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Bending as Key Mechanism in the Tactile Perception of Fibrillar Surfaces

*Angelika Gedsun, Riad Sahli, Xing Meng, René Hensel, and Roland Bennewitz**

The touching of fibrillar surfaces elicits a broad range of affective reactions, which range from the adverse stinginess of a stiff bristle brush to the pleasant feel of velvet. To study the tactile perception of model fibrillar surfaces, a unique set of samples carrying dense, regular arrays of cylindrical microfibrils with high aspect ratio made from different elastomer materials have been created. Fibril length and material compliance are varied independently such that their respective influence on tactile perception can be elucidated. This work finds that the tactile perception of similarity between samples is dominated by bending of the fibrils under sliding touch. The results demonstrate that variations of material stiffness and of surface structure are not necessarily perceived independently by touch. In the case of fibrillar elastomer surfaces, it is rather the ratio of fibril length and storage modulus which determines fibril bending and becomes the dominant tactile dimension. Visual access to the sample during tactile exploration improves the tactile perception of fibril bendability. Experiments with colored samples show a distraction by color in participants' decisions regarding tactile similarity only for yellow samples of outstanding brightness.

1. Introduction

Touch is an essential element of human interaction with materials. By touch we explore the pleasantness of a piece of velvet, check the mechanical functionality of a dishwashing brush, or confirm the surface finish of a wooden table. Research into tactile perception of materials relates the properties and structure of materials to the processes in which we identify and evaluate these materials by touch. The results of research into tactile perception allow us to design and engineer materials with a pre-determined haptic appeal.

The tactile perception of natural and every-day materials is often described along so-called tactile dimensions, which are defined by word pairs including rough/smooth, hard/soft, cold/warm, and sticky/slippery.[1] These tactile dimensions have been established in psychophysical studies, which analyzed the correlation of subjective judgments by study participants with physical material properties such as roughness, elastic compliance, thermal effusivity, and friction. The mechanisms underlying perception in the tactile dimensions and the corresponding acuity are subject of ongoing research. One important research strategy is the creation of well-defined model materials with a systematic variation of only one parameter such as surface roughness or sample compliance, and the goal to stimulate specific tactile dimensions. Magnitude estimations of quantities such as perceived smoothness or decisions on perceived similarity between these samples by study participants provide insight into relevant material parameters and just noticeable differences in tactile perception.

A significant body of research work addressed the rough/smooth dimension in experiments with systematically varied surface structures. To name only a few examples, Lederman and Taylor quantified how magnitude estimates of perceived roughness depend on the geometry and widths of grooves machined into a metal surface.[2] Hollins studied touch of abrasive papers with varying particle sizes to provide evidence for the duplex theory of texture perception, which predicts that tactile perception is dominated by vibrational cues for fine structures below 100–200 µm and by spatial static cues for coarse structures.[3] Skedung prepared replicas of strain-induced surface wrinkles and demonstrated that human touch can discriminate amplitudes at the nanometer scale.[4] Beyond psychophysical studies, neurophysiological studies on the touch of textured surfaces provide insights into the neural mechanisms underlying roughness perception at different scales.[5] The human ability to discriminate surface chemistry by touch has been demonstrated on flat surfaces, both for different materials[6] and for different chemical surface modifications.[7]

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The tactile hard/soft dimension was investigated by Srinivasan and LaMotte who compared compliant samples with deformable and rigid surfaces and found that the tactile detection of surface deformation is sufficient for softness perception, while the kinesthetic detection of sample compression is not.[8] The idea was extended by Bergmann Tiest and Kappers using sandwiched elastomer samples of different elastic modulus. The approach allowed to decouple the overall sample stiffness from the elastic modulus and confirmed that tactile perception of compliance was clearly dominated by surface deformation, compared to sample stiffness as experienced by the overall force-distance relation.[9] Experiments with everyday materials of varying surface structure have shown that the tactile perception of softness may have more dimensions than physical material compliance, exemplified in the high perceived softness of fur or velvet.[10]

Here, we report on the tactile perception of surfaces where microstructure and compliance both vary independently. Our unique samples are made from different elastomers and are equipped with dense, regular arrays of well-defined flexible microfibrils with varying length, realizing aspect ratios of up to 5 in cylindrical fibrils. By creating the structures from different elastic materials, the study goes thus beyond recent haptics work on rigid surfaces with micro-pillar structures.[11] The design of our samples is motivated by strong affective responses to touching fibrillar surfaces, which range from adverse reactions to a micrometer-scale bristle to the pleasant touch of velvet, and by a potential relation to the perception of textile pile.[12] The mechanical properties of regular fibrillar elastomer surfaces have recently attracted significant interest in materials science following a biomimetic approach to reproduce the function of gecko feet.[13] We produced a set of 40 samples with fibrils of 400 µm diameter of four different lengths from four elastomer materials with different elastic modulus and added pigments for different coloration to two of the materials. This sample set allows for the first perception study where material compliance and surface microstructure are varied independently. Based on the results of psychophysical experiments, we show that for microfibrillar elastomer surfaces microstructure and compliance are not perceived independently, but that tactile perception is dominated by the bending of the fibrils. We furthermore present results for distraction from the perceptional task by visual access to the dyed samples during tactile exploration, which is inspired by recent interest in the relation between visual and tactile perception of materials.[14]

2. Materials and Methods

2.1. Materials

Fibrillar elastomer samples were prepared by replica molding using aluminum molds with milled microscopic holes. Square samples with a side length of 50 mm carried a hexagonal array of fibrils with a diameter of 400 µm and a center-to-center distance of 800 µm, i.e., 180.4 fibrils per cm^2 (see **Figure 1**a). The flat top surfaces of the fibrils cover a fraction of $\pi / 8\sqrt{3} \approx 22.6\%$ of the sample area. Four different lengths of fibrils were produced with aspect ratios of 1, 2, 3, and 5, where the aspect ratio is defined as the length divided by the fixed diameter. The thickness of the backing layer was 5 mm. Surface structures with these dimensions were found to be mechanically stable over many cycles of tactile exploration for all materials while providing the participants with the experience of a fibrillar surfaces rather than an array of single fibrils.

For the elastomers, we used five different materials: two polydimethylsiloxanes (PDMS, Elastosil M4601 from Wacker Chemie AG, München, Germany and Sylgard 184 from Dow Corning, Midland, MI, USA), and three polyurethanes (PU, Poly GlassRub 50 from Polytek Dev. Corp., Easton, PA, USA PU 7750 and PU 1470 from Polyconform, Düsseldorf, Germany). All materials were two-component systems that were mixed immediately before replica molding. The mixing ratios were according to the quantities given in the data sheets. The pre-polymer mixtures of PDMS and PU were poured into the aluminum molds and subsequently cured at 95 °C and 60 °C, respectively, for 4 h in an oven. Upon demolding samples were used without any further treatments. Transparent materials were also colored by adding 10 wt% pigments. Yellow (Scholz Farben PK 9417) and green (Degussa PK 4045) pigments were added to PU 1470 and yellow, green, and blue (Scholtz Farben PK 5091) pigments were added to PDMS Sylgard 184. The sample made from PU 7750 with a fibril aspect ratio of 5 (2000 µm length) broke during the experiments and was excluded from the data analysis.

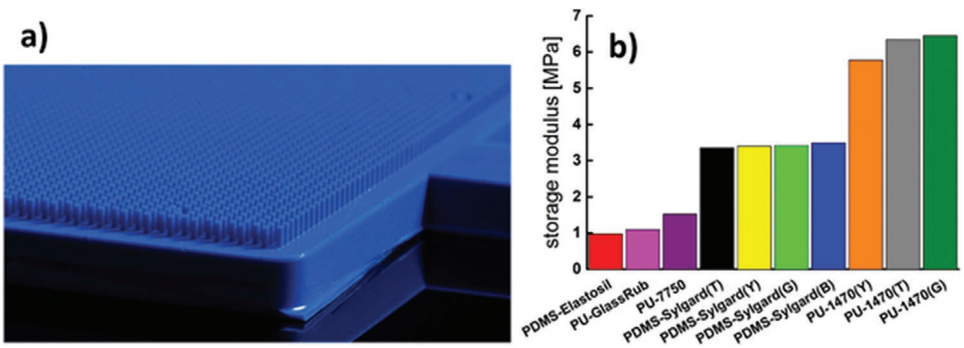

Figure 1. Sample structure and compliance. a) Photograph of a sample made from polydimethylsiloxanes (PDMS) Sylgard 184 with blue pigments. The aspect ratio is 3, i.e., the fibril height is 3 times the fibril diameter of 400 µm. b) Storage modulus of the ten sample materials. Values are recorded at a frequency of 10 Hz by dynamic mechanical analysis (DMA). Samples colors are indicated as transparent (T), green (G), blue (B), and yellow (Y).

The elastic modulus of the 10 different materials was determined by Dynamic Mechanical Analysis (DMA). The results for the storage modulus varied from $E = 1$ MPa for the soft PDMS Elastosil to $E = 6.5$ MPa for the stiff PU 1470. The addition of color pigments did not induce a significant change in the storage modulus as summarized in Figure 1b. We report the storage modulus for a test frequency of 10 Hz to match a characteristic time scale of tactile exploration, namely the typical velocity of the exploring fingertip (≈8 mm s^{-1}) divided by length scale of fibrils (0.8 mm).

2.2. Participants

All participants were volunteers who work and study at the INM—Leibniz Institute for New Materials or at Saarland University. 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. They were free to stop the experiments at any times without giving a reason. 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 all experiments, participants explored the samples by moving the fingertip of their straight index finger in circles over the surface of the samples. Before experiments, participants washed their hands with soap, dried them with a paper towel, and waited at least 2 min before beginning the experiment.

2.3. Experiments

In total, we performed three experiments. In the first experiment, five participants rated the similarity between couples of samples as perceived in touch. Each participant rated 228 pairs out of 741 possible combinations, typically in a time of 2 h. Rating categories were "equal," "similar," "somewhat similar," "different," or "very different." We did not specify with respect to what similarity was to be judged as we intended to reveal a perceptional focus of participants which evolves in the context of the comparison process.[15] Analysis of the similarity judgments allows to sort samples in a tactile space and to identify possible tactile dimensions and their relation to physical quantities.[16] All participants of the first experiment were naïve regarding the goals of the study and the materials or structure of the samples. Participants did not see the samples before or during the tactile exploration.

In a second experiment, we measured the friction between all samples and the index fingertip of 12 different participants. Normal (F_z) and lateral forces (F_x,F_y) were recorded simultaneously (K3D120, ME-Messysteme, Germany). The order of samples was randomized differently for each participant. Participants could not see the sample before or during the experiment. Finger moisture was measured just before the experiment (Corneometer, Courage + Khazaka electronic GmbH). The friction coefficient μ for each sample and participant was determined as the time average of

$$\mu = \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \tag{1}$$

In the third experiment, the participants had a forced-choice ordering task: out of a triple of samples, they had to decide whether the left or the right sample is more similar to the middle reference sample. In these experiments, 8 participants performed the tasks without visual access to the samples, 12 participants with visual access to the samples, and 8 participants gained or lost visual access after half of their trials had been finished. While participants were asked to disregard sample color in their decision, these experiments aimed at a possible distraction from the perceptional task by the visual stimulus color.

3. Experimental Results

3.1. Rating of Perceived Dissimilarity

The influence of the difference in aspect ratio, i.e., the difference in fibril length, on the dissimilarity perceived in touch is

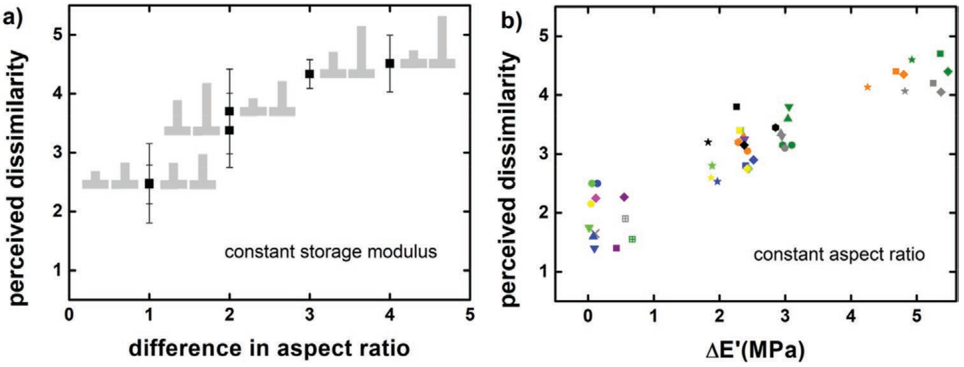

Figure 2. Perceived dissimilarity (1 equal, 2 very similar, 3 somewhat similar, 4 different, 5 very different) of sample pairs. a) Pairs of samples of the same material but with different aspect ratio, i.e., fibril length. Results are averaged over participants and materials. The icons indicate the aspect ratios of the samples compared. b) Pairs of samples with the same aspect ratio, i.e., fibril length, but made of different materials. Results are averaged over participants and aspect ratios. Colors indicate the material of the first sample (Refer to Figure 1), symbols the material of the second sample.

presented in **Figure 2**a for couples of samples made from the same material (Experiment 1). Fibrils with a difference in aspect ratio of 1, corresponding to a length difference of 400 µm, were perceived as between "very similar" and "somewhat similar." The average perceived dissimilarity is the same for couples with aspect ratios 1 and 2 as for couples with aspect ratios 2 and 3. A difference in aspect ratio of 2 was rated between "somewhat similar" and "different," differences of 3 and 4 were rated between "somewhat different" and "different." We conclude that differences in fibril length were perceived in touch and dissimilarity ratings varied significantly between differences in aspect ratio of 1 and 3 or 4.

The dissimilarity perceived between samples made from different materials but with equal aspect ratio is presented in Figure 2b. The results are plotted as function of the difference in storage modulus E'. The perceived dissimilarity increases with increasing difference in storage modulus $\Delta E'$. Materials made from the same PDMS in different colors were perceived as "equal," "similar" or sometimes "somewhat similar." Samples with the largest differences in storage modulus were perceived as "different" or "very different." The perception of similarity could also be influenced by other differences between the materials like the addition of color pigments or the surface energy. The two base materials used in this study, PDMS and PU, have surface energies of typically 20 and 35 mJ m^{-2}. We determined the residues of a linear fit to the data in Figure 2b to analyze any systematic dependence on whether the two samples compared were made from the same base materials or whether color pigments were added to only one of the samples (see Figure S1, Supporting Information). No systematic influence of the base material or of the addition of color pigments was found. As a first conclusion, the tactile perception of similarity between our fibrillar samples depends on both the difference in fibril length and the difference in elastic modulus.

3.2. Multidimensional Scaling Analysis

To reveal a possible interdependence between fibril length and elastic modulus in the tactile perception of similarity, we performed a nonmetric multidimensional scaling (MDS) analysis,[16a] now also including the ratings on sample pairs which differed in both fibril length and elastic modulus. MDS analysis results in a map of the perceptional space, where samples are positioned at a distance which is as close as possible to the dissimilarity ratings (1–5) of participants. The dissimilarity matrix was constructed as the average perceived difference from all participants who evaluated a given pair of samples. The MDS was performed using the *mdscale* function of MatLab using the *stress1* criterion for nonmetric scaling. We repeated the MDS for each dimension 10 000 times with randomly distributed starting positions and report the results with the lowest stress (see Figure S2, Supporting Information, for the stress values).

The result of the one-dimensional MDS is shown in **Figure 3** as function of the elastic modulus of the materials. The value in the perceptual dimension decreases with increasing elastic modulus, but it also increases with increasing aspect ratio, i.e., with increasing length of the fibrils. The monotonic dependence of the tactile dimension on both parameters suggests that the perception of similarity between samples follows some combination of elastic modulus E' and fibril length L. Short fibrils of a compliant material are perceived as similar to long fibrils of a stiffer material. The strongest correlation with a power law constructed from the two quantities was found for log E'/L, see Figure 3b. The correlation was better than for log E'/L^2, but comparable to log $E'/L^{1.5}$. The correlation with the logarithm of the powers is expected from the Fechner–Weber law, which predicts that the perception of a difference between two stimuli scales with the strength of the stimuli. Considering the sliding contact of the fingertip with the fibril, we suggest that the perceptual dimension correlates with bending and shearing of the fibrils. The stiffer the material and the lower the length of the fibrils, the more difficult it is to bend and shear them, a characteristic which is reflected in the tactile dimension presented in Figure 3. In small-force approximation, the angular bending of the pillars scales with E'/L^2, while the shear deformation scales with E'/L.[17]

Expanding the multidimensional scaling analysis to two dimensions does not change the picture. One dimension of the two-dimensional MDS anaylsis correlates strongly with the one dimension in Figure 3 (Pearson r = 0.992), while the second dimension does not correlate to any of the physical parameters of the samples. Further analysis of the MDS results confirms

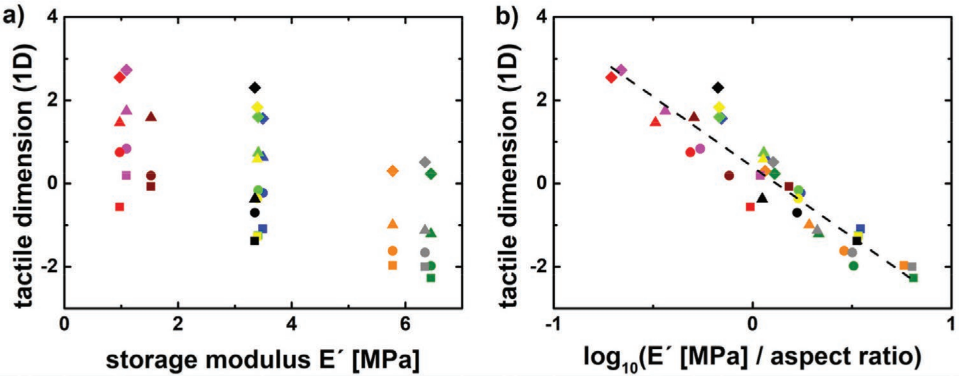

Figure 3. Results for the one-dimensional scaling analysis plotted versus a) the elastic modulus of the materials and b) the logarithm of the elastic modulus E′ divided by the aspect ratio. Shape of symbols indicate the aspect ratio (◆ 5, ▲ 3, ● 2, ■ 1) and colors the elastic modulus. The dotted line is a linear fit to the data (Pearson $r = -0.93$).

that the first dimension is already a good description of the tactile peception of similarity between our samples (see Figures S3 and S4, Supporting Information).

3.3. Physical Mechanisms Underlying Tactile Perception

We suggest that the physical property which correlates to the tactile dimension is bending of the fibrils. This suggestion is supported by the photographs of a fingertip sliding over samples in **Figure 4**a. For the material with the highest elastic modulus (PU 1470), the shortest pillars appear unbent under sliding fingertip. With increasing fibril length, the bending increases and the longest fibrils are bent halfway. For the material with the lowest elastic modulus (PDMS elastosil), even the shortest fibrils are bent to a certain degree and the longest fibrils are bent fully into a 90° flat configuration.

The bending angle θ depends on the applied force and increases from 0 to $\pi/2$ when increasing the force. We can estimate θ based on the analysis of large deformations of a cantilever beam under lateral point force at the free tip by Wang et al.[17b] Lateral force refers to a force applied in the direction perpendicular to the unbent fibril. We approximate Wang's numerical result (filled circles in Figure 2[17b]) as

$$\theta(\alpha) = \frac{\pi}{2}\left(1 - e^{-\alpha/\pi}\right) \qquad (2)$$

with $\alpha = \frac{PL^2}{EI}$. In this equation, P is the lateral point load applied to the end of one pillar, L is the length of the pillar, E its elastic modulus, and I the axial moment of inertia $I = \frac{\pi}{4} R^4$ with $R = 200$ μm the radius of the pillar. The small-angle linear approximation of this equation agrees with the bending of pillars $\theta(\alpha) = \frac{\alpha}{2}$ in the small-load limit.[17b] Equation 2 provides a lower limit estimate of the bending angle because the force of the fingertip is not purely lateral but has a normal component of almost the same order of magnitude. Furthermore, the angle is larger than predicted by Equation 2 in our system because the moment acting on the pillar induces a tilt of its base on the compliant backing.[17a]

In our study on fingertip friction (Experiment 2), the average lateral force surface used by 8 participants to explore the same samples was $F_L = 0.76$ N. The average normal force was $F_N = 0.62$ N. The overall geometric contact between fingertip and sample can be estimated as $A_0 = 97\, F_N^{0.36} = 81.7\ \text{mm}^2$.[18] The number of pillars in contact is then about 148 and the point load to the tip of one pillar $P = 0.76\text{N}/148 = 0.00514$ N. These values have been used to calculate the estimated bending angle of pillars under the sliding fingertip for each sample. In Figure 4b, we plot the tactile dimension versus the estimated bending angle of the pillars and find a better correlation without introducing free parameters (Pearson $r = 0.935$).

The dependence of friction on elastic modulus and on fibril length is presented in **Figure 5**a. Average friction coefficients for the participants varied between 1.0 and 2.7. Generally, the coefficient of friction increases for softer materials, with the notable exception of the PDMS elastosil (red data points). Increased friction for surfaces of softer materials can be explained by the larger real contact area contact between rough skin and structured material. There is no significant dependence of friction on the aspect ratio, i.e., on the fibril length (see Figure S5, Supporting Information). However, the tactile perception of similarity depends on the fibril length (Figures 1 and 3) and, therefore, friction by itself is not expected to correlate strongly to the tactile dimension. Figure 5b shows this correlation, which is by far weaker than the correlation with the bending angle shown in Figure 4b. We conclude that for our samples the role of fingertip friction is limited to the perception of material stiffness. However, in this study the friction experiments were separated from the perception experiments. Simultaneous recording of fingertip friction and of the perception of similarity has previously revealed the important role of friction in the individual perception of randomly rough surfaces.[16b]

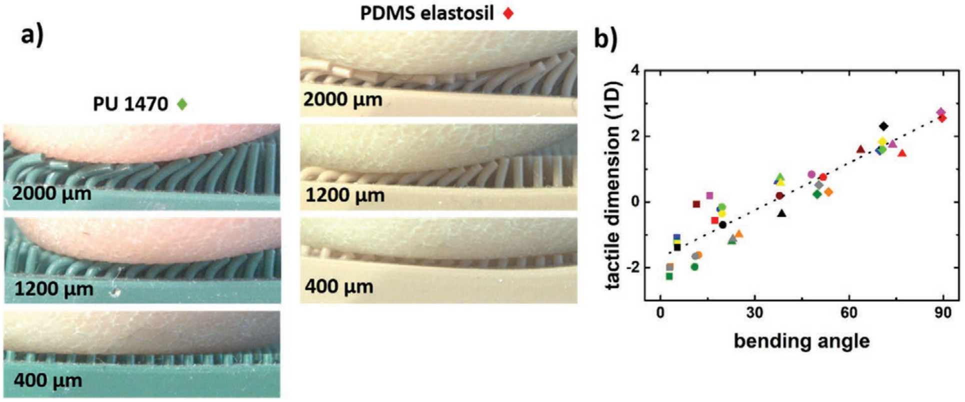

Figure 4. a) Photographs of a fingertip sliding over fibrillar samples made from the material with the highest elastic modulus (PU 1470) and the lowest elastic modulus (polydimethylsiloxanes (PDMS) elastosil) with fibrils of aspect ratio 1 (400 μm), 3 (1200 μm), and 5 (2000 μm). The photographs can only illustrate the bending of fibrils because the optical access requires that half of the fingertip be in contact with the rim of each sample. Images are ordered with increasing bending angle from bottom to top. b) Tactile dimension as result of the multi-dimensional scaling (MDS) analysis as function of the estimated bending angle (see text). The dotted line is a linear fit with Pearson $r = 0.935$.

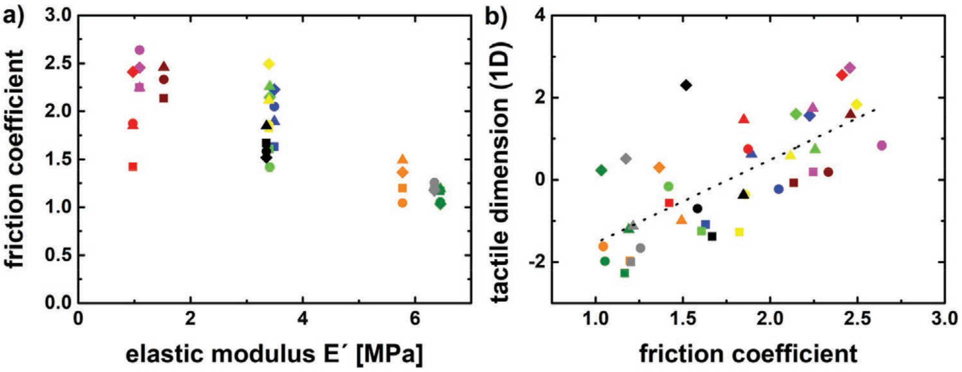

Figure 5. a) Average coefficient of friction for 12 participants plotted as function of the elastic modulus. b) Tactile dimension of the multi-dimensional scaling (MDS) analysis versus coefficient of friction. The dotted line is a linear fit to the data with Pearson $r = 0.712$. Symbols and colors have the same meaning as in Figure 3.

3.4. Effects of Visual Access to Color of Samples

To investigate a possible distraction of participants from a purely tactile judgment by looking at the samples, we performed an additional study (Experiment 3) on a reduced sample set, namely the nine samples with aspect ratio 1, 2, and 3 which were all made from PDMS Sylgard 184 and colored blue, green, and yellow by pigments. For these sample, we consider the elastic modulus to be the same for all samples. Participants evaluated triples of samples by judging if the left or the right sample felt more similar to the middle reference sample. With this design we intended to reduce perceptional bias.[19] In these experiments, participants could see the samples they were exploring in half of the trials. Half of the participants started with visual access to the sample, which was blocked after half of the trials were completed. The other half of participants started without visual access to the samples, which was then allowed after half of the trials were completed. For the trials with visual access, participants were asked to disregard color in their judgment of which sample felt more similar to the reference sample.

We first analyze decisions on those sample triples, where the aspect ratio of the fibrils was different between all three samples. As expected, participants judged samples with aspect ratio 1 to be more similar to samples with aspect ratio 2 than to samples with aspect ratio 3 (92%). Samples with aspect ratio 3 were judged to be more similar to aspect ratio 2 then to aspect ratio 1 (96%). For details see **Table 1**. When comparing aspect ratio 1 and 3 to a reference with aspect ratio 2, there was a significant preference for aspect ratio 3 to be more similar (71%). This result is in line with the conclusion from Figures 3b and 4b that not the length of the fibrils but resistance to bending dominates tactile perception of similarity. Fibril bending was found to scale with the inverse of the aspect ratio and, thus, it was expected that aspect ratios 2 and 3 are closer than aspect ratios 1 and 2.

The numbers presented in Table 1 indicate that these tendencies in similarity perception are enhanced when participants saw the samples during tactile exploration. When we analyzed decisions on those triples, where one sample had the same aspect ratio as the reference and the other sample had a different aspect ratio, more than 95% of all decisions judged the sample with the same aspect ratio as feeling more similar.

In the experiments on triples of the same material, we recorded the coefficient of friction for each trial and participant. We could therefore analyze how many decisions as feeling more similar to the reference were taken for the sample which also had a smaller difference in the coefficient of friction to the reference sample. For trials with visual access, 62% of decisions followed the expectation based on the smaller difference in friction, in blind trials the fraction was 68%. We conclude that with and without visual access, there was a significant correlation between friction differences and the decision about similarity (*Pr* < 0.01%). However, no significant influence of friction on perceived tactile similarity was found when we limited the analysis to cases where the left and the right sample had the same aspect ratio. We conclude that the role of friction for tactile perception cannot be disentangled from the role of fibril length and bending, even if friction results are available for each single trial.

Finally, we were interested to know if the color of the samples influenced the judgment of perceived tactile similarity despite the task to disregard color in the decisions. We considered only those triples where the aspect ratio of the left and the right sample were the same to exclude a judgment dominated by the fibril length. When one of the two samples had the same color as the reference sample, there was a small but significant preference to choose this sample as feeling more similar (59%, *Pr* = 4.1%, see **Table 2**). When we separated the analysis

Table 1. Summary of decisions for sample triples, where all three samples had different aspect ratio, i.e., different fibril lengths.

Reference		AR1			AR2			AR3		
Decision		AR2	AR3	*Pr*	AR1	AR3	*Pr*	AR1	AR2	*Pr*
Blind	abs	76	7	< 0.01%	23	57	< 0.01%	3	74	< 0.01%
	rel	92%	8%		29%	71%		4%	96%	
Visual	abs	70	6		7	81		0	76	
	rel	92%	8%		8%	92%		0	100%	

The table lists the absolute and relative number of trials with a decision for the respective sample as feeling more similar to the reference, for trials without and with visual access to the samples. The significance level *Pr* quantifies the probability of the null hypothesis that the distribution of decisions is random, which is considered rejected for *Pr* < 5%.

Table 2. Summary of decisions for sample triples, where the left and the right sample had the same aspect ratio, i.e., the same fibril lengths.

Reference		Blue			Green			Yellow			Total amount		
Decision		blue	not blue	*Pr*	green	not green	*Pr*	yellow	not yellow	*Pr*	same with Ref.	different from Ref.	*Pr*
Blind	abs	20	19	50%	22	18	32%	14	19	24%	56	56	54%
	rel	51%	49%		55%	45%		41%	59%		50%	50%	
Visual	abs	16	17	50%	20	15	25%	27	12	1.2%	63	44	4.1%
	rel	49%	51%		57%	43%		70%	30%		59%	41%	

The table lists the absolute and relative number of trials with a decision for the respective sample as feeling more similar to the reference, for trials without and with visual access to the samples. The significance level *Pr* quantifies the probability of the null hypothesis that the distribution of decisions is random, which is considered rejected for $Pr < 5\%$.

with respect to the color of the reference sample, we found that the influence of identical color on the decision about tactile similarity is significant only for yellow reference samples. No significant difference between blue, green, and yellow samples was found in elastic modulus, water contact angle, or surface structure as apparent in scanning electron microscopy. We tentatively conclude that the influence of yellow color on the similarity decisions was induced by the visual modality. No significant influence of color was found when all three samples had different colors.

4. Discussion

Our results demonstrate that fibril bending is the key mechanism for the tactile perception of similarity between microfibrillar elastomer samples. The fibrils exhibited different length and were made from elastomers with varying elastic modulus. A physical quantity derived from these material parameters which correlates well with the tactile dimension is given by $\log E'/L$ or $\log E'/L^{1.5}$. An even better correlation was found with the actual bending angle of the fibrils. Under the sliding fingertip, the bending of the fibrils varies significantly, from almost no bending of short and stiff fibrils to full bending and contact to the side walls of long and soft fibrils. We therefore will discuss possible mechanisms in the tactile perception associated with fibril bending.

As a first mechanism, the bending of fibrils may be perceived as softness of the surface. Tactile perception of compliance relies mostly on deformation of the surface.[8–9,20] However, Cavdan et al. have shown that the perception of softness correlates not only with compliance but also with furriness or fibrousness of materials.[10] In a study on 3D-printed hairy surfaces as versatile material mimics in virtual realities, Degraen et al. found that participants perceived variations of hair length as change in hardness.[21] If the elastic modulus and fibrillar structure of our samples were perceived jointly as sample softness, the resulting force-deformation characteristic can be expected to be nonlinear. Different nonlinear compliances across samples might introduce more than one tactile dimension, but Piovarci et al. already found that one tactile dimension is sufficient to describe compliance perception on objects with a nonlinear mechanical characteristic.[22]

Our friction results have shown a rather weak correlation with the tactile dimension. We do not expect significant adhesive contributions to friction which have been reported for gecko-mimicking structures on flat surfaces. The roughness of the fingertip skin suppresses adhesion as well as adhesion enhancement by fibrils for all our samples.[23] No adhesive forces comparable to the friction forces were detected during tactile exploration experiments. Although friction is expected to be associated with the elastic energy stored in bent fibrils,[24] it has been reported that friction depends weakly and nonmonotonously on the fibril length when strong bending is involved.[13d]

A third mechanism to be discussed is the perception of fibril bending as change in roughness. Massimiani et al. found in a study on hedonistic perception of samples with stiff fibrils that samples with our geometry (diameter 400 µm, length 800 µm) were categorized as "rough."[11a] The authors also measured friction-induced vibrations on the fingertip, which are believed to play a major role in roughness discrimination.[25] Microstructures with a periodicity of 800 µm induced vibration in the sliding fingertip which reflected the periodicity of both the surface structure and the finger ridges.[26] Tymms et al. investigated the perceived smoothness of surfaces carrying dense arrays of sub-millimeter sized stiff textons, i.e., hillocks of different shape.[11c] They found that the tactile perception of smoothness depends on the shape of the textons, with larger contact area leading to perception of a smoother surface. The authors argued that papillary ridges act as tactile processing units for textons of different shape at this length scale. The photographs in Figure 4a show that fibrils change their shape upon bending and we suggest that the effectiveness of mechanical stimulation of papillary ridges may depend strongly on the bending angle or rather on the exposure of the fibril edge at small bending angles and a large contact area at large bending angles. In this picture, the change of fibril shape due to bending would lead to a strong variation in perceived smoothness and thus to the observed influence of fibril bending on the tactile perception of similarity.

Based on the available data we cannot decide to what degree the tactile dimension of fibril bending can be attributed to a perception of softness/hardness or to a perception of smoothness/roughness. Future dedicated psychophysical experiments could clarify if the unique role of fibril bending in the perception of similarity between our samples can and should be understood in terms of these classical tactile dimensions of materials perception.

Visual access to the samples during tactile exploration led to a small increase in the percentage of decisions which confirmed the expected perception of similarity, i.e., for sample with equal aspect ratio or for sample pairs with aspect ratios 2 and 3 as compared to pairs with aspect ratios 1 and 2. Differences in fibril heigh of 0.4 mm can be detected in visual inspection and support the similarity decision. Degraen et al. found that adding visual information in virtual reality also increased the ability of participants to distinguish small differences in the length of 3D-printed fibrils.[21] We hypothesized that the color of samples could guide the decision about perceived similarity, even when the task was to judge based on tactile exploration and to disregard color. However, we found no such distraction effect even in the case when the left and the right sample had the same fibril length so that no tactile difference was expected. Only if the reference sample was yellow, participants chose a yellow sample as feeling more similar to the reference than the non-yellow sample. We suggest that the particular influence of yellow originates in the outstanding brightness of our yellow samples compared to blue and green samples, rather than in a particular differentiation in the perception of yellow color.[27]

5. Conclusion

The tactile perception of similarity between fibrillar surfaces can be described by one tactile dimension, which corresponds to the degree of fibril bending induced by the sliding fingertip. We prepared surfaces carrying regular arrays of fibrils with equal diameter but varying length from elastomers with varying storage modulus. Surfaces with shorter fibrils made of more compliant material felt similar to surfaces with longer fibrils of stiffer material due the perceptional focus on fibril bending. The perception of materials by touch is often described by tactile dimensions which are characterized as soft/hard, smooth/rough, cold/warm, and slippery/sticky. We suggest that the fibril bending under the exploring fingertip may effectively contribute to softness and roughness perception, but that the systematic variation of only fibril length and of storage modulus in our sample set reduced the tactile perception to one dimension, which was associated to fibril bending. Comparing results for tactile exploration with and without visual access to the samples revealed rather small differences, and only a bright yellow color distracted participants from their task to judge similarity only based on touch, when the reference sample and one of two otherwise equal comparison samples were colored yellow. Our results demonstrate that variations of material stiffness and of surface structure are not necessarily perceived independently by touch. In the case of fibrillar surfaces, it is rather the resistance to bending which can become the dominant tactile dimension. Our observations can support the design of materials which mimic the pleasant feel of velvet structures or use fibrillar structures to engineer the tactile perception of materials.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

elastomers, fibrillar surfaces, friction, tactile perception

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