhesive.

The surfaces of three elastic polyurethane samples carry a hexagonal array of bendable micropillars with flat top whose dimensions in diameter and height are 100 μm /100 μm ("100/100"), 100 μm /200 μm ("100/200"), and 150 μm /450 μm ("150/450"). The distance between pillars equals their respective diameter. The samples are produced from the polyurethane 'Neukadur high elastic A50' (Altropol) by replica molding as described in Ref. [12]. The micro-structuring avoids the stick-slip phenomenon often observed in fingertip friction on smooth elastomer samples.

Previous studies have shown that surfaces with high surface energy also exhibit high friction [24]. To explore this relation, we performed water contact angle measurements and determined the effective surface energy of the samples. The static contact angle measurements (SCA20-M4) were performed using the sessile drop method. A 3 μl water droplet was placed on the structured side of the samples, with the droplet base larger than the structure dimension. The contact angle was determined after 5 s of relaxation, as a compromise between slow relaxation on polyurethane and swelling of paper samples. The surface energy of the materials polyurethane and polyacrylate was additionally measured by placing the droplet on a flat surface of the material. We report the average contact angle (θ) of five measurements and calculate the effective surface energy as [25]

$$W = \gamma(1 + \cos\theta) \tag{1}$$

where γ is the surface tension of water. When comparing the surface energy of the materials polyurethane and polyacrylate with structure (W_{eff}) and without structure (W_{mat}), it was found that the randomly rough topography of the polyacrylate samples did not change the surface energy ($W_{\text{mat}} = 120$ mN/m, $120 < W_{\text{eff}}\,[\text{mN/m}] < 125$), while the micropillar structure decreased the surface energy ($W_{\text{mat}} = 80$ mN/m, $50 < W_{\text{eff}}[\text{mN/m}] < 70$). The calculated values for surface energy (W_{eff}) for each sample are listed in Tab. S1 of the Supplemental Information (SI).

We asked 28 participants (14 male, two left-handed, aged between 18 and 55 years, with an average of 25.3 years) to explore the nine samples by circular movements of the straight index finger of their dominant hand. The circles were to be performed at different speeds, which were indicated to the participants by a red dot moving on a blue circle on a computer screen.

During the tactile exploration, we measured the applied normal force (F_N) and the friction force ($F_F = \sqrt{F_x^2 + F_y^2}$) with a 3-axis force sensor (K3D120 with GSV-8 amplifier, ME-Messysteme, Germany). The friction coefficient, that reflects the ratio between friction force and normal force, was calculated as $\mu = F_F/F_N$. For the materials studied here, F_F increased linearly with F_N, so that μ did not depend on the applied normal force (examples are shown in Fig. S1 of SI). The friction coefficient is a constant not only of the material, but of the system consisting of material, surface structure, fingertip skin, and finger physiology. In the comparison of friction between samples, we report a normalized friction coefficient $\mu_{\text{norm.}}$ to avoid giving participants with higher average friction coefficients more weight in the comparison. For normalization, each value of μ is divided by the average friction coefficient for all indicated speeds of that participant and that sample.

We tracked the position of the exploring finger using an IR-reflective marker placed on the fingernail of each participant (V120: Trio, OptiTrack). Both position and forces were recorded at a synchronized rate of 120 Hz.

Before starting the experiment, we asked participants to wash their hands. In the beginning and after the experiment we measured the fingertip skin moisture m using a Corneometer (CM825, Courage & Khazaka). The device reports skin moisture in an instrument specific scale between 0 and 120 a.u. by measuring the humidity of the first $20\,\mu\mathrm{m}$ of *stratum corneum* with capacitance moisture detection.

We evaluated the speed as a relative change of the position in the x-y plane, using

$$v_i = \sqrt{\left(\frac{dx_i}{dt}\right)^2 + \left(\frac{dy_i}{dt}\right)^2} \tag{2}$$

$$\text{with} \quad \frac{dx_i}{dt} = \frac{x_{i+1} - x_i}{t_{i+1} - t_i},$$

$$\frac{dy_i}{dt} = \frac{y_{i+1} - y_i}{t_{i+1} - t_i},$$

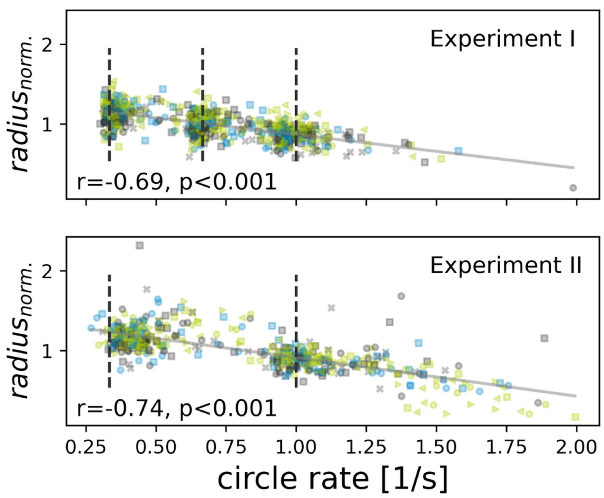

Fig. 1. The normalized radius (radius divided by mean radius per participant and experiment) is plotted against the applied circle rate for Experiment I and Experiment II. The specified circle rate is indicated by the dashed lines. The participants tend to chose higher circle rates than specified, particularly in Experiment II. Colors and markers are defined in Fig. 3.

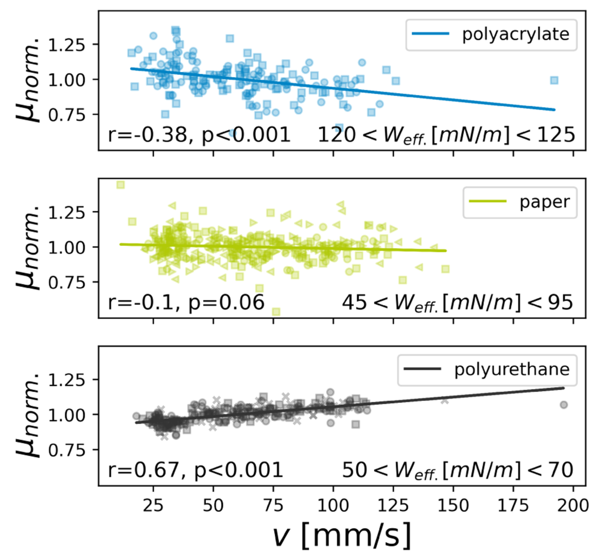

Fig. 2. Speed dependence of fingertip friction for three different materials, namely polyacrylate, paper and polyurethane. Each participant is represented with three data points per sample. The range of effective surface energy is given for each material.

$$dt = \frac{1}{120} \text{ Hz.}$$

We report the median values for each trial of both - friction coefficient and speed. Calculating speed or friction as weighted average of multiple points did not change the median values.

The study was approved by the local university ethics committee (Antrag 21-06 "'Taktiles Weiß' für die Fingerspitze - Materialstrukturierung für niedrige Reibung").

III. Experiment I

Speed dependence of friction was the focus of the first experiment. The participants were asked to perform circles at three different circle rates (0.33, 0.67 and 1 per second). All three circle rates were shown side by side on the monitor, in randomized order. They were instructed to use the circle rates as indicated from the left to the right. Participants maintained the specified circle rates of 0.33, 0.67 and 1 per second with an average of 0.37 ± 0.06 1/s, 0.69 ± 0.09 1/s and 1.00 ± 0.13 1/s. The average deviation of the circle rate was independent of the specified order of the rates (One-way ANOVA: F(2, N) $= 0.73$, p $= 0.48$). The circles were performed with radii between 10.6 and 16.8mm. Participants used significantly smaller radii for higher circle rates on all samples and in both experiments (Fig. 1). Due to the different radii of their circular movements, the median speeds varied between 11.5 and 25.0 mm/s for the slow, between 26.0 and 48.3 mm/s for the medium and between 62 and 186 mm/s for the fast speed. Two-sided Mann-Whitney U tests showed that the median values of the three speeds were pairwise significantly different for all but one test. We performed the tests for 28 participants, 9 samples and 3 comparisons which are $28 \cdot 9 \cdot 3 = 756$ tests. For 755 tests we report $t \in [2236, 43 \cdot 10^6]$ and p < 0.001, for one test the medium speed did not differ significantly from the low speed (ID24, sample 150/450: $v_{slow} = 25.43$ mm/s, $v_{middle} = 25.79$ mm/s, $t = 31 \cdot 10^6$, p $= 0.58$).

Fig. 2 summarizes the variation in the normalized coefficient of friction as a function of speed. We found different correlations for the three materials tested. While friction increases significantly with increasing sliding speed for all polyurethane samples, friction decreases significantly for all polyacrylate samples. For paper samples, friction exhibits variability, with both slight increases and slight decreases observed on different samples, so that the material paper does not show any general speed-dependent friction.

It is important to note that in the following perceptional study friction may increase or decrease at higher fingertip sliding speed, depending on the sample material and the participant.

As a predictor for the speed dependence of friction ($\text{slope}_{\mu_{\text{norm.}}(v)}$), the effective surface energy (W_{eff}) of the samples would explain a variance of 34.1%, however the linear regression is not significant with p $= 0.058$ ($F(1,7) = 5.14$, $\beta = -30.91$ s/mm).

The individual moisture of the fingertip skin is a key parameter for friction on most materials [18]. All samples show a significantly higher coefficient of friction for participants with higher finger moisture, when averaging over the three speeds ($0.37 < r < 0.77$, $p < 0.05$, see Fig. S2 in SI for data plots).

Fig. 3 shows that the slope of the friction with respect to skin moisture ($\text{slope}_{\mu(m)}$) is a significant predictor for the speed dependence of friction ($\text{slope}_{\mu_{\text{norm.}}(v)}$), it explains 77.8% of the variance in the speed dependence of friction ($F(1,7) = 28.98$, p $= 0.001$, $\beta = -0.2$ s/mm). Samples exhibiting a strong dependence of friction on moisture levels also tend to show a decrease in friction at higher speeds.

IV. Experiment II

Perception of the variation in friction for different speeds was the focus of this psychophysical experiment with forced-choice task. We asked the participants to explore the nine samples as described above, but now with only two simultaneously indicated

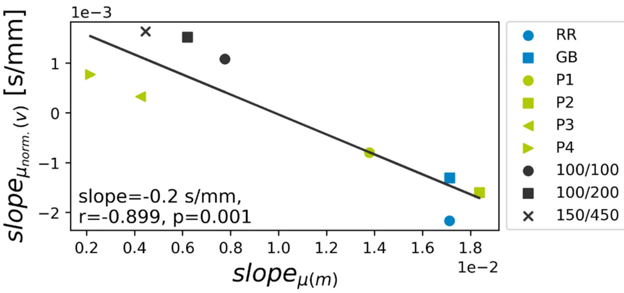

Fig. 3. Dependence of the slopes in the relation between the friction coefficient and both sliding speed and finger moisture. Samples with a low moisture dependence of friction show higher friction at higher speed, while samples with a high moisture dependence tend to show decreasing friction with increasing speed.

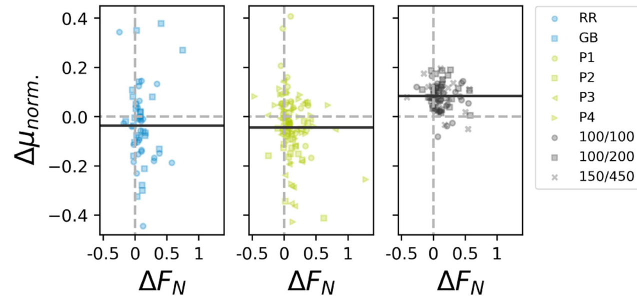

Fig. 4. Difference in normal forces and coefficients of friction at fast and slow speeds in Experiment II, plotted separately for the three materials. The position of the mean $\Delta\mu_{\text{norm.}}$ is indicated by a black line. Its location below 0in the graphs for polyacrylate (blue) and paper (green) indicates decreasing friction coefficient with increasing speed, while the friction coefficient is increasing with increasing speed on polyurethane (black) samples. The distribution of data points to the right of $\Delta F_N = 0$ shows the prevalent trend of participants to use a higher normal force at higher speeds on all materials.

TABLE I
NUMBER OF TRIALS IN WHICH THE MEASURED FRICTION COEFFICIENT μ WAS HIGHER FOR SLOW/FAST SPEED AND THE NORMAL FORCE F_N WAS HIGHER FOR SLOW/FAST SPEED (BLACK NUMBERS)

		higher measured μ		
		slow	fast	
higher measured F_N	slow	19 = 2+17	32=18+14	51=20+31
	fast	90=28+62	102=34+68	192=62+130
		109=30+79	134=52+82	

Number of answers which were in disagreement with the measured friction coefficient are in magenta, in agreement in green.

circle rates (0.33, 1 per second). The participants did not see the samples and wore noise-reducing headphones to avoid that sound or vision influence the decision. The order of samples was randomized between participants.The participants were allowed to switch between the two circle rates as often as they wanted and were not restricted in time to answer the question:

"For which of the two speeds do you feel more resistance against the movement of your fingertip over the surface?".

On average, there were 2.6 switches between the samples, with the minimum number of changes being one and the maximum being 13.

Responses of one participant (ID21) were excluded from the analysis because we forgot to include the noise-reducing headphones.

The specified circle rates were maintained less precisely than in Experiment I (Fig. 1). The measured mean rates were 0.47 ± 0.13 1/s and 1.16 ± 0.24 1/s. The participants tended to circulate at a higher rate than specified. The radii varied between 7.1 and 15.5mm, a little smaller than in Experiment I. The slow speeds in Experiment II varied between 21 and 78 mm/s and the fast speeds between 62 and 186 mm/s. The Mann-Whitney U test confirmed significant differences between the two median speeds for each individual and sample ($t \in [3 \cdot 10^6, 346 \cdot 10^6]$ and $p < 0.001$).

In the forced-choice task, the participants perceived the friction to be higher at faster speeds for 31.5%, 29.6%, and 77.8% of the trials on polyacrylate, paper and polyurethane respectively. Our measurements show that friction coefficients were higher for 31.5%, 38% and 93.8% of the trials in the same order of materials. In Fig. 4 we plot the difference in friction coefficient and normal force ($\Delta\mu_{\text{norm.}} = \mu_{\text{fast, norm.}} - \mu_{\text{slow, norm.}}$, $\Delta F_N = F_{\text{N, fast}} - F_{\text{N, slow}}$) for all three materials. This presentation of the data serves two purposes: First, the speed dependence of Experiment I is confirmed for the friction measurements conducted during Experiment II (see also Fig. S3 in SI). Second, we investigate whether changes in speed coincide with alterations in the normal force, which could have influenced participants' decisions. The mean of the distributions of $\Delta\mu_{\text{norm.}}$, indicated by a black line, confirm that in Experiment II, friction is lower for higher speed for polyacrylate samples (one-sided t-test, $t = -1.69$, $p < 0.05$) and higher for polyurethane samples (one-sided t-test, $t = 13.12$, $p < 0.001$), which demonstrates the reproducibility of the material-dependent speed dependence of friction. For paper we observe a more negative speed dependence than in Experiment I (Fig. 2), as supported by a one-sided t-test ($t = -3.16$, $p = 0.001$).

The distribution of data points located to the right of $\Delta F_N = 0$ indicates a prevalent trend among participants to apply increased pressure at higher speeds across all materials (one-sided t-test, $t = 12.8$, $p < 0.001$). This result underscores the need to further investigate the role of normal force in participants' decision-making processes.

Table I summarizes the frequency of occurrence of the four cases, $\Delta F_N < 0$ and $\Delta\mu < 0$, $\Delta F_N > 0$ and $\Delta\mu < 0$, $\Delta F_N > 0$ and $\Delta\mu > 0$, $\Delta F_N < 0$ and $\Delta\mu > 0$, for all materials. It shows how often we measured higher or lower friction coefficients, and how often the participants applied higher or lower normal forces for the two speeds. Additionally, the table indicates for each case how often participants answered in agreement with the measured friction coefficient.

The measured friction was higher in 109 cases at low and 134 times at high speed, showing a balanced distribution (exact binomial test, two-sided, $p = 0.12$, $n = 243$). In 66.3% (161/243) of the cases, participants identified the higher resistance in agreement with the measured friction coefficient, significantly above chance (exact binomial test, one-sided, $p < 0.001$, $n = 243$).

In 72% (79/109) of the cases where friction was higher at low speed and in 61% (82/134) of the cases where friction was higher at high speed participants judged the higher resistance in agreement with the measured friction, both significantly above chance (exact binomial test, one sided, $p < 0.001$ and $p = 0.006$ resp.) and thus confirming that the perception of friction was independent of the direction of its speed dependence.

There is a weak negative correlation between skin moisture and the friction difference between fast and slow speeds ($r = -0.29$, $p < 0.001$). Participants with drier skin show a slight tendency to have more positive friction differences. Nevertheless, skin moisture had no impact on the number of responses in agreement with the measured friction coefficient ($r = -0.01$, $p = 0.95$).

The table also shows that participants applied a higher normal force at higher speed in 192 cases, a significantly different use of the normal force at the two speeds (exact binomial test, two-sided, $p < 0.001$, $n = 243$).

We analyzed if the application of a higher normal force at higher speed in the majority of trials had an influence on the answers to the perceptional task. We calculated the conditional probabilities of how likely participants responded in agreement with the measured friction coefficient, when they applied a higher normal force at the speed with higher friction, as well as when they applied a lower normal force at that speed. We compared these probabilities with the probability of a correct answer for all trials. With the values listed in Table I we find:

- P(decision in agreement | higher F_N with higher μ) = $(17+68)/(19+102) = 70.2\%$
- P(decision in agreement | higher F_N with lower μ) = $(62+14)/(90+32) = 62.3\%$
- P(decision in agreement) = $(161)/(243) = 66.3\%$

A Pearson's Chi-squared test was conducted to examine the distribution of responses across three subgroups. The results revealed a non-significant association, $\chi^2 = 1.72$, $p = 0.42$, indicating no significant differences in response distribution among the groups. The participants' decision is independent of the normal force applied. This finding is a first indication that the participants used the friction coefficient as criterion for their decision, and not the absolute friction force which depends on the individually applied normal force.

The friction force shows a larger mean relative difference $|\Delta F_F / F_F| = 0.31 \pm 0.23$ than the coefficient of friction $|\Delta\mu/\mu| = 0.10 \pm 0.09$, which is attributed to the participants, who actively apply higher normal forces for the higher speed.

Table II summarizes the decisions of the participants, split into the four cases where $\Delta F_F < 0$ and $\Delta\mu < 0$, $\Delta F_F > 0$ and $\Delta\mu < 0$, $\Delta F_F > 0$ and $\Delta\mu > 0$, $\Delta F_F < 0$ and $\Delta\mu > 0$, for all materials. The decision was in agreement with friction force in 55.56% $((23+73+13+26)/(27+22+82+112))$ of the cases. As previously calculated, the participants answered in 66.3% of the cases in agreement with the measured friction coefficient.

To decide which physical quantity our participants were most responsive to, we were interested in those contradictory trials where a higher μ is combined with a lower F_F at the higher speed and vice versa. In these cases, 62.5% $((9+56)/(22+82))$ were answered in agreement with the friction coefficient and only 37.5% $((13+26)/(22+82))$ in agreement with the friction force. Pearson's Chi-squared test was again conducted to show the significant difference in the results of the two groups ($\chi^2 = 12.02$, $p < 0.001$). We conclude that the friction coefficient is more important in the perception of resistance against sliding than the friction force.

To determine the just noticeable difference (JND) in friction caused by speed changes, we plot the binary responses from participants (in agreement/disagreement with measured μ) in a binned form as the probability of agreeing with the friction coefficient. This is shown as a function of the relative difference in friction, $|\Delta\mu/\mu|$, in Fig. 5. A fitted sigmoidal function (Weibull, lower bound 0.5, upper bound 1) exceeds 0.75 at a difference of 20%. The physics of speed dependence led to many friction differences below and close to this JND, but only in a few trials to much larger differences. For this reason, the Weibull-function does not reach the 100% level which would confirm an unambiguous perception of larger effects of speed on friction. To estimate the uncertainty of the JND, we performed 10,000 bootstrap samples (see S4 in SI), obtaining a median of 19% and an interquartile range (IQR) from 15 to 24%.

TABLE II
NUMBER OF TRIALS IN WHICH THE MEASURED FRICTION COEFFICIENT μ WAS HIGHER FOR SLOW/FAST SPEED AND THE FRICTION FORCE F_F WAS HIGHER FOR SLOW/FAST SPEED (BLACK NUMBERS)

		higher measured μ: slow	higher measured μ: fast	
higher measured F_F	slow	27 = 4+23	22=13+9	49=17+32
	fast	82=26+56	112=39+73	194=65+129
		109=30+79	134=52+82	

Number of answers which were in disagreement with the measured friction coefficient are in magenta, in agreement in green.

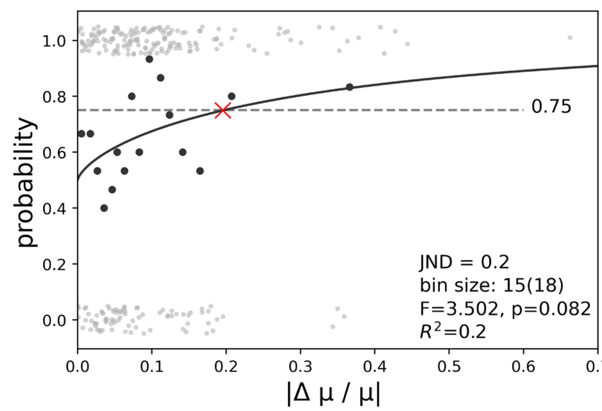

Fig. 5. Binned histogram with 16 bins and 15 data points per bin (18 in the last), to indicate the probability that the participants' answers were in agreement with the measured relative difference in friction coefficient (black dots). The plotted Weibull-function (lower bound 0.5, upper bound 1) shows a JND of 20%. The fit explains 20 % of the variance (R^2). The F-statistic, which compares the variance explained by the fit to the residual variance, just misses statistical significance at the 0.05 level ($F(2,14)=3.502$, $p = 0.082$). The light grey data points represent binary answers of the participants on each sample that agrees (1) or disagrees (0) with the measured friction coefficient.

V. Discussion

Tactile exploration of materials can involve variation of fingertip sliding speed and applied normal forces. We will now discuss our findings about the speed dependence of fingertip friction and its perception in active exploration of textured materials.

We observed that fingertip friction does depend on the chosen sliding speed, and that the correlation can be positive or negative depending on the material. We measured these friction correlations with speed for each participant and each sample during the actual exploration which was the basis for the subjective ratings of friction.

Analysis of all data revealed that for each sample the correlation between individuals' skin moisture and average friction coefficient for that sample is a significant predictor for the speed dependence of friction. Samples with a strong increase of friction with skin moisture have a negative correlation between friction and speed, samples with a weak increase of friction with skin moisture have a positive correlation of friction and speed (Fig. 3). We conclude that moisture-mediated interactions are important for the speed dependence of friction. Tomlinson et al. summarized three models which help understanding this trend [26]. The first model attributes increasing friction with moisture to the expansion of the contact area between the finger and the material, owing to increasing skin elasticity with increasing water content [27]. A second model suggests that moisture leads to capillary bridges which contribute to friction forces [28]. The third model explains increased moisture-dependent shear forces by the formation of hydrogen bonds [16]. We propose to interpret the moisture-dependence of friction as a measure for the role of capillary bridges between textured surface and finger ridges, in agreement with the second model. Capillary bridges contribute less to friction at higher speeds due to their delayed condensation. This mechanisms has been established to explain the negative speed dependence of friction on hydrophilic surfaces, in contrast to hydrophobic surfaces which exhibit a positive speed dependence of friction [29]. Similarly, all previous reports of a negative correlation of skin friction with speed have discussed the moisture-dependence of skin friction for their respective materials [16], [17], [18].

The just-noticeable difference for the speed dependence of friction was 20%, higher but still comparable to the JND of 11% reported for transient changes on a ultrasonic haptic display [11] and of 15% for samples with different surface microstructure [12]. We note that the complexity of task increased from the fingertip on the haptic display, over the switching between samples, to the active control of different sliding speeds in this study. One could hypothesize that the efforts of maintaining higher sliding speed distract the participants' attention from identifying friction as the origin of resistance against movement of the fingertip.

Our results show that participants did perceive positive and negative differences in friction for higher speed equally well, independent of the efforts in maintaining the specified speed. Participants made smaller circles and used higher normal forces when implementing the higher circle rates. We can only speculate that the smaller circles meant to reduce absolute speed while implementing the higher circle rate and that the higher normal force was applied to compensate a loss in force sensitivity at higher speed [30].

Given that we had a dual-task scenario in Experiment II, where participants had to maintain specific speeds and discriminate friction, we also took a look at potential interference between these tasks. The display of a moving red dot on a blue circle proved to be an effective way of prompting participants to use the specified circle rates. However, the additional tactile perception task in Experiment II caused larger deviations of the circle rate from the specified value than in Experiment I (Fig. 1). Prior studies have shown that performance in tactile perception tasks declines when a second task is added [31], [32], especially for the task which receives lower priority in attention [33]. We suggest that participants maintained the specified rate in Experiment I by focusing their attention on the only task, while the redirection of attention to the friction discrimination in Experiment II made participants use circle rates with larger deviation. The requirement for a friction judgment shifted participants' focus away from motor control, resulting in less precise performance.

The analysis of the participants' responses in the psychophysical part of our study showed that the question about the perceived resistance against sliding prompted participants to rather report the higher friction coefficient, i.e. ratio of friction to normal force, than the higher friction force. The processing of the perceived friction forces accounted for the normal force applied by the participants by reflecting the linear relationship between friction and normal forces. The results support our hypothesis that friction is perceived as coefficient of friction, which is a combined property of skin and sample.

The results reveal a perceptual constancy in the judgement of friction during active exploration. Participants successfully reported the speed dependence of the friction coefficient for each material, despite the assigned variation in speed and the observed variations in applied normal force. The variation of normal force has been reported to affect the tactile discrimination of sliding speed by spatiotemporal [34] or vibrational cues [35]. Future research should thus attempt to separate the cues in friction discrimination to investigate possible limits of perceptual constancy in friction perception at varying normal force.

VI. Conclusion

In conclusion, our studies on active tactile exploration of different textured materials reveal a speed dependence of fingertip friction. The friction coefficient is a property of sample and fingertip physiology together, where skin moisture plays an important role. If friction on a sample increases strongly with the individuals' skin moisture, we observed a negative correlation of friction with speed. If friction was rather independent of moisture, the speed dependence of friction was positive. Participants in the study reported the differences in the friction coefficient at different exploration speed mostly correct if these differences were larger than 20%, despite the required efforts to maintain the prescribed speed. Furthermore, participants varied the applied normal forces and still reported friction differences rather according to differences in the friction coefficient than in the absolute forces. These observations indicate a perceptual constancy in tactile perception of friction where participants include the speed of their fingertip motion and the applied normal force in their estimates of friction.

Data availability

Data for Experiment II is published as Fehlberg, M., Monfort, E., Saikumar, S., & Drewing, K. (2024). Data set for manuscript "Perceptual Constancy in the Speed Dependence of Friction During Active Tactile Exploration" [Data set]. Zenodo. https://doi.org/10.5281/zenodo.13366859

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