Tactile Perception of Coated Smooth Surfaces

Easa AliAbbasi, Volkan Aydingul, Alperen Sezgin, Utku Er, Seniz Turkuz, and Cagatay Basdogan

***Abstract*—Although surface coating is commonly utilized in many industries for improving the aesthetics and functionality of the end product, our tactile perception of coated surfaces has not been investigated in depth yet. In fact, there are only a few studies investigating the effect of coating material on our tactile perception of extremely smooth surfaces having roughness amplitudes in the order of a few nanometers. Moreover, the current literature needs more studies linking the physical measurements performed on these surfaces to our tactile perception in order to further understand the adhesive contact mechanism leading to our percept. In this study, we first perform 2AFC experiments with 8 participants to quantify their tactile discrimination ability of 5 smooth glass surfaces coated with 3 different materials. We then measure the coefficient of friction between human finger and those 5 surfaces via a custom-made tribometer and their surface energies via Sessile drop test performed with 4 different liquids. The results of our psychophysical experiments and the physical measurements show that coating material has a strong influence on our tactile perception and human finger is capable of detecting differences in surface chemistry due to, possibly, molecular interactions.**

***Index Terms*—surface haptics, tactile perception, surface coating, contact mechanics, friction, surface energy, atomic force microscopy, roughness, adhesion.**

I. Introduction

TACTILE perception of surfaces play a critical role in purchasing of consumer products in many industries such as mobile devices, automotive, home appliances, furniture, and glass to count a few. For example, when purchasing a car, we instinctively touch and explore its outer surface, dashboard, and seat covers. Similarly, when purchasing a household glassware, we hold it and explore its surface with our fingers.

Despite these compelling examples, the factors contributing to our tactile experience of a surface are still not fully known. One major reason for that the contact interactions between human finger and a surface is complex and our fingers are highly sensitive to even slight differences in surface topography and material properties, which results in mechanical deformations at the fingerpad skin in varying stimulation amplitudes and frequencies. Cutaneous mechanoreceptors under fingerpad skin and proprioceptors in joints, muscles, and tendons convert these mechanical signals to electrical signals (i.e. mechanotransduction) to form our tactile percept at the brain [1].

In the area of tactile perception, most of the earlier studies have focused on the textured surfaces. These studies have identified the perceptual dimensions of texture perception as rough/smooth, hard/soft, sticky/slippery, and warm/cool [2], [3] though the link between these dimensions and the physical properties has not been fully understood yet. Among these perceptual dimensions, rough/smooth dimension is considered as the most significant one.

The initial studies by Hollins et al. [4] using multi-dimensional scaling (MDS) techniques and then neuronal recordings acquired from SA1, RA, and PC afferents of Rhesus macaques by Weber et al. [5] revealed that the mechanism underlying roughness perception is different for micro and macro textures where the threshold for inter-element spacing was determined as approximately 200 microns (see a review in Klatzky and Lederman [6]). It appears that spatial cues play a dominant role in tactile perception of macro textures while the temporal ones in micro textures.

Although the roughness perception of macro textures can be investigated using periodic raised dots and gratings manufactured by conventional techniques, it is more difficult to apply the same techniques to periodic micro-scale textures. Moreover, compared to the periodic textures, manufacturing randomly rough surfaces is even more difficult since the surface topography follows some probabilistic distribution and the height profile should be sampled from it. The recent advances in additive manufacturing could be helpful in investigating human tactile perception of randomly rough surfaces in a systematic manner [7], [8].

In order to produce surfaces with features smaller than micro-scale, micro/nano scale surface coating techniques are necessary. Skedung et al. [9] used such techniques to produce wrinkled surfaces with wavelengths ranging from 300 nm to 90 μm and amplitudes between 7 nm and 4.5 μm. They then conducted psychophysical studies involving similarity scaling on those surfaces. The results of the study show that the lowest amplitude of the periodic wrinkles distinguished by humans is approximately 10 nm. If this value is taken as the limit of our tactile perception (though it may not directly apply to ”non-periodic” surfaces), the surfaces having roughness amplitudes below this limit can be accepted as extremely smooth.

In tribology literature, it is known that adhesive forces significantly affect the friction between a soft object such as the human finger and an extremely smooth surface, especially at low normal contact forces (F_n) [10]. The friction force acting on a finger sliding on a smooth surface can be written as $F_t = F_{adh} = \tau A_{\mathrm{real}}$, where τ is the interfacial shear stress and A_{real} is the real area of contact, which varies nonlinearly with the normal force applied by the finger on the surface. The real contact area is difficult to measure or estimate since human finger pad has surface roughness at different length scales and each asperity makes adhesive contacts down to nanoscale and supports the adhesive shear load proportional to its own contact area, contributing to the tangential force, shearing those contacts [11]. The adhesive contacts between finger and an extremely smooth surface are mainly formed due to van der Waals, electrostatic, and hydrogen bonding forces. Derler et al. [10] measured the coefficient of friction (CoF = F_t/F_n) between finger and smooth and rough glass surfaces under dry and wet conditions and concluded that adhesion significantly affected the frictional interactions with smooth (rough) surfaces under dry (wet) conditions.

Compared to the earlier studies on macro and micro textures, the number of studies investigating the human tactile perception of extremely smooth surfaces having a roughness of a few nanometers is highly limited. Moreover, to this time, a very few studies investigated the effect of coating type (material) on tactile perception of such surfaces. Gueorguiev et al. [12] conducted 2-alternative forced-choice (2AFC) experiments with glass and polymethyl methacrylate (PMMA) plastic plates having similar roughness magnitudes at nanoscale and observed that the human participants with dry

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Manuscript received XX XX, 202X; revised XX XX, 202x.

fingers could successfully discriminate them though they resulted in similar CoF. They attributed this result to the difference in molecular structures of glass and PMMA. Carpenter et al. [13] showed that human participants can differentiate Silicon surfaces that differ only by a single layer of molecules. Their results demonstrate that surface chemistry plays an important role in tactile perception. Skedung et al. [14] prepared a stimuli set consisting of 10 glass surfaces with different coatings and measured their water contact angle, contact angle hysteresis, and surface free energy. They also measured the CoF between human finger and the samples. The surfaces were evaluated in terms of perceived similarities by 10 female participants who were able to distinguish between the surfaces varying in coating material. The multi-dimensional scaling (MDS) analysis revealed that the primary perceptual dimension correlates with surface free energy, but both CoF and surface energy contribute to this dimension depending on whether the coating is organic or inorganic. Ajovalasit et al. [15] prepared 20 smooth aluminum surfaces consisted of 4 uncoated substrates and 16 coated substrates (4 different types of coatings applied on each of the 4 uncoated substrates) to conduct tactile perception studies with human participants. A total of 40 participants rated the surfaces based on their perceived slipperiness, roughness, and glossiness. They also measured surface roughness, friction coefficient, surface free energy, and surface glossiness of the coated surfaces. They concluded that the coating type had significant effects on perceived slipperiness and roughness, while both coating type and manufacturing process had significant effects on glossiness.

The aim of our study is to investigate the relationship between tactile perception of extremely smooth surfaces coated with different materials and the adhesive contact interactions between human finger and those surfaces due to the potential effect of surface chemistry. In particular, the glass company that we collaborate with is interested in developing standards for the classification of smooth surfaces with different coatings since the roughness and stickiness of such surfaces are both important for aesthetics and functionality of an end product. Stickiness, for example, may contribute not just to the affective attributes of a glass product such as pleasantness, but also its functional attributes such as scratch resistance. Our study shows that human finger can function as a tactile sensor to detect the differences in surface chemistry and hence to differentiate the surfaces with different coatings successfully.

TABLE I The five sample surfaces used in our study.

Sample	Top layer	Layer below the top
S1	Titanium Oxide (TiOx)	Silicon Oxynitride (SiOxNy)
S2	Titanium Oxide (TiOx)	Silicon Nitride (SiN)
S3	Silicon Oxynitride (SiOxNy)	Silicon Nitride (SiN)
S4	Silicon Nitride (SiN)	Nickel Chromium (NiCr)
S5	Zirconium Oxide (ZrOx)	Silicon Nitride (SiN)

The rest of the paper is organized as follows: in Section II, we explain our sample preparation process and the procedure utilized for the psychophysical experiments. Using 2AFC method, we displayed the coated surfaces in pairs side by side to 8 participants and asked them to explore the surfaces with their index fingers and select the surface feeling more "resistive" to sliding. In the same section, we also present our experimental set-up and the procedure followed for the measurement of dynamic CoF between the index finger of 7 participants and the sample surfaces. In the following, we introduce contact angle measurements performed by Sessile drop test to calculate the surface free energies and contact angle hysteresis of the sample surfaces. Finally, we talk about our AFM measurements for surface roughness. The results of our tactile perception experiments and the physical measurements are reported in Section III and discussed in Section IV. A conclusion of the study is provided in Section V.

II. Material and Methods

A. Sample Preparation

Multi-layer thin film stacks were deposited on soda-lime float glasses in an inline horizontal coater using magnetron sputtering technique. Each individual thin film layer was deposited in desired thicknesses by adjusting the related process parameters such as carrier speed, power, temperature, and process gases. A total of 5 substrate surfaces (S1-S5) were produced by the glass manufacturer for testing in this study (see Table I). Note that only the material type at the top coating layer and the layer below the top one are reported in the table though there are other layers below. The layer thicknesses are in the

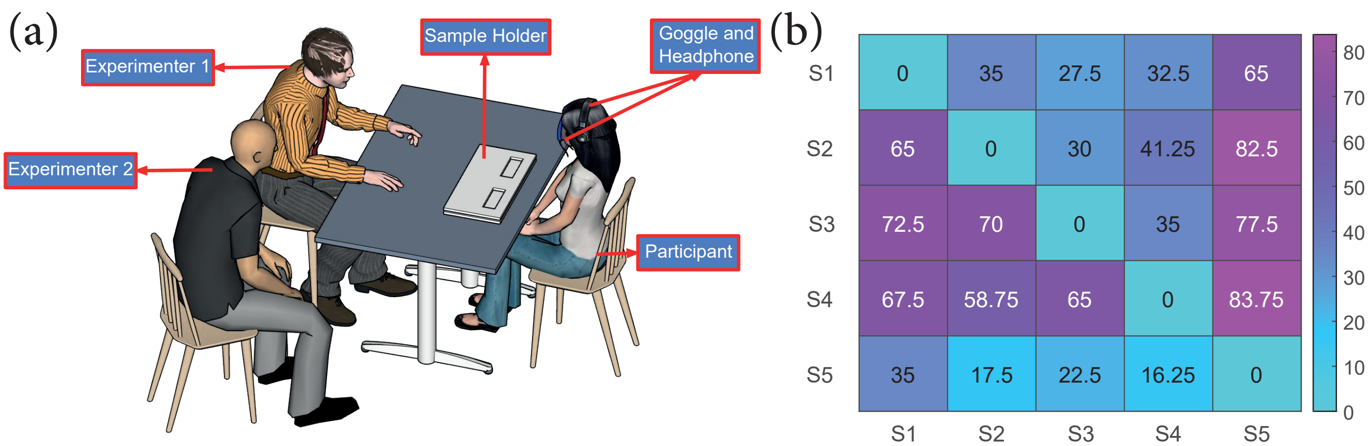

Fig. 1 a) The set-up used in our psychophysical experiments. A sample-holder made of plexiglass is utilized to secure the sample surfaces for stable tactile exploration. Throughout the whole experiments, participants were asked to wear a headphone displaying white noise and a goggle covering their eyes. Experimenter 1 shown in the rendering was responsible for starting and stopping each trial by tapping the passive hand of the participant placed on the table and also replacing the samples between the trials. Experimenter 2 was solely responsible for the timing of trials. b) The confusion matrix based on the averaged responses of participants; each row represents the percentage of a particular sample as being felt more resistant to sliding compared to the others.

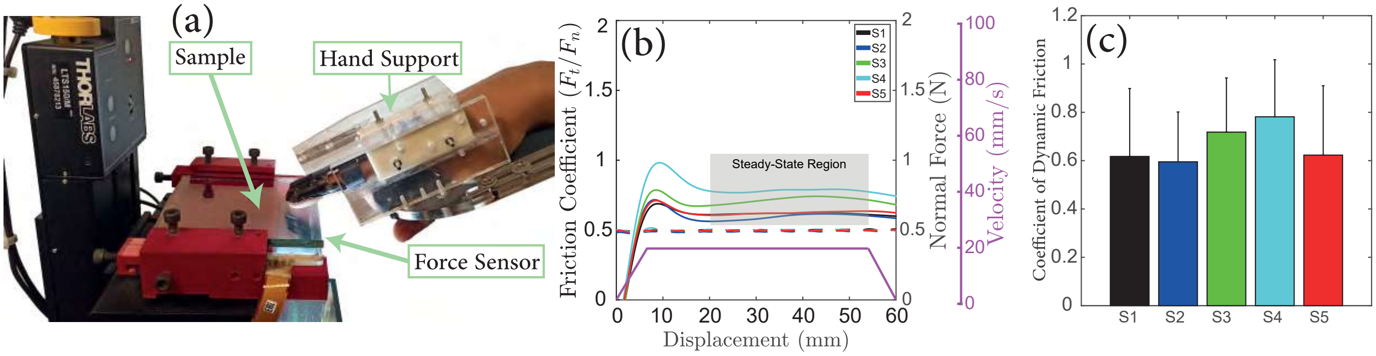

Fig. 2 The results of our friction experiments; a) The set-up used for the measurements. b) Coefficient of friction (CoF), normal force, and the velocity profile of the horizontal stage as a function of relative displacement between finger and the sample surface. c) Mean steady-state values of dynamic CoF with standard error of means.

order of nanometers, but we are not allowed to provide the details here since they are the trade secrets of the manufacturing company. With respect to the type of material at the top layer, the samples are grouped into three (G1, G2, G3): Titanium-based (S1, S2), Silicon-based (S3, S4), and Zirconium-based (S5). The difference between the sample S1 and S2 is the coating material utilized in the layer below the top layer. We aimed to see if the coatings in lower layers have any significant effect on the tactile perception of the top layer.

B. *Tactile Perception Experiments*

1) Participants: Eight healthy participants (3 females, 5 males; mean age = 24.88, SD = 3.14) were selected to take part in this study. A consent form was read and signed by the participants before the experiment, which was approved by the Ethical Committee for Human Participants of Koc University. The study conformed to the principles of the Declaration of Helsinki, and the experiment was performed following relevant guidelines and regulations.

2) Apparatus: We developed a set-up to conduct our tactile perception experiments (Fig. 1b). It is comprised of a sample holder designed and cut from plexiglass with two housings for placing a pair of sample surfaces side by side on a table, a headphone for playing white noise to the ears of participants, and a goggle to cover the eyes of participants. In this way, we ensured that there was no visual and auditory interference. Hence, the participants were able to make their decision purely based on tactile cues.

3) Procedure: The 2AFC method was utilized in this experiment. The samples were displayed in pairs in random order, and the participants were asked to explore both samples consecutively with their index fingers and choose the one that resisted more to sliding. We intentionally did not want to use the adjectives “rough/smooth” or “sticky/slippery” for the following reasons: First, our study investigates which physical cues play a role in tactile discrimination of smooth surfaces and we did not want to bias the participants by hinting those cues. Second, those adjectives are not easy to explain to the subjects since all the samples in our study are glass with extremely smooth surfaces. Our pilot study revealed that the participants indeed had difficulty in understanding and differentiating those adjectives. There were a total of 10 pairs and each pair was displayed 10 times to each participant. Hence, each participant performed 100 trials and there were a total of 800 trials in the experiments (10 pairs $\times$ 10 repetitions/pair $\times$ 8 participants). The location of the samples in each pair was randomized such that each sample was displayed 5 times on each side (left/right) of the sample holder.

A separate training session was conducted for each participant. Before the training session, the experimenter explained the experimental procedure to the participant. During the training session, all samples were displayed to the participants once and they were asked to explore the surfaces with their index fingers to get familiar with them. The participants washed their hands with soap and rinsed them with water before the actual experiment. One experimenter sat in front of the participant to replace the samples and another one held the time. The communication between the experimenter and the participant was ensured by tapping the passive hand of the participant placed on the table. One tap meant the new set of samples was ready for exploration (i.e. new trial), and two taps meant the 15 seconds time limit was reached for exploring the samples and the participant must make a decision. Participants responded verbally by stating *right* or *left*, and their voices were recorded using a microphone for post-processing of the responses.

C. *Measurement of Coefficient of Friction*

The goal of the experiment was to measure the coefficient of friction between finger and the samples. This was achieved by dividing the measured tangential force to the normal force (F_t/F_n).

1) Participants: Seven subjects (2 females, 5 males; mean age = 24.71, SD = 3.14) participated in the friction experiments.

2) Apparatus: The set-up developed by [16] was slightly modified to measure the dynamic CoF between human finger and the sample surfaces (see Fig. 2a). The major components of this set-up consist of a force/torque sensor (Mini40-SI-80-4, ATI Inc.) with a force resolution of 20 mN in the tangential direction for measuring normal and tangential forces acting on the finger and two linear translational stages (LTS150, Thorlabs Inc.) to move the sample surface in normal and tangential directions with respect to the participant’s finger. During the measurements, we kept the normal force constant at F_n = 0.5 N with a PID controller by regulating the movements of the sample surface with respect to the finger using one of the stages. The other stage was used to move the sample surface in the tangential direction at a constant speed of 20 mm/s. The normal and tangential forces acting on the finger were acquired at 2.5 kHz using a data acquisition (DAQ) card (PCIe-6034E, National Instruments Inc.).

3) Procedure: Each participant completed the experiment in one session. They were instructed to put their index finger inside the hand support to keep it stationary. During the experiments, the sample placed under their finger was moved in tangential direction and the normal and tangential forces acting on the finger were measured. Participants were asked to minimize their body movement during the measurements as much as possible to reduce any possible noise in the data. Using a micropipette, 1 μL liquid vaseline was injected on the surface of participants’ fingertip to eliminate the stick-to-slip behavior. Before collecting data, the sample surface was moved back and forth 10 times beneath the finger under a constant normal force and sliding velocity to establish a homogeneous sliding path. The experiment was repeated 3 times for each sample.

D. Calculation of Surface Free Energy

1) Concept: Surface free energy determines how materials adhere to each other [17]. Adhesive forces are generated at the interface due to the molecular interactions between surfaces. For example, a strong adhesive force tends a liquid to spread over a smooth surface making a small angle of contact.

According to the acid-base theory, nonpolar and polar components constitute the total surface free energy of any material. The nonpolar component (Lifshitz-van der Waals) is denoted by γ^{LW} and the polar component has two sub-components: Lewis acid and Lewis base denoted by γ^{+} and γ^{-}, respectively. Hence, the total surface free energy of any material is calculated using the following equation [18]:

$$\gamma^{Total} = \gamma^{LW} + 2\sqrt{\gamma^{+}\gamma^{-}} \quad (1)$$

If the surface free energy components of a liquid (L) and a smooth surface (S) in contact are known in advance, the work required to separate them (i.e. adhesive work) can be calculated as:

$$W_{LS} = 2\sqrt{\gamma_L^{LW}\gamma_S^{LW}} + 2\sqrt{\gamma_L^{+}\gamma_S^{-}} + 2\sqrt{\gamma_L^{-}\gamma_S^{+}} \quad (2)$$

On the other hand, if the contact angle (θ) between a liquid and a smooth surface is known, the adhesive work between them can also be estimated by:

$$W_{LS} = \gamma_L \left(1 + \cos\theta\right) \quad (3)$$

Hence, the following equality is obtained:

$$\gamma_L \left(1 + \cos\theta\right) = 2\sqrt{\gamma_S^{LW}\gamma_L^{LW}} + 2\sqrt{\gamma_S^{+}\gamma_L^{-}} + 2\sqrt{\gamma_S^{-}\gamma_L^{+}} \quad (4)$$

Little and Bhasin [17] suggested that 3 unknown components of the surface free energy for any solid surface (γ_S^{LW}, γ_S^{+}, and γ_S^{-}) can be calculated by measuring the contact angles between the surface and at least 3 liquids with known surface free energy components and then solving for Eq. 4.

2) Measurement of Contact Angle: The static contact angles between the sample surfaces and 4 different liquids were measured by Sessile drop test. Using a contact angle meter (Attension ThetaLite TL101-Auto1, Biolin Scientific Inc.), we put a droplet of liquid on each sample surface and then measured the contact angle via image processing techniques. For this purpose, we utilized 4 probe liquids: DI water, Glycerol, Ethylene Glycol, and Formamide. The surface free energy components of the selected probe liquids are tabulated in Table II. Fig. 3a shows the images of a DI water droplet on each sample surface and the contact angles it make with the surfaces.

The dynamic contact angles for a droplet of DI water was measured by inflating and deflating the drop via a micropipette [19]. A droplet of DI water (5 μL) was dispensed on each sample surface and the volume of the droplet was increased until the maximum advancing contact angle was reached; followed by a subsequent decrease in volume until the droplet disappeared. Throughout this process, images of the advancing and receding contact angles were captured by the video camera of the contact angle meter.

E. Measurement of Surface Roughness

Surface roughness of each sample was measured using an atomic force microscope (AFM) having a resolution of 0.1 nm along the direction of surface normal (Dimension Icon SPM, Bruker Inc.).

TABLE II Surface free energy components of the probe liquids utilized in contact angle measurements. The values are taken from [18].

Liquid	γ^{LW}	γ^{+}	γ^{-}	γ^{Total}
DI Water	21.80	25.50	25.50	72.80
Glycerol	34.00	3.92	57.40	64.00
Ethylene Glycol	29.00	1.92	47.00	47.99
Formamide	39.00	2.28	39.60	58.00

III. Results

1) Tactile Perception Experiments: We recorded the responses of all participants and generated a confusion matrix based on the average of those responses (see Fig. 1b). Each row of the confusion matrix shows the percentage of a particular sample as being felt more resistant to sliding compared to the others. According to this matrix, the samples can be ranked based on their resistivity to sliding as S5 (the least), S1, S2, S3, S4 (the most).

2) Measurement of Coefficient of Friction: The CoF curve reported in Fig. 2b are the mean values of 21 trials recorded for each sample (3 trials/participant $\times$ 7 participants). The same figure also shows the average normal force for each sample and the horizontal stage's velocity profile as a function of displacement. The steady-state region for all CoF curves was taken as the interval from 20 mm to 50 mm and the mean values of dynamic CoF together with their standard error of means are presented in Fig. 2c. One-way ANOVA showed significant effect of coating material (G1, G2, G3) on dynamic CoF ($F(2, 102) = 4.34$, $p = 0.015$). Post hoc comparisons using the Tukey HSD test showed that G2 is significantly higher than G1 in terms of dynamic CoF ($p < 0.017$).

3) Measurement of Contact Angle and Calculation of Surface Free Energy: For each sample, we measured the static contact angles (between the sample surfaces and the probe liquids) at 3 different locations on the surface. The measured contact angle for each location is the arithmetic mean of the angles formed on the right and left-hand sides of the droplet. The measured contact angles between the surfaces of samples and the 4 probe liquids are presented in Fig. 3b.

Using the measured contact angles, the surface free energy components of the 4 liquids tabulated in Table II, and Eq.4, we estimated the surface free energy of the samples. For this purpose, we first solved a set of 4 nonlinear and over-determined equations in order to calculate the components of the surface free energy for each sample. Then, the total surface energy for each sample was calculated by Eq. 1 and the results are reported in Fig. 3c. One-way ANOVA showed significant effect of coating material on surface free energy ($F(2, 12) = 5549.57$, $p < 0.001$). Post hoc comparisons using the Tukey HSD test showed that G2 is significantly higher than G1 ($p < 0.001$) and G3 ($p < 0.001$).

The contact angle hysteresis was calculated as the difference between the maximum advancing and minimum receding contact angles. The measurements were repeated 3 times and the mean values with their corresponding standard deviations for the advancing and receding contact angles and the contact angle hysteresis are presented in Fig. 3d and 3e, respectively. One-way ANOVA showed significant effect of coating material on contact angle hysteresis ($F(2, 12) = 24.62$, $p < 0.001$). Post hoc comparisons using the Tukey HSD test showed that G2 is significantly lower than G1 ($p < 0.001$) and G3 ($p < 0.001$)

4) Measurement of Surface Roughness: We measured the surface roughness of sample surfaces by AFM in tapping mode at 2 different sites on the surface for an area of 1 $\mu m \times 1$ μm. The sample surfaces were transferred directly from the coating lab to the measurement

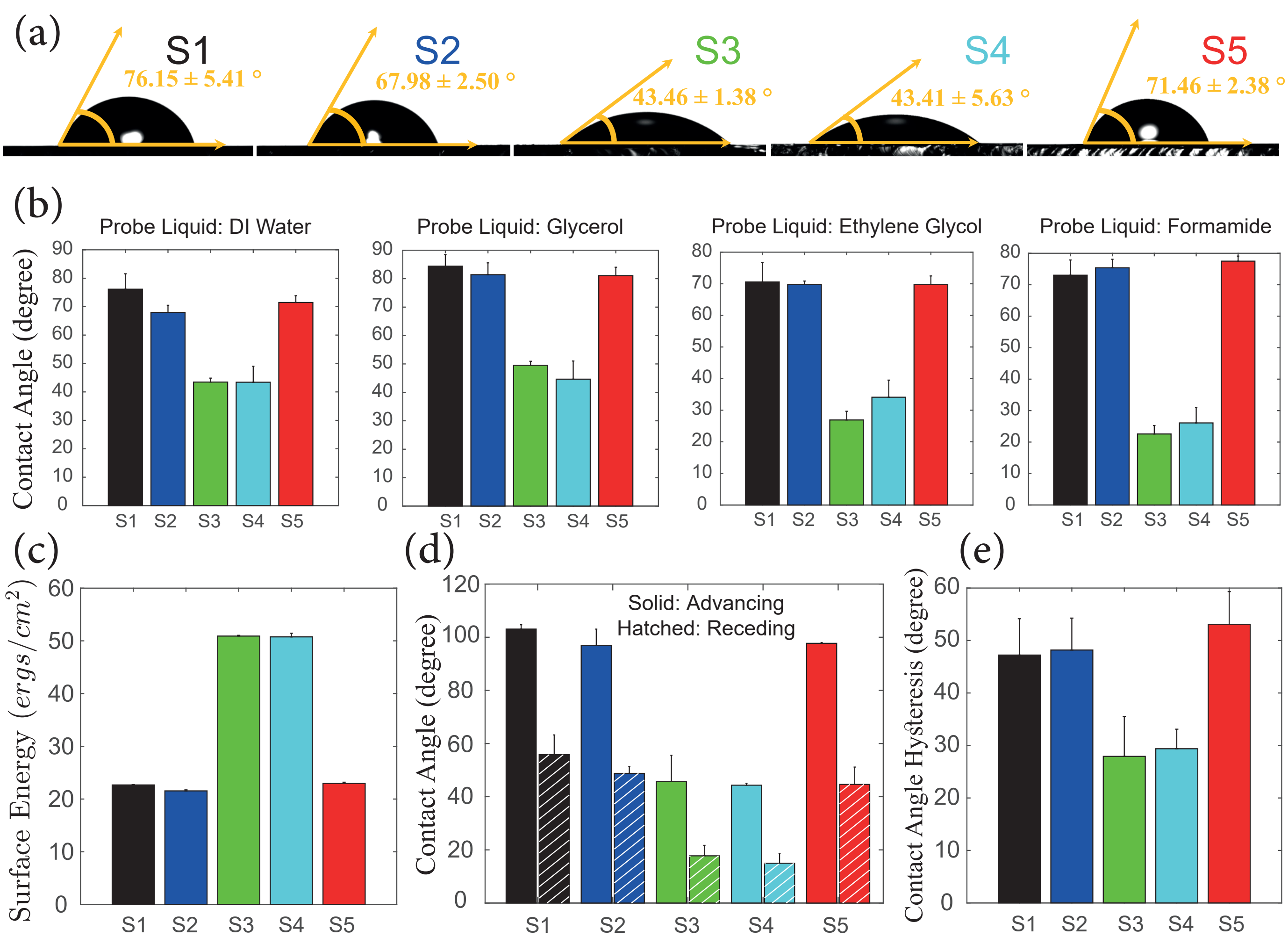

Fig. 3 a) Images of DI water dropped on the sample surfaces S1-S5 showing their wettability, b) measured static contact angles between the sample surfaces and the 4 probe liquids used in the Sessile drop test, c) the surface free energy of the samples calculated from the measured contact angles, d) the advancing and receding contact angles of the samples for DI water, and e) the contact angle hysteresis of the samples, which was calculated as the difference between the advancing and receding contact angles.

room inside a dust-free sample box. A special care was given to keep the surfaces clean and untouched. The results of the AFM measurements are tabulated in Table III. These results are the mean values and standard deviations of 2 measurements for each sample. Fig. 4 presents the topographic 2D images (a), the average 1D vertical power spectrum densities (b), and the average line scans (c) of the sample surfaces.

IV. Discussion

The results of our tactile perception experiments show that the participants can successfully discriminate the samples based on the tactile cues alone. According to the results reported in Fig. 1b, we conclude that the sample surface S5 (G3) felt least resistive to the sliding finger of participants, followed by the samples in group G1 (S1 and S2). In general, the samples in group G2 (S3 and S4) are felt most resistive to the sliding finger. Since all the surfaces in our study are extremely smooth with surface roughness magnitudes in the order of a few nanometers as measured by AFM and there is no clear correlation between the AFM metrics (see Table. III) and the results of our tactile perception study, the tactile discrimination ability of the participants is more likely due to the surface chemistry and not the surface topography. Our results are inline with those of the earlier studies suggesting surface chemistry could play a role in tactile perception of smooth surfaces ([13], [14]).

Our physical measurements performed with the same samples support the results of our tactile perception experiments. Our friction

TABLE III Results of surface roughness measurements for the samples used in this study

Parameter	Definition	S1	S2	S3	S4	S5	Unit
S_q	RMS Roughness	0.33 ± 0.02	0.60 ± 0.04	0.46 ± 0.02	0.15 ± 0.02	0.37 ± 0.03	nm
S_a	Average Roughness	0.26 ± 0.01	0.44 ± 0.05	0.36 ± 0.02	0.11 ± 0.01	0.29 ± 0.02	nm
S_{sk}	Skewness	0.02 ± 0.04	0.48 ± 0.40	0.57 ± 0.12	-0.26 ± 0.03	0.14 ± 0.07	-
S_{ku}	Kurtosis	3.10 ± 0.002	5.86 ± 2.34	4.09 ± 0.46	3.48 ± 0.06	3.70 ± 0.30	-
S_z	Maximum Height	2.83 ± 0.03	7.07 ± 1.27	5.45 ± 0.03	1.60 ± 0.15	3.91 ± 0.15	nm

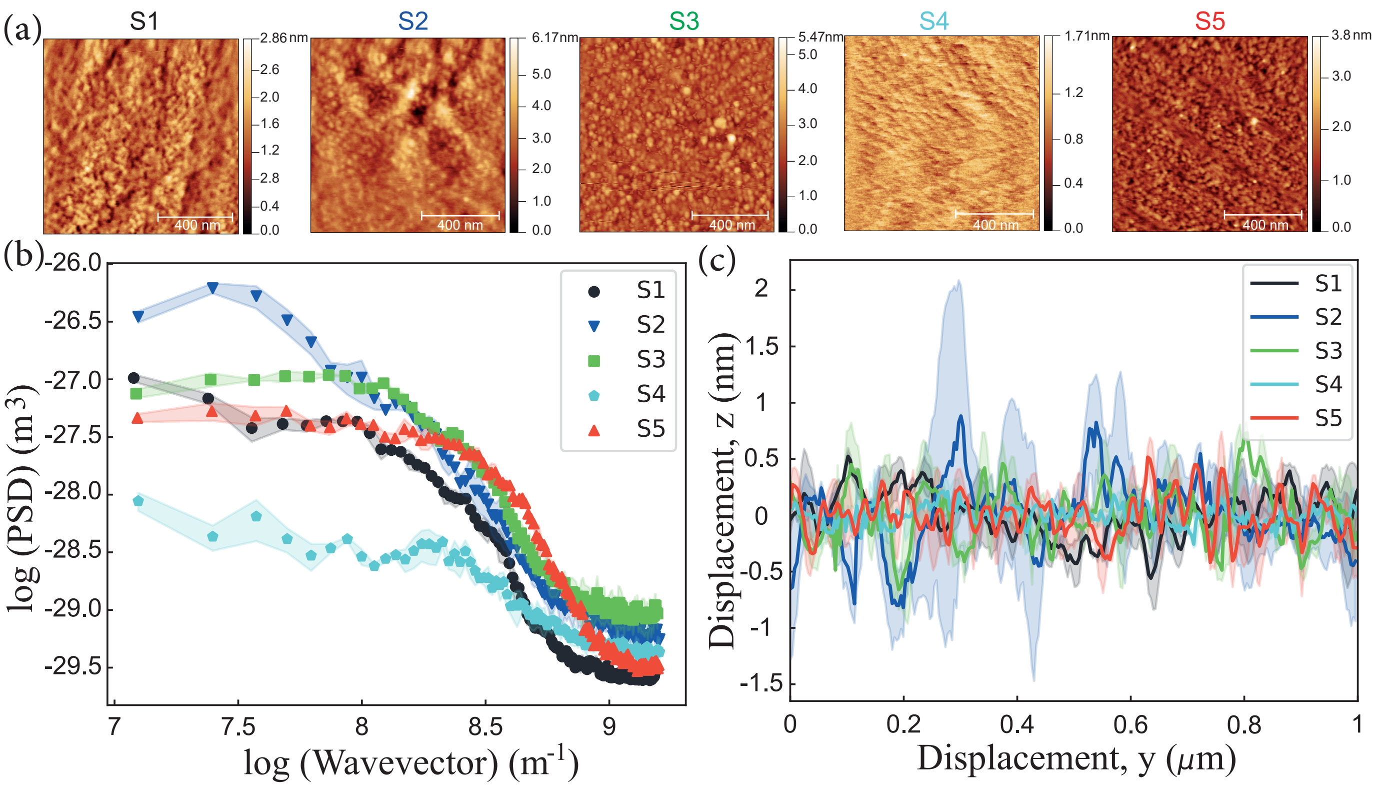

Fig. 4 Results of AFM measurements performed at 2 sites on each sample surface. a) Topographic 2D images, b) average 1D vertical power spectrum densities with their corresponding standard deviations (shaded areas), and c) average line scans with their standard deviations (shaded areas).

measurements reveal that the samples in group G2 (S3 and S4) have higher CoF compared to those in group G1 (S1 and S2), and group G3 (S5) while the differences between G1 and G3 are not significant. However, we should mention that a small amount of vaseline was applied to the surfaces and the interface was in mixed boundary lubrication, and hence dry friction models might not be sufficient to describe the contact mechanics between the finger and surfaces. Similarly, the results of the Sessile drop tests show that the samples in G2 (S3 and S4) make significantly lower contact angles with the 4 liquids used in the measurements, indicating higher surface energies. Again, the differences between G1 (S1 and S2) and G3 (S5) are not significant. The results also show that the contact angle hysteresis for the samples in G1 and G3 are higher than those in G2. This result suggests that either the surface roughness is higher or the surface chemistry is inhomogeneous for the samples in G1 and G3, compared to G2. Since the surface roughness of our samples is very low (in the order of a few nanometers), it is more likely that inhomogeneous surface chemistry affects the tactile perception of the participants.

All these results suggest that the type of coating material used at the top layer of the surfaces has an influence on our tactile perception (though the coating layer below the top one does not seem to have any influence). In this regard, the sample with Zirconium Oxide coating (S5) appears to be the least resistive to sliding finger, followed by the samples with Titanium Oxide coatings (S1, S2). The samples with Silicon-based coatings (S3, S4) are the most resistive.

V. Conclusion

The results of our study show that human finger is an exceptionally good sensor capable of detecting contact forces at nanometer scale to discriminate surface chemistry. Although a few earlier studies, similar to ours, have already investigated human tactile perception of extremely smooth surfaces having an average roughness at nanometer levels, the contact mechanism underlying our ability to discriminate these surfaces is still not fully understood. Moreover, the literature is missing physical measurements supporting human tactile perception studies to reveal the details behind this discrimination ability. For example, although it is known that adhesion plays a major role in our tactile interactions with smooth surfaces, we still do not know how much each adhesive force component (such as van der Waals, electrostatic, hydrogen bonding) contributes to the sliding friction between the finger and a smooth surface coated with a certain type of material. Furthermore, finger moisture, humidity and temperature of the air, and surface treatment applied to the coated surface to make it hydrophobic and/or oleophobic are the additional factors that contribute to the contact interactions between finger and a smooth surface, which require a systematic and interdisciplinary approach involving tribology, psychophysics, and material science to tackle them. We believe that our work constitutes the initial steps towards this aim.

Appendix A Supplementary Data

The dataset can be accessed from IEEE Dataport doi: https://dx.doi.org/10.21227/bw4t-g724.

Acknowledgment

The authors are grateful to Amir Motallebzadeh for his help with the surface roughness measurements performed by AFM at Koc University Surface Science and Technology Center. We also acknowledge the use of contact angle meter at n^{2}STAR-Koc University Nanofabrication and Nanocharacterization Center for Scientific and Technological Advanced Research. Finally, we acknowledge the financial support provided by the Scientific and Technological Research Council of Turkey (TUBITAK) under contract number 117E954 for the development of set-up presented in Fig. 2.

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