

Contact Mechanics for Electrovibration

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Contact Mechanics for Electrovibration

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This is to certify that I have examined this copy of a doctoral dissertation by

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ABSTRACT

The understanding and control of human skin contact against technological substrates is the key aspect behind the design of several electro-mechanical devices. Among these, surface haptic displays that modulate the friction between the human finger and touch surface are emerging as new user interfaces. One such modulation can be achieved by applying an alternating voltage to the conducting layer of a capacitive touchscreen, in order to control electroadhesion between its surface and the finger-pad. However, our knowledge and understanding on the underlying contact mechanics is very limited. We conducted an experimental study to investigate the contact mechanics between the human finger and a touchscreen under electrovibration using a robotic set-up and an imaging system. The results show that the coefficient of friction increases under electrovibration as expected, but the apparent contact area is significantly smaller during full slip when compared to that of no electrovibration condition. We speculate that the main cause of the increase in friction is an increase in real contact area and the reduction in apparent area is due to stiffening of the finger skin in tangential direction. We also present the adverse effect of fingertip skin moisture on electrovibration. We speculate that high moisture decreases the electrical impedance of the interfacial gap between the finger and the touchscreen, leading to a smaller increase in frictional force under electrovibration. Finally, we use a mean field theory based on multiscale contact mechanics to investigate the effect of electroadhesion on sliding friction, and the dependency of the finger–touchscreen interaction on the applied voltage and other physical parameters.

ÖZETÇE

Son zamanlarda geliştirilen dokunsal geri beslemeli dokunmatik ekranlar sayesinde, insan parmağı ve ekranın yüzeyi arasındaki sürtünmeyi kontrol etmek mümkün hale gelmiştir. Bu tür ekranlarda sürtünmeyi değiştirmek için dokunmatik ekranın iletken katmanına alternatif bir voltaj uygulanır ve parmak ile yüzey arasındaki elektrostatik kuvvetlerden doğan bir yapışma sağlanır. Bu etkileşimin mekaniği konusunda sınırlı bilgiye sahibiz. Dokunmatik ekrana elektro-titreşim vererek, ekran ile insan parmağı arasındaki temas mekaniğini incelemek için robotik bazlı bir görüntüleme sistemi kullandık ve deneysel çalışmalar yaptık. Sonuçlar, sürtünme katsayısının beklediği gibi uygulanan voltajın genliği ile arttığını, ancak kayma esnasında görünür temas alanının elektro-titreşimin olmadığı durumla karşılaştırıldığında önemli ölçüde azaldığını gösterdi. Sürtünmedeki artışın parmağın temas ettiği gerçek alanın artışından, görünür alandaki azalmanın ise parmak derisinin hareket yönünde sertleşmesinden kaynaklandığını öngörüyoruz. Ayrıca, parmaktaki nemin elektro-titreşim üzerinde negatif etkileri olduğunu da gözlemledik. Bunun sebebini, yüksek nemden dolayı parmak ile ekranın yüzeyi arasındaki hava boşluğunun elektriksel empedansının azalmasına bağlıyoruz. Son olarak, elektro-titreşimin, ekran ile parmak arasındaki sürtünme kuvvetine etkisini ve bu etkinin uygulanan voltaj ve diğer fiziksel parametrelerle ilişkisini, temas mekaniğine dayalı bir model üzerinden inceliyoruz.

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Chapter 1

INTRODUCTION

Touchscreen, a display screen that is sensitive to the touch of a finger or stylus, has been available for nearly half a century. It has been widely used on ATM machines, retail point-of-sale terminals, game consoles, car navigation systems, medical monitors, and industrial control panels. After the introduction of touchscreen-based mobile devices in the late 2000s, the capacitive touchscreen has become widely popular on handheld devices such as personal computers, tablets, personal digital assistants, smart watches, and e-book readers. Today, the touchscreen is one of the easiest to use and most intuitive of all computer interfaces, which allows users to naturally and directly interact with what is displayed (text, pictures and other data), rather than using a traditional keyboard or mouse. One important effort to make this interaction more powerful is to provide effective, feasible and inexpensive tactile feedback to the user. In this regard, there are two major techniques, namely ultrasonic and electrostatic actuation, for displaying tactile feedback through a touch surface. In both techniques, the aim is to modulate the frictional forces between finger pad and the surface, though their working principles are different. When a touch surface is actuated at an ultrasonic resonance frequency, friction is reduced between the surface and finger [Watanabe and Fukui, 1995]. On the contrary, in electrostatic actuation, a voltage is applied to the conductive layer of a surface capacitive touchscreen to generate an electroadhesive force between its surface and a finger sliding on it, which leads to an increase in frictional forces applied to the finger opposite to the direction of movement [Xu et al., 2011, Vardar et al., 2017, Meyer et al., 2013]. This thesis focuses on the latter technique, electroadhesion.

1.1 Problem Definition and Approach

The electrical attraction between a charged surface and human skin was discovered by Johnsen and Rahbek [Johnsen and Rahbek, 1923] in 1923. Later, in 1953 Mallinckrodt [Mallinckrodt et al., 1953] reported an increase in the friction during touch when an alternating voltage is applied to an insulated aluminum plate. He observed that the input voltage signal creates an alternating electrostatic force that periodically attracts and releases the finger from the surface, producing a friction-like rubbery sensations when the finger moves on the surface.

When an alternating electric potential is applied to the conductive layer of a touchscreen, the insulating layer on the glass plate and the finger are polarized by induction (i.e., charges of opposite sign are accumulated on the surfaces at the contacting interface). Thus, an electrostatic attraction force due to “electroadhesion”, is generated between the finger and the counter surface in the normal direction; which increases the sliding friction between the finger and the glass plate. This phenomenon was referred to as “electrovibration” by Grimnes, [Grimnes, 1983] who also reported that the generated tactile sensation depends on the roughness and moisture of the finger.

The human skin is highly sensitive to variations in friction force. The nature of the contact interface and involved materials (e.g., surface topographies, contamination films, and the atomic and molecular characteristics) strongly influence the sliding friction [Persson, 2000, Gnecco and Meyer, 2015, Israelachvili, 2011] in addition to the external conditions such as temperature, humidity, mechanical vibrations and electric fields. For example, the friction force generated by the electrostatic attraction depends on the frequency, waveform and the amplitude of the applied electric potential [Xu et al., 2011, Wijekoon et al., 2012, Vardar et al., 2017]. A rich set of tactile effects can be potentially generated by varying these parameters [Kim et al., 2013].

A surface capacitive touch screen has a single layer of conductive ITO (indium tin oxide) placed above a glass substrate and covered by an insulator layer (Figure 1.1). When a voltage is applied to this conductive layer, a uniform and attractive

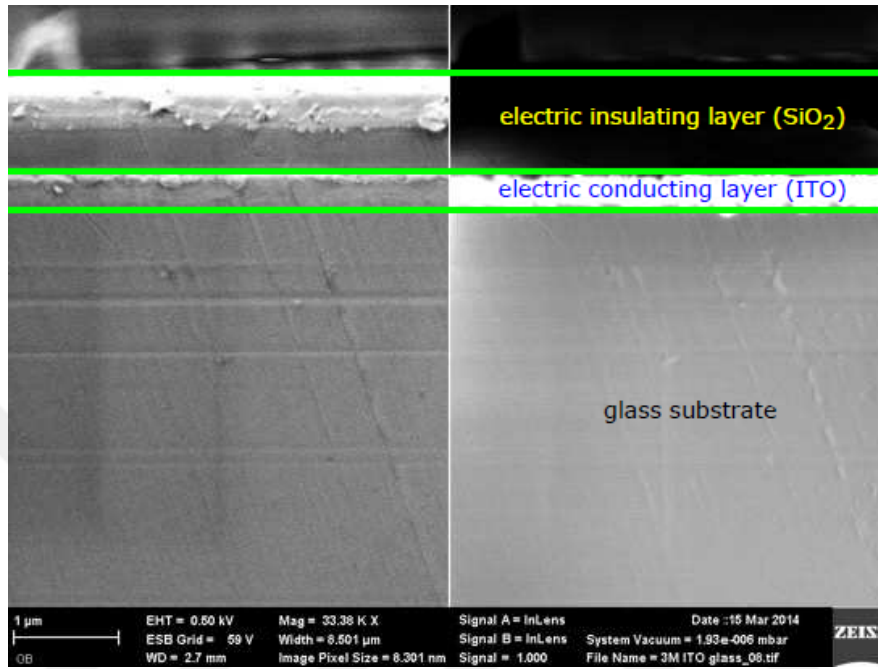


Figure 1.1: Cross section image of a capacitive touchscreen (Model: SCT-3250, 3M) obtained by field emission scanning electron microscopy (FESEM, Zeiss Ultra Plus).

electrostatic force field is generated between finger pad and the touch screen in the direction normal to its surface. Although the magnitude of this electrostatic force is small relative to the normal force applied by the finger, it results in a perceivable frictional force in tangential direction when the finger pad slides on the touch screen (Figure 1.2). Although the technology for generating tactile feedback on a touch screen via electrovibration is already in place and straightforward to implement, our knowledge on the underlying contact mechanics and tactile perception are both highly limited. In particular, we still do not know the exact mechanism leading to an increase in tangential frictional forces under electrovibration.

To estimate the electrostatic forces between finger pad and touch screen, models based on parallel-plate capacitor theory have been proposed (see the summary in Vodlak et al., 2016 [Vodlak et al., 2016]). These models assume a constant air gap between two surfaces and ignore the rounded shape of the finger pad and the asperities on its surface. On the other hand, to estimate the frictional forces in tangential

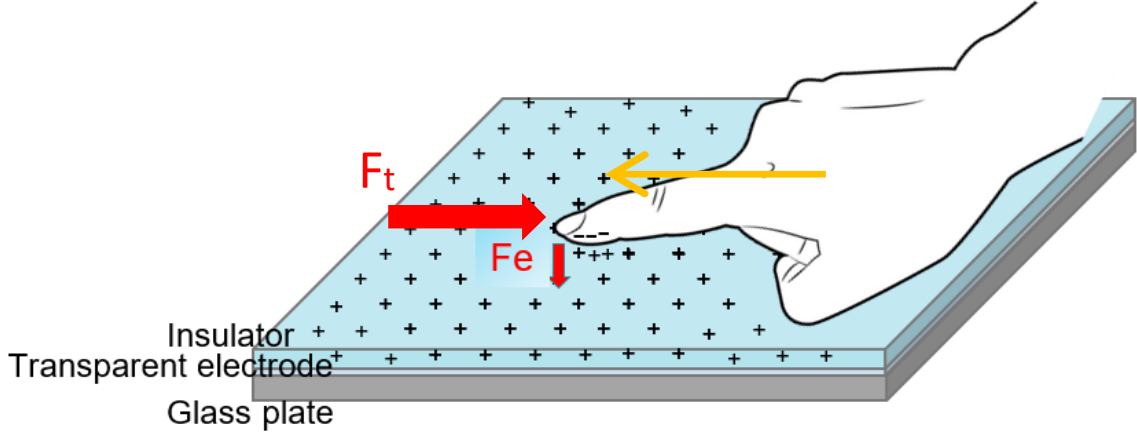


Figure 1.2: Schematic of the friction between the touch screen and the skin of the finger moving on it.

direction during sliding, the Coulomb model of friction utilizing a constant coefficient of dynamic friction between finger pad and touch screen has been used so far [Meyer et al., 2013]. The increase in tangential force has been explained by simply adding the force due to electrostatic attraction to the normal force applied by the finger, $F_t = \mu(F_n + F_e)$, where μ is the friction coefficient, F_t , F_n , and F_e represent the tangential, normal, and electrostatic forces, respectively. However, friction of human skin against smooth surfaces is governed by adhesion model of friction [Duvefelt et al., 2016, Johnson et al., 1993, Derler et al., 2009], which depends on interfacial shear strength and real area of contact. The frictional force due to adhesion is given by $F_t = \tau A_r$, where τ is the interfacial shear strength and A_r is the real area of contact. It is highly difficult to measure or estimate the real area of contact, which varies nonlinearly with the normal force. In earlier studies, the real contact area has been taken as the contact area of finger ridges, A_{ridge} , which is smaller than the apparent contact area, A_{app} , estimated by the fingerprint images, using the boundaries of finger pad in contact with surface [Dzidek et al., 2017]. On the other hand, if the Persson's contact theory is considered [Persson, 2000], A_r is, in fact, much smaller than A_{ridge}

since only the finger asperities at finer resolution make contacts with the surface. For the interfacial shear strength of skin, Adams et al. [Adams et al., 2007a] adopted the model from an early study on glassy organic polymers suggesting that τ increases linearly with the mean contact pressure [Briscoe and Tabor, 1978] as $\tau = \tau_0 + \alpha p_r$, where τ_0 is the intrinsic shear strength, α is the pressure coefficient, and $p_r = F_n/A_r$ is the real contact pressure. Hence, the adhesive friction can be expressed as $F_t = \tau_0 A_r + \alpha F_n$. Briscoe and Tabor [Briscoe and Tabor, 1978] suggested that for polymers, the pressure coefficient α contributes to friction only when the contact pressure p_r is higher than 10^9 Pa which is much lower and around 10^6 Pa for the contact between finger pad and touchscreen. Hence, under the assumption that α does not vary much when electrovibration is OFF or ON for the same normal load and sliding velocity, then the main factors affecting the adhesive friction are intrinsic shear strength (τ_0) and real contact area (A_r).

1.2 Contribution

In this thesis, we first investigate the increase in adhesive frictional force due to electrovibration. We show that during the transition from a stuck to a fully slipping contact, the frictional force acting on the finger is similar when electrovibration is OFF or ON, suggesting that intrinsic shear strength (τ_0) does not change. However, we observed that tangential frictional force increases significantly after full slip when electrovibration is ON. We claimed that this increase is due to an increase in real contact area. We support this claim by presenting the results of experiments conducted with six human subjects at a constant finger sliding velocity under three different normal loads. We then investigate human tactile detection threshold for AC and DC voltage signals applied to the touchscreen. We showed that the detection threshold under AC condition is significantly lower than that of the DC condition even though we observed no significant difference in contact mechanics between these two conditions. Hence, we argue that the fluctuating nature of the tactile stimuli, which is mainly detected by Pacinian channel, is important for the tactile perception

of electrovibration. We also showed the adverse effect of fingertip skin moisture on tactile perception of electrovibration.

In the second study, the dependency of the finger–touchscreen interaction on the applied voltage, and on several other contact parameters, was investigated using a mean field theory based on multiscale contact mechanics. For the experimental measurements, a tribometer was developed to move the index finger of an experimenter back and forth on the touchscreen using a motorized slider. The friction force at the sliding speed of $v = 50$ mm/s was recorded as a function of the normal force, varied incrementally 0.2 N and 2 N. The amplitude of the voltage signal applied to the conductive layer of the touchscreen at 125 Hz was varied between $V_0 = 0$ V to $V_0 = 200$ V (with an increment of 25 V). The experimental results were compared to those produced by the theory. Also, the dependency of the electroadhesion friction on the frequency of the oscillating electric potential was investigated using the proposed theory. Finally, a discussion on the origin and enhancement of the friction due to electroadhesion is provided, along with the corresponding design criteria; and also the limitations of the study and the challenges ahead are discussed.

Chapter 2

CONTACT EVOLUTION AND TACTILE PERCEPTION UNDER ELECTROVIBRATION

2.1 *Summary*

In this chapter, we investigated the contact mechanics between the human finger and a touchscreen under electrovibration using a robotic set-up and an imaging system. An experimental study was conducted with 6 subjects. The frictional forces acting on the subjects' index finger and the apparent contact area of their finger pad were measured for different 3 different normal loads at a constant finger speed during transition from stick to full slip and when electrovibration was OFF and ON. The results of the study showed that the coefficient of friction increased under the ON condition, as expected, but surprisingly the apparent contact area was significantly smaller during full slip when compared to that of the OFF condition. On the other hand, the evolution of tangential frictional force and the apparent contact area followed a similar profile for the OFF and ON conditions before the full slip, suggesting that the electrovibration has no effect on contact mechanics before the full slip suggesting that intrinsic shear strength (τ_0) does not change. Under the light of above observations, we speculated that the main cause in increase in tangential frictional force under electrovibration during full slip is due to an increase in real contact area. We argue that the increase in frictional forces under electrovibration causes a further reduction in apparent contact area due to nonlinear stiffening of finger in tangential direction, which results in an increase in real contact area due to the rounded geometry of fingerpad and existence of its asperities. We then investigated human tactile detection threshold for AC and DC voltage signals applied to the touchscreen. We show that the detection

threshold under AC condition is significantly lower than under the DC condition even though we observed no significant difference in contact mechanics between these two conditions. Hence, we argue that the fluctuating nature of the tactile stimuli, which is mainly detected by Pacinian channel, is important for the tactile perception of electrovibration. Finally, we showed the adverse effect of fingertip skin moisture on tactile perception under electrovibration and supported this observation with contact mechanics measurements.

2.2 Methods

2.2.1 Set-up

The contact mechanics experiments were performed with the help of a robotic system to maintain a constant normal contact force between the finger and a touch screen while ensuring a constant sliding speed between the finger and the touch screen (see Figure 2.1). A surface capacitive touch screen (SCT3250, 3M Inc.) was cut in dimensions of 10x10 cm and attached to the end-effector of the robot (DENSO HS4535G) along with two force sensors (Mini-40, ATI) to measure contact forces between the index finger of user and touch screen in tangential and normal directions. The measured normal force was fed back to a PID controller to keep the normal contact force applied by the user constant. The tangential force was measured when electrovibration was OFF and ON. To turn the electrovibration on, the touch screen was stimulated with a voltage signal generated by a signal generator (Model 182A, Wavetek) and augmented by an amplifier (E-413, Physik Instrumente). The subject's index finger was fixed in a support to maintain a constant angle of contact (20 degrees) with the touch screen. The end-effector position was servo-controlled to translate the touch screen at a constant speed during the experiments. The fingerprint images were acquired at 200 Hz by an imaging system that includes a light source, mirrors, and a high-resolution camera (MC1362, 1280x1024 pixels, Mikrotрон Eosens). The details of the set-up and the data collection methods are available in Delhayе et al. [Delhayе et al., 2014].

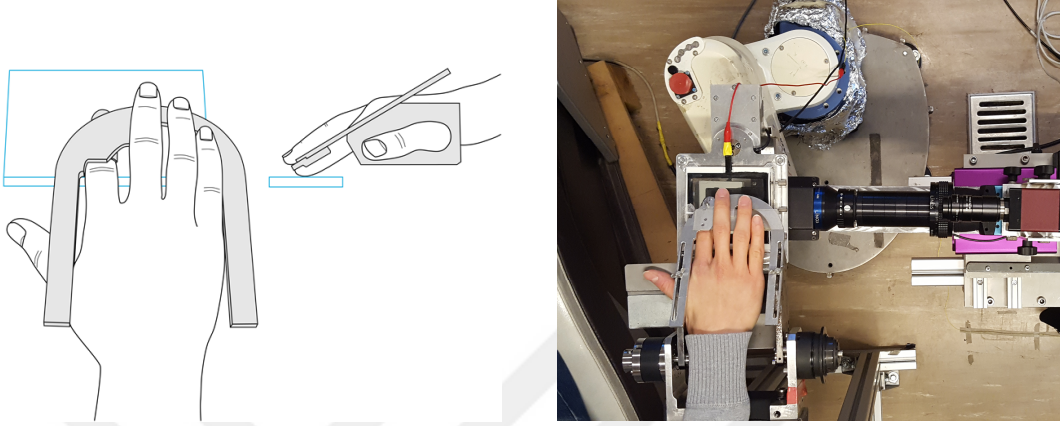


Figure 2.1: Experimental set-up used for contact mechanics experiments.

The main components of the experimental set-up used for the perception experiments were a) the touch screen used in the contact mechanics experiments, which was placed above an LCD monitor, b) a high-resolution force sensor (Nano 17, ATI Inc.) placed below the monitor to measure contact forces, and c) an IR frame, placed above the touch screen to detect finger position. The touch screen was excited by a voltage amplifier (E-413, PI Inc.) connected to a DAQ card (PCI-6025E, National Instruments Inc.) (see Figure 2.2). The details of the set-up and the data collection methods are available in Vardar et al. [Vardar et al., 2017].

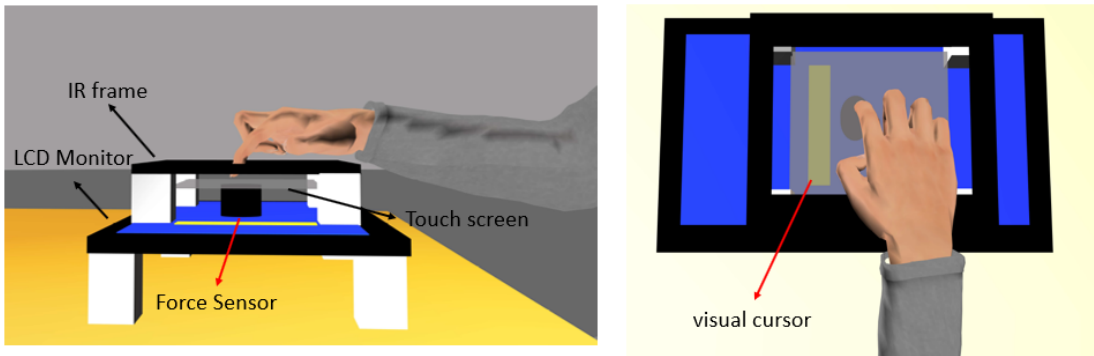


Figure 2.2: Schematic of the experimental set-up used for the perception experiments.

2.2.2 Participants

The contact mechanics experiments were conducted with 6 adult subjects having an average age of 32.3 years (SD: 15.1). The subjects used the index finger of their right hand during the experiments. The ethics committee on human research of Université catholique de Louvain approved the study. The perception experiments were conducted with 10 adult subjects (4 females and 6 males) having the average age of 29.4 years (SD: 5.9). The subjects read the consent form and approved it before the experiments. The form was approved by Ethical Committee for Human Participants of Koc University. The subjects washed their hands with soap, rinsed with water, and dried them in room temperature before the experimentation. Moreover, the touch screen was cleaned by alcohol before each experiment.

2.2.3 Experimental Procedure

During the contact mechanics experiments, the subjects placed their index finger into the support to make a constant angle of contact with the touch screen. The robot was commanded to move the touch screen with a constant velocity of 20 mm/s while keeping the normal force constant. The moisture level of subject's fingertip skin was measured by a Corneometer (CM 825, Courage - Khazaka Electronic) before the first and after the last trial of each experiment. To ensure a good contrast in captured images of the contact area, a small amount of liquid Vaseline oil was applied to the imaged fingertip before starting each experiment. Then, the tangential and normal forces were recorded as a function of displacement under OFF and ON EV conditions. To activate electrovibration (ON condition), a sinusoidal voltage, at a frequency of 125 Hz with an amplitude of 200 Vpp, was applied to the touch screen. The experiments were conducted for 3 different normal forces (0.5, 1, and 2 N). Hence, each subject performed 30 trials (3 normal forces x 1 finger velocity x 2 experimental conditions x 5 repetitions). To investigate human tactile detection threshold for AC and DC voltage signals, we conducted absolute detection experiment using 2AFC paradigm as implemented in Vardar et al. [Vardar et al., 2017]. During the experiments, subjects

were asked to move their index fingers on the touch screen from left to right twice for a distance of 100 mm in each trial. The tactile stimulus was displayed only in one of the passes, which was randomized to eliminate any bias. Subjects were asked to determine the pass (interval) in which they felt a tactile effect. In order to regulate their scan speed, a visual cursor moving with a speed of 20 mm/s was displayed on the LCD monitor and the subjects were asked to follow it with their finger (see Figure 2.2). In each trial, average normal force and scanning speed were recorded (see Figures 2.3 and 2.4). The average normal force for all participants was 0.332 N (SD: 0.073) and 0.334 N (SD: 0.084) under AC and DC conditions, respectively. The average speed for all participants was 20.06 mm/s (SD: 0.87) and 20.01 mm/s (SD: 1.34) under AC and DC conditions, respectively. If the normal force or the scan speed of a participant was not in the desired range (0.1-0.6 N; 10-30 mm/s), the trial was repeated until a measurement within the range was obtained.

Subjects put on headphones playing white noise to prevent their tactile perception from being affected by any external auditory cue. Before starting the experiments, participants were given instructions and asked to complete a training session. This training session enabled participants to adjust their finger scanning speed and normal force before the actual experimentation. The amplitude of voltage signal applied to the touch screen (and hence the magnitude of the tactile stimulus) was altered using the three-up/one-down adaptive staircase method as described in Vardar et al. [Vardar et al., 2017]. In order to determine the detection thresholds for AC signal at 125 Hz and the corresponding DC signal, the experiment started with voltage amplitude of 200 Vpp and 70.7 Vrms, respectively. It is worth noting here that the initial voltage amplitude provided sufficiently high intensity for all subjects under the AC condition, but not under the DC condition. However, for safety reasons, the maximum voltage was limited to 100 Vrms in DC experiments. If a participant gave three correct responses (not necessarily consecutive), the voltage level was decreased by 5 dB. If a participant gave one incorrect response, the voltage level was increased by 5 dB. The change in response from correct to incorrect or vice versa was counted as

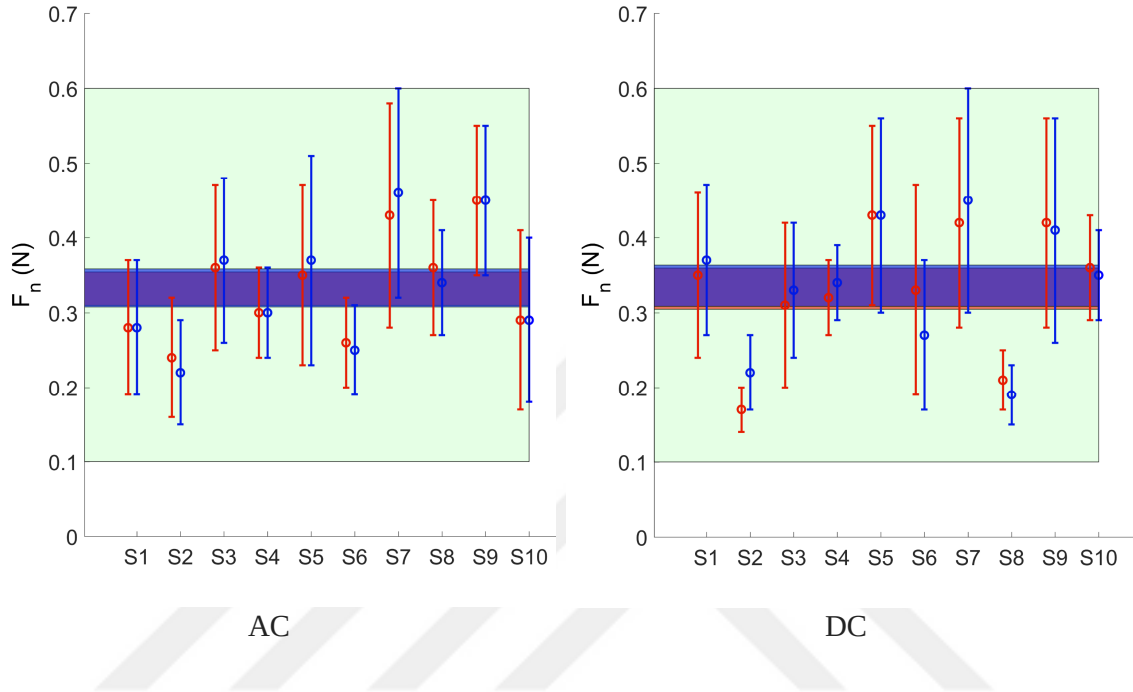


Figure 2.3: The average normal force applied by each participant during threshold experiments and their standard deviations (excluding out of range values, which were observed in 37 trials out of 539 trials under AC condition and 26 trials out of 274 trials under DC condition). The error bars represent the standard errors of the means (Red and blue colors are used for ON and OFF conditions, respectively). The average normal force for all participants was 0.332 N (SD: 0.073) and 0.334 N (SD: 0.084) under AC and DC conditions, respectively. For out of range measurements, the trial was repeated. The range for the desired normal force is marked as the light green area.

one reversal. After one reversal, the step size was decreased to 1 dB. The experiments were stopped automatically if the reversal count was five at the ± 1 dB level (Figure 2.11a, b). The threshold was calculated as the mean of the last five reversals. The moisture level of each subject was measured by a Corneometer (CM 825, Courage - Khazaka Electronic) 4 times just before and right after the experiment and the average of 8 measurements was reported for each subject (see Table 2.1).

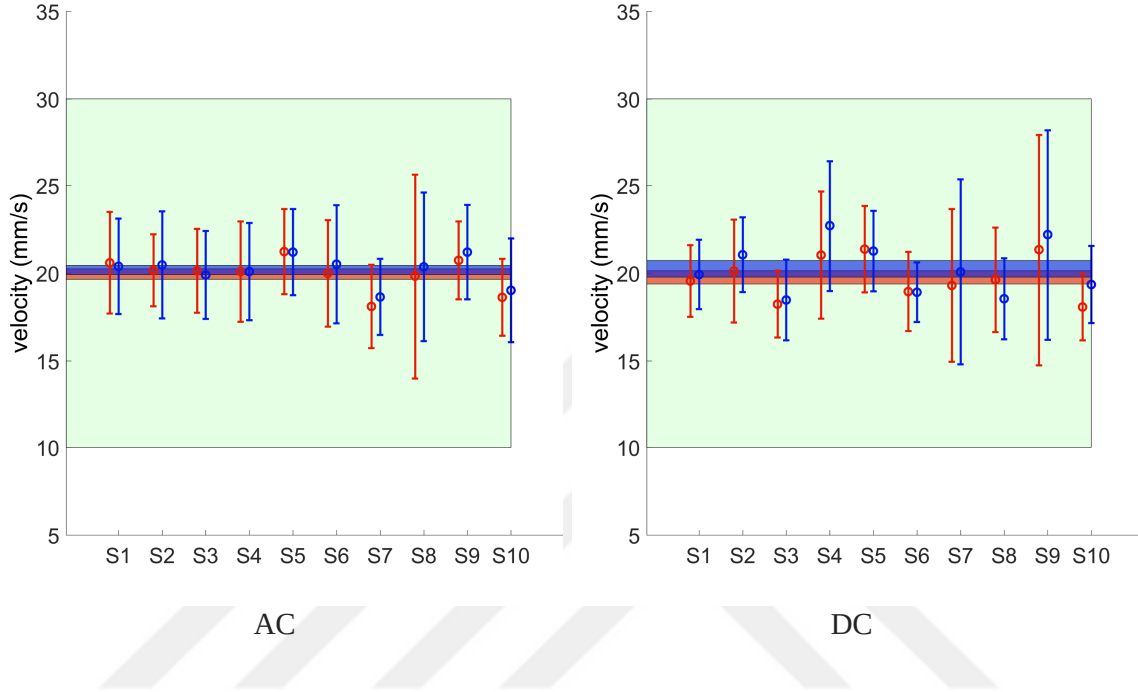


Figure 2.4: The average finger speed of each participant measured during threshold experiments and their standard deviations (excluding out of range values, which were observed in 11 trials out of 539 trials under AC condition and 6 trials out of 274 trials under DC condition). The error bars represent the standard errors of the means (Red and blue colors are used for ON and OFF conditions, respectively). The average speed for all participants was 20.06 mm/s (SD: 0.87) and 20.01 (SD: 1.34) mm/s under AC and DC conditions, respectively. For out of range measurements, the trial was repeated. The range for the desired velocity is marked as the light green area.

2.3 Results

2.3.1 Experiment 1. Contact Evolution

Before Full Slip: To quantify the proportion of contact area slipping against the glass, feature points were sampled within the contact area and tracked using optical flow. The onset of full slip was defined as the moment when all tracked points were moving relative to the glass. This corresponds to a stick ratio of zero ($SR=0$), where SR is defined as the proportion of the contact moving with the glass, i.e. the ratio of the no-slip area to the initial apparent contact area. In this formalism, $SR=1$ for a

stuck contact and decreases down to 0 during the transition from stick to slip. Figure 2.5a shows the evolution of SR as a function of the tangential force for a normal force of 2 N when electrovibration (EV) was OFF and ON. We performed three-way analysis of variance (ANOVA) with repeated measures on the tangential force using electrovibration (ON, OFF), normal force ($F_n = 0.5, 1 \text{ N}, 2 \text{ N}$), and the stick ratio ($SR = 1, 0.75, 0.50, 0.25$) as the main factors. We did not observe a significant difference between the tangential forces for the OFF and ON EV conditions ($F(1,5) = 1.54, p = 0.27$) though the normal force and the stick ratio significantly affected the tangential force, as expected.

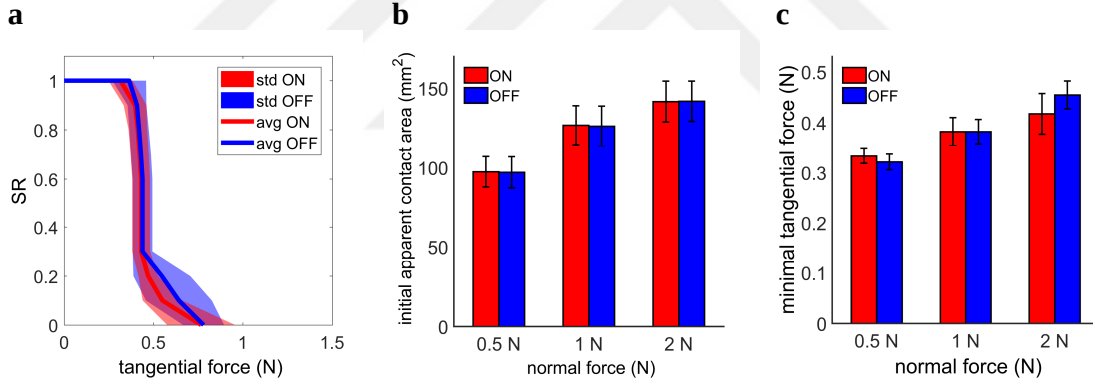


Figure 2.5: (a) The evolution of the stick ratio of one subject as a function of tangential force for a normal force of 2 N. The solid lines represent the average of 5 trials while the shaded areas around them represent the standard deviations. (b,c) Mean values (average of 6 subjects) of the initial apparent contact area and minimal tangential force to start a slip as a function of normal force. The error bars represent the standard errors of the means.

Figure 2.5b depicts the initial (no motion) apparent contact area (A_0) of subjects' finger pad for different normal forces (0.5 N, 1 N, 2 N) under the OFF and ON EV conditions. We analyzed the results using two-way ANOVA with repeated measures. We did not observe a significant difference between the initial apparent contact areas for the OFF and ON EV conditions ($F(1,5) = 0.254, p = 0.635$). However, the effect of normal force on the initial apparent contact area was significant ($F(2,10)$

$= 146.529$, $p < 0.001$), as expected. There was no statistically significant interaction between electrovibration and normal force.

After Full Slip: Figure 2.6a shows the normalized apparent contact area (A_{app}/A_0) as a function of finger displacement for each subject. The normalization helps to compare the change in apparent contact area across subjects. We observed that the apparent contact area of each subject reached a steady-state value after full slip for OFF and ON EV conditions. Figure 2.6c displays the fingerprint images of subject 4 (S4). The steady-state value of the apparent contact area (A_{ss}) was calculated by using the image data corresponding to the displacement of last 5 mm and then the percent reduction in A_{ss} with respect to the initial apparent contact area (A_0) was reported in Figure 2.6b. We observed that the percent reduction in A_{ss} (with respect to A_0) was larger when electrovibration was ON. We analyzed the results using two-way ANOVA with repeated measures. The ANOVA results showed that both electrovibration ($F(1,5) = 60.71$, $p = 0.001$) and normal force ($F(2,10) = 16.793$, $p = 0.001$) had a significant effect on the percent change in A_{ss} with respect to A_0 . There was no statistically significant interaction between electrovibration and normal force.

Figure 2.7a shows the coefficient of friction μ as a function of finger displacement for each subject. We observed that the coefficient of friction reached to a steady-state value (μ_{ss}) for OFF and ON EV conditions. Figure 2.7b shows the mean values of μ_{ss} (estimated from the friction data corresponding to the finger displacement of last 5 mm) for 3 different normal forces. We observed that the μ_{ss} increased under electrovibration for all normal forces. We analyzed the results using two-way ANOVA with repeated measures. The ANOVA results showed that both electrovibration ($F(1,5) = 21.659$, $p = 0.007$) and normal force ($F(2,10) = 34.413$, $p < 0.001$) had a significant effect on the μ_{ss} . There was a statistically significant interaction between electrovibration and normal force ($F(2,10) = 11.248$, $p = 0.003$). The effect of electrovibration on the μ_{ss} for each normal force was further analyzed by paired t-tests and found significant ($p < 0.05$).

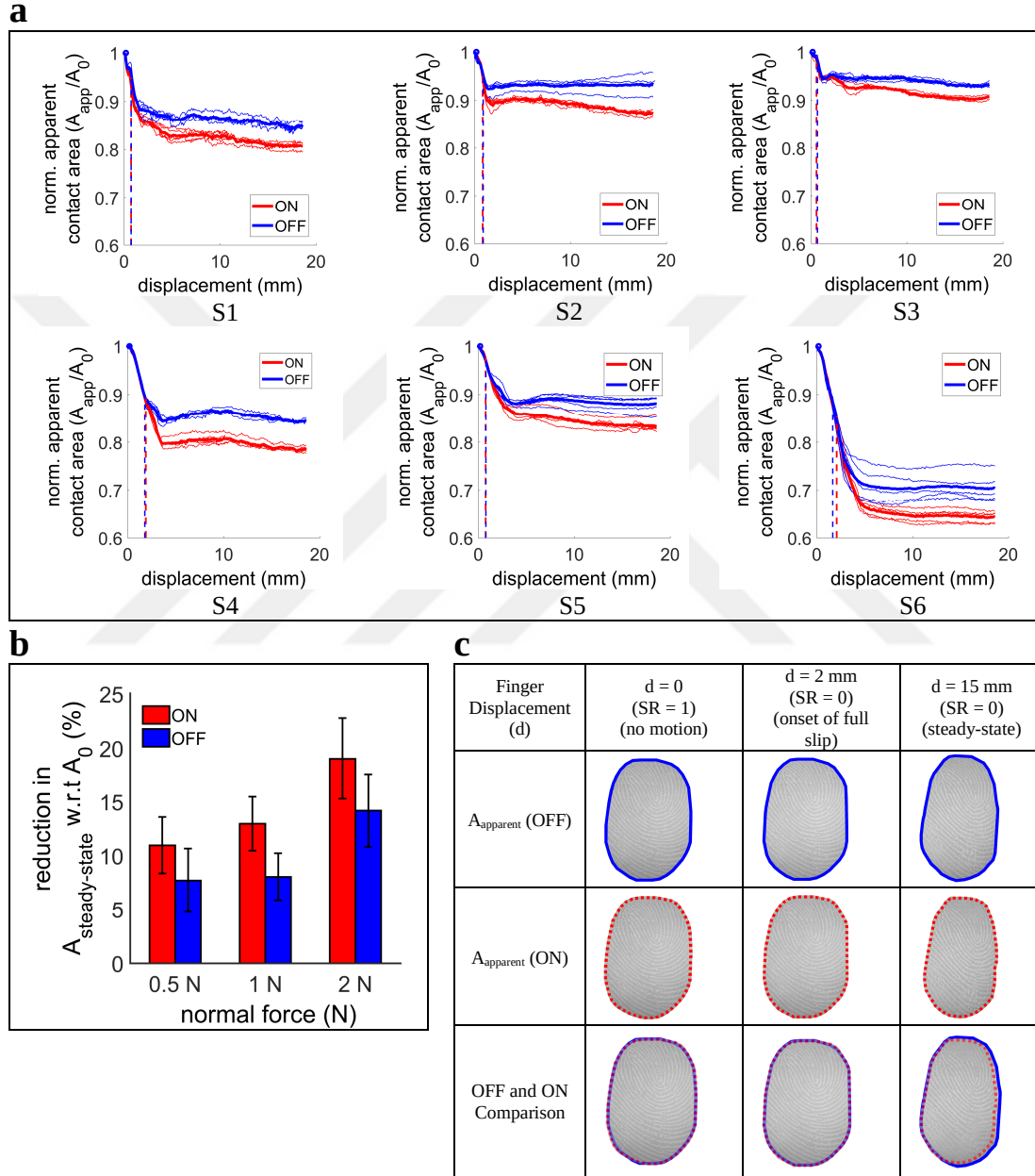


Figure 2.6: **(a)** Normalized apparent contact area of each subject as a function of finger displacement for a normal force of 2N. The vertical dashed lines mark the instant of full slip ($SR = 0$). **(b)** Mean values (average of 6 subjects) of the percent reduction in A_s s with respect to A_0 for 3 different normal forces. The error bars represent the standard errors of the means. **(c)** Fingerprint images of subject 4 (S4).

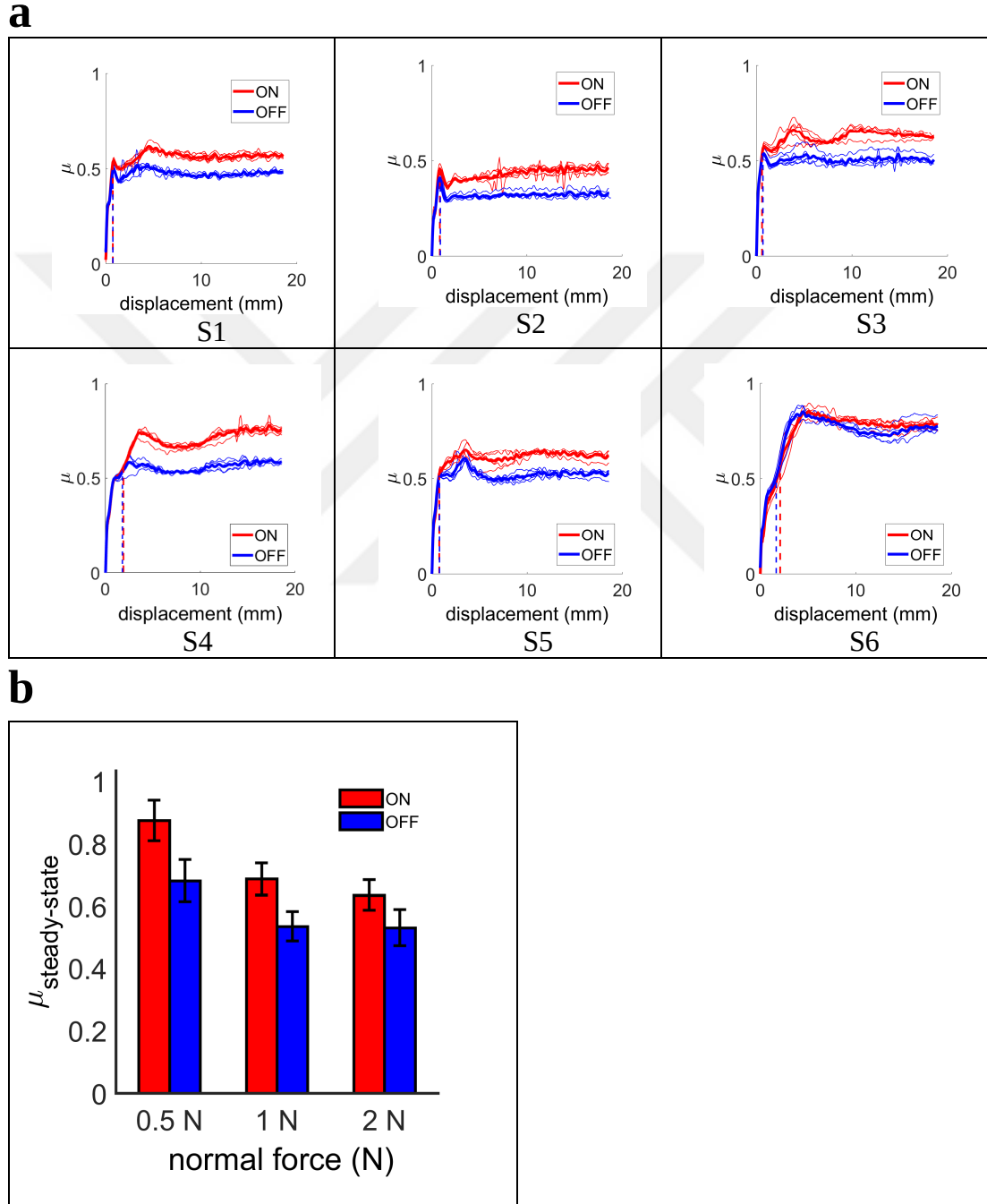


Figure 2.7: (a) The coefficient of friction (μ) of each subject as a function of finger displacement for a normal force of 2N. (b) Mean values (average of 6 subjects) of the steady-state friction coefficient (μ_{ss}) for 3 different normal forces.

Effect of Moisture: The coefficient of friction on smooth glass has been shown to vary due to fingertip skin moisture [Pasumarty et al., 2011]. The moisture accumulates as a result of skin surface occlusion and can be a critical factor affecting the friction. In our study, the moisture level of the subjects' finger pad was measured by a Corneometer before the first and after the last trial of each experiment (in increasing order; $S1 = 34.5 \pm 2.7$, $S2 = 40.6 \pm 7.1$, $S3 = 55.1 \pm 10.2$, $S4 = 72.3 \pm 10.4$, $S5 = 77.0 \pm 6.9$, $S6 = 114.1 \pm 1.8$). Since the fingertip skin moisture level of each subject is different, we investigated the relative effect of moisture on the coefficient of friction for OFF and ON EV conditions. As shown in Figure 2.8, the relative increase in coefficient of friction is smaller for higher levels of fingertip skin moisture, suggesting an adverse effect of moisture on the capacity of electrovibration to modulate friction.

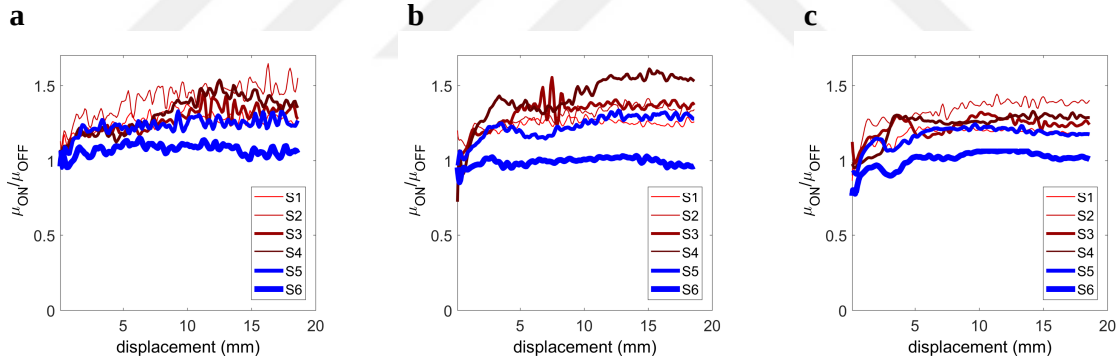


Figure 2.8: The ratio of coefficient of friction (ON to OFF) as a function of finger displacement of each subject having a different level of fingertip skin moisture for 3 different normal forces **a** 0.5 N, **b** 1 N, **c** 2 N. Subjects are ordered according to their moisture level from S1 having the lowest level of moisture to S6 having the highest level of moisture.

Effect of Input Signal: Figure 2.9a shows the contrast in dynamic coefficient of friction ($\mu_C = 1 - \mu_{OFF}/\mu_{ON}$) for the AC and DC signals applied to the touchscreen. We performed two-way analysis of variance (ANOVA) with repeated measures on the contrast using signal type (AC, DC) and normal force F_n (0.5, 1 N, 2 N) as the main factors. We did not observe a significant difference between the AC and DC conditions in terms of μ_C ($F(1,4) = 2.71$, $p = 0.175$). Figure 2.9b shows the contrast

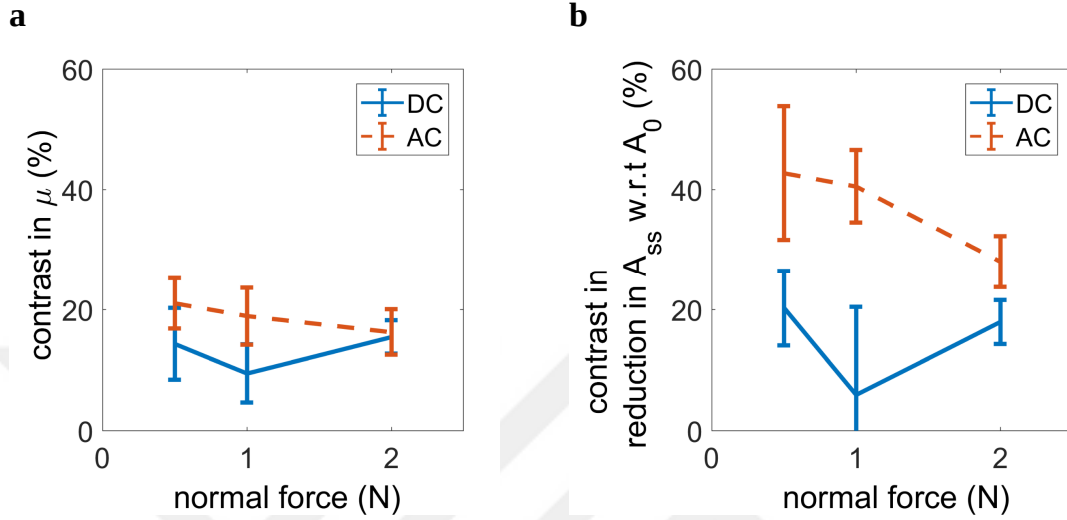


Figure 2.9: **a** Mean values (average of 6 subjects) of friction contrast (μC) for 3 different normal forces. The error bars represent the standard errors of the means. **(b)** Mean values (average of 6 subjects) of the contrast in reduction in A_{ss} (with respect to A_0) for 3 different normal forces. The error bars represent the standard errors of the means.

in reduction in A_{ss} with respect to A_0 . ANOVA results did not show any significant difference between the AC and DC signals ($F(1,4) = 6.986$, $p = 0.057$).

2.3.2 Experiment 2. Tactile Perception

Effect of Input Signal: Table 2.1 tabulates the threshold voltages and fingertip skin moisture level of each subject under AC and DC conditions. The results showed that the threshold voltage under AC condition was significantly lower than that of DC condition for all subjects. There was a clear converge for all subjects under AC condition while no convergence under DC condition (Note that the experiments were stopped automatically if the reversal count was five at ± 1 dB level). The threshold voltage was calculated as the mean of the last five reversals. The average threshold value obtained under AC condition (30.41 V) is consistent with the threshold value reported by Vardar et al. [Vardar et al., 2016] at 125 Hz.

Effect of Moisture: We performed ANOVA with repeated measures on the mois-

ture levels of subjects using the measurement time (before and after the experiment) and the signal type (AC vs DC) as the main factors. We did not observe a significant difference between the moisture levels before and after the experiments ($F(1,9) = 0.205$, $p = 0.661$) and AC versus DC ($F(1,9) = 5.126$, $p = 0.051$). However, the threshold voltages of the subjects having a moist finger (S6, S7, S9) was higher than the other subjects (Figure 2.10) under AC condition. This result is consistent with the results of the earlier experiment reported in this study (Figure 2.8) and supports our claim that moisture has an adverse effect on the capacity of electrovibration to modulate friction, which in turn affects the tactile perception of electrovibration.

Table 2.1: The threshold voltages and fingertip skin moisture level of each subject under AC and DC conditions.

	Threshold (V)		Moisture Level	
	AC (V_{pp})	DC (V_{rms})	AC	DC
S1	27.30	94.62	46.37	49.42
S2	11.85	77.30	38.21	45.38
S3	37.90	89.05	55.55	68.71
S4	17.98	70.64	57.59	65.85
S5	8.82	88.50	54.75	36.11
S6	52.01	92.20	103.90	97.16
S7	51.60	82.20	108.70	108.63
S8	19.22	64.77	35.19	32.91
S9	62.53	71.38	94.71	105.29
S10	14.90	92.91	67.09	64.25
Mean $\pm$ Std	30.41 $\pm$ 19.28	82.36 $\pm$ 10.72	66.21 $\pm$ 26.87	67 $\pm$ 27.91

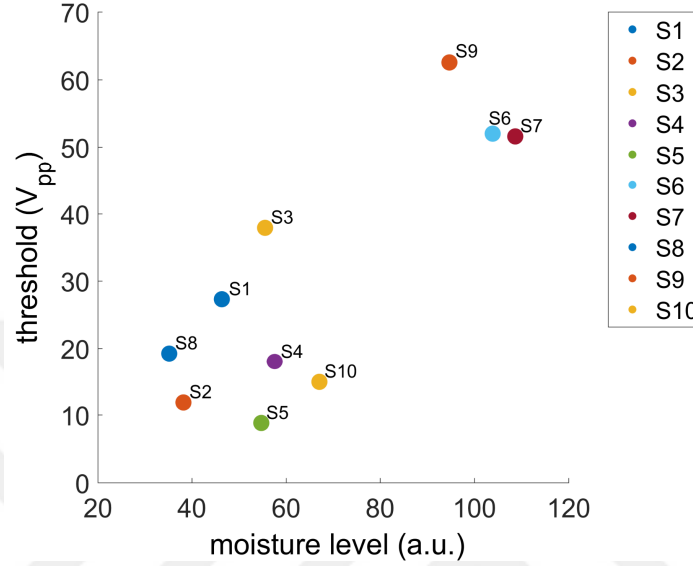


Figure 2.10: The threshold voltage versus moisture level of each subject under AC condition. Moisture measurements are given in arbitrary units (a.u.) that range from 20 (dry skin) to 120 (very wet skin).

2.4 Discussion

During the transition from stick to full slip, the transient behavior of stick ratio (SR) as a function of tangential force was similar for OFF and ON EV conditions under different normal forces (Figure 2.5a). In addition, our results also showed that the apparent contact areas before the onset of full slip were similar (Figure 2.5b). Delhaye et al. investigated the evolution of the area of contact between finger and glass during stick-to-slip transition on a smooth glass surface without electrovibration [Delhaye et al., 2014]. They estimated the intrinsic shear strength τ_0 from the minimal tangential force causing a partial slip. They observed that this force increases with normal force but decreases with speed. Since the minimal tangential force (Figure 2.5c) and the apparent contact area did not change when electrovibration was ON in our study, we argue that the values of intrinsic shear strength were similar when electrovibration was OFF and ON. In fact, all the results suggest that the effect of electrovibration on contact mechanics was negligible before the onset of full slip. On the other hand, once

the stick-to-slip transition was over and the slip started, the apparent contact area was reduced significantly under electrovibration. There was a clear difference in the apparent contact areas between OFF and ON EV conditions for all tested subjects (Figure 2.6a). The increase in frictional forces under ON condition led to further reduction in apparent contact area (Figure 2.6b). Earlier studies performed on smooth glass (without electrovibration) also reported a reduction in apparent contact area when the tangential force was increased [Delhay et al., 2014, André et al., 2011]. The authors explained this phenomenon by nonlinear stiffening of the skin in tangential direction. In our study, the tangential frictional force (and hence the coefficient of friction) also increased under electrovibration, as observed in the earlier studies [Meyer et al., 2013, Shultz et al., 2015, Vodlak et al., 2016, Vardar et al., 2017]. We argue that the increase in friction when electrovibration was ON was due to an increase in real contact area. First of all, we observed a decrease in coefficient of friction when the normal force was increased, which suggested that load-independent Coulomb friction model was not applicable. Instead, when the adhesive friction model of Adams et al. is adopted, the coefficient of friction becomes a function of normal load, intrinsic shear strength, pressure coefficient, and the real contact area. Our results suggest that intrinsic shear strength does not change under electrovibration. The pressure coefficient is effective for large contact pressures only and assumed unchanging under electrovibration. Therefore, the main cause for the change in frictional force is likely due to an increase in real contact area since the normal force and finger velocity were controlled and maintained constant during OFF and ON EV conditions. We argue that the increase in real contact area is due to the electroadhesive forces, causing the finger asperities make more contacts with the surface of touchscreen at microscopic scale. A support for our claim on the effect of real contact area comes from Persson's sliding friction theory [Persson, 2000], which suggests that the real contact area for elastic surfaces having different length scales (such as human finger) is significantly larger than it is originally thought for increasing normal load. Hence, when electrovibration is turned ON, microscopic asperities of fingertip skin make more contacts

with the touch screen, leading to an increase in real contact area. As shown in previous work [Wiertlewski et al., 2016], each asperity making microscopic contact can further support adhesive shear load proportional to its own contact area, increasing the overall magnitude of tangential forces shearing those contacts. We observed that electrovibration was adversely affected by fingertip skin moisture, which has not been reported before. The electrovibration was less prominent for subjects having higher levels of fingertip skin moisture (Figure 2.8). For example, the skin moisture level of subject 6 (S6) was significantly higher than for other subjects. This resulted in his coefficient of friction be higher than those of the other subjects, but the relative change in his coefficient of friction due to electrovibration was less than those of the other subjects. Earlier studies performed on smooth glass surfaces (without electrovibration) showed that the coefficient of friction increases when there is a thin layer of water between finger and glass surface [Adams et al., 2007a]. This was explained by the softening of the finger, also known as plasticization, which results in an increase in contact area and thus the tangential frictional force. In addition to the finger softening due to moisture, in our case, the air gap between finger and the surface is filled by water particles, causing a reduction in the electrostatic force. We also investigated the effect of moisture on the tactile detection threshold voltage and found that the subjects having a moist finger (S6, S7, S9) had significantly higher threshold level than the other subjects (Figure 2.10). For those subjects, the increase in real contact area (and hence friction) due to the moisture was already significant and a relatively small increase in the real contact area due to electrovibration did not contribute much to their tactile perception. Finally, we investigated the effect of input voltage signal (AC vs. DC) on contact mechanics and the tactile perception of electrovibration. The results did not show any significant difference between AC and DC signals in terms of coefficient of friction and reduction in apparent contact area (Figure 2.9). However, the results of the tactile detection experiment showed that the threshold voltage under AC condition was significantly lower than that of DC condition for all subjects (Table 2.1). This result is consistent with our earlier findings

suggesting that the Pacinian channel is mainly responsible for the tactile perception of electrovibration [Vardar et al., 2017, Vardar et al., 2016]. Since the Pacinian channel is not stimulated when a DC signal is applied to the touch screen (Figure 2.11e), it is not surprising that the magnitude of the perceived tactile stimulus is reduced. Our threshold experiment showed that the detection of electrovibration stimuli not only depends on the amplitude of the voltage applied to the touch screen but also on the human psychophysical sensitivity to tactile stimuli, as showed by Vardar et al. [Vardar et al., 2017]. Each psychophysical channel is sensitive to different input frequencies, which partially overlap. In our threshold experiments, the frequency of the input voltage under AC condition was 125 Hz, which was primarily detected by the Pacinian channel at 250 Hz. It is worth noting here that the electrostatic force is proportional to the square of the input voltage; therefore, the frequency of the output force signal is twice the frequency of the input voltage applied to the touch screen [Vardar et al., 2016]. As shown in Figure 2.11c, the FFT analysis of the tangential force under AC condition shows a peak at 250 Hz (see the 3rd and 12th trials). The FFT magnitude of the peak in the 3rd trial (Figure 2.11c) is already high due to the high voltage applied to the touchscreen while the one in the 12th trial (Figure 2.11d) is lower in magnitude than those of some other frequencies. However, it is known that human vibrotactile perception is frequency-dependent, with a sensitivity peak around 250 Hz. In addition, if the energy contained by each frequency component is multiplied by the inverse of the normalized human sensitivity curve as suggested by Vardar et al. [Vardar et al., 2016], then one can more easily appreciate why the small peak observed at 250 Hz in the 12th trial affects the subject's tactile perception significantly. This argument is also supported by the fact that the subject has successfully given a correct response under AC condition not only in the 12th trial but also in the following 8 trials (Figure 2.11a), despite the amplitudes of voltage signals applied to the screen are much lower than the one, for example, applied to the screen in the 7th trial (Figure 2.11b) under DC condition.

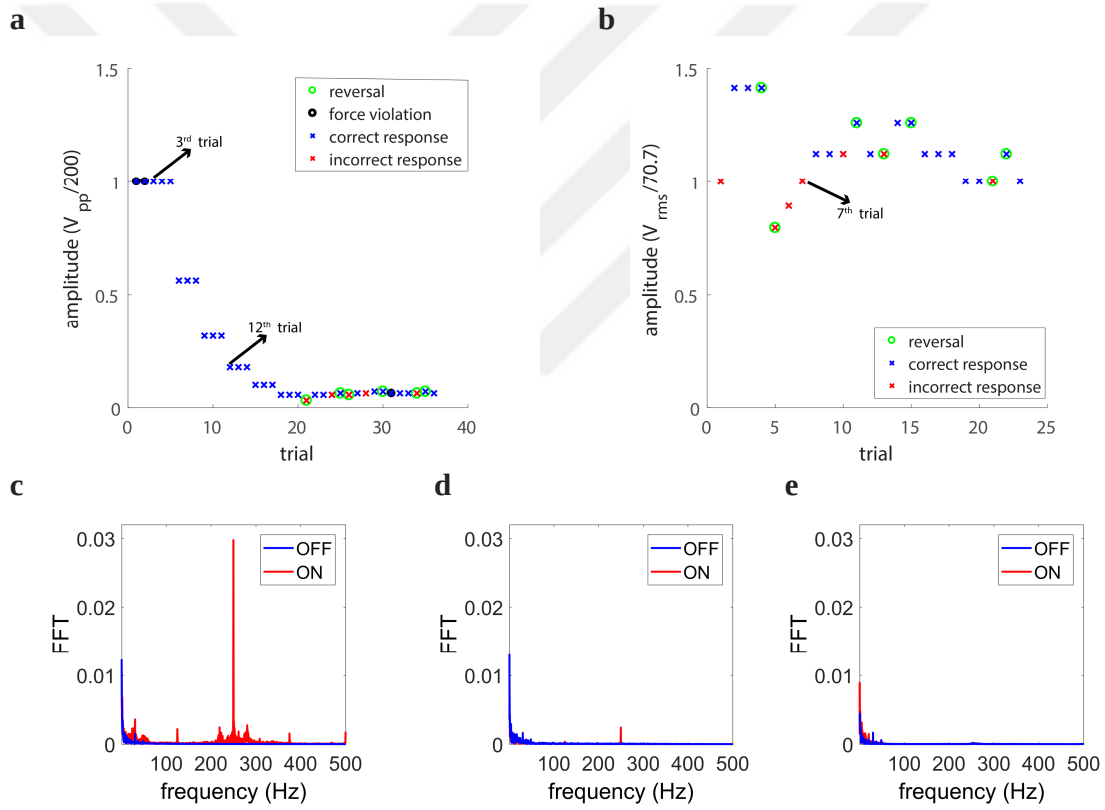


Figure 2.11: **(a, b)** An exemplar staircase data obtained by the threshold experiments under AC and DC conditions. **(c, d, e)** FFT analysis of the tangential force under AC condition for the 3rd and 12th trials and under DC condition for the 7th trial.

Chapter 3

CONTACT MECHANICS BETWEEN THE HUMAN FINGER AND A TOUCHSCREEN UNDER ELECTROADHESION

3.1 *Summary*

In this chapter, we use a mean field theory based on multiscale contact mechanics to investigate the effect of electroadhesion on sliding friction, and the dependency of the finger–touchscreen interaction on the applied voltage and other physical parameters. We present experimental results on how the friction between a finger and a touchscreen depends on the electrostatic attraction between them. The proposed model is successfully validated against full-scale (but computationally demanding) contact mechanics simulations, and the experimental data. Our study shows that electroadhesion causes an increase in the real contact area at microscopic level, leading to an increase in the electrovibrating tangential frictional force. We find that it should be possible to further augment the friction force, and thus the human tactile sensing, by using a thinner insulating film on the touchscreen than used in current devices.

3.2 *Theory*

Figure 3.1a shows an elastic solid having a multi–scale surface roughness above a rigid solid having a flat and smooth surface. Both solids are conducting materials with insulating surface layers of thickness d_1 and d_2 , and dielectric constants ϵ_1 and ϵ_2 . We define the effective insulator thickness as $h_0 = d_1/\epsilon_1 + d_2/\epsilon_2$. The interfacial separation $u = u(\mathbf{x})$ between the solids depends on the lateral coordinate $\mathbf{x} = (x, y)$.

The solids make atomic contact in a fraction A/A_0 of the nominal contact area

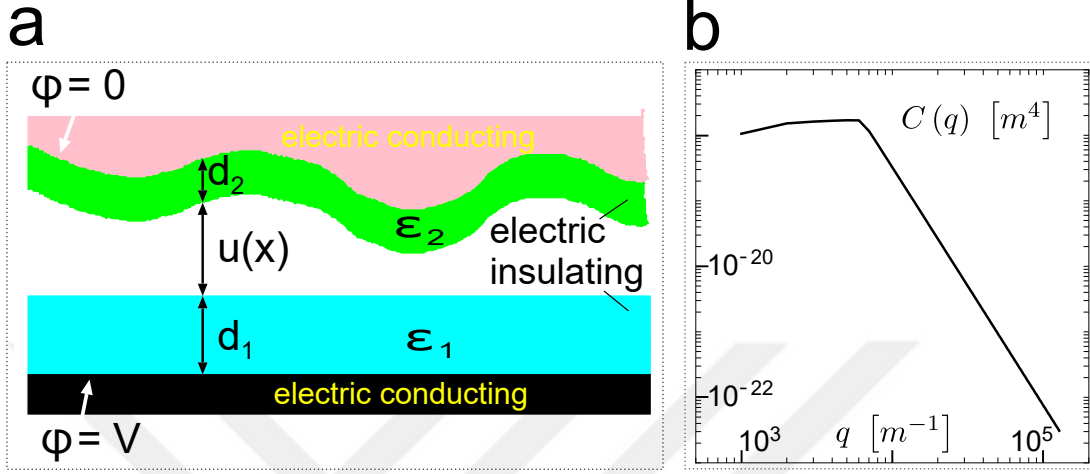


Figure 3.1: Skin/touchscreen mean field model properties. (a) Adopted micro-contact model: an elastic solid with surface roughness above a rigid solid with a flat surface and (b) the PSD used for the comparison of the models. Both solids are conducting materials with insulating surface layers of thickness d_1 and d_2 and dielectric constants ϵ_1 and ϵ_2 . An electric voltage difference V occur between the two conducting solids.

A_0 (in the figure $A = 0$). The non-contact regions are filled with air but we can consider these regions as vacuum because of the (relative) dielectric constant of air ($\epsilon_{\text{air}} \approx 1.00059$) is nearly the same as of vacuum ($\epsilon = 1$).

Assume now that an electric potential $\phi(t) = V_0 \cos(\omega_0 t)$ is applied between the solids as indicated in Figure 3.1a. This will give rise to an electric field in the air-gap between the solids, which results in an attractive force that can be calculated from the zz -component of the Maxwell stress tensor: [Persson, 2018]

$$\sigma_{zz} = \frac{1}{2} \epsilon_0 E_z^2, \quad (1)$$

where ϵ_0 is the dielectric function of vacuum. The electric field at bottom surface of the upper solid (the SC-air interface) is: [Persson, 2018]

$$E_z = -\text{Re} \left[\frac{V_0 e^{-i\omega_0 t}}{u + h_0(\omega)} \right]. \quad (2)$$

The normal stress averaged over the surface roughness becomes

$$\langle \sigma_{zz} \rangle = \frac{1}{4} \epsilon_0 V_0^2 \int_0^\infty du P(p, u) \frac{1 + \cos(2\omega_0 t + 2\phi)}{|u + h_0(\omega_0)|^2}, \quad (3)$$

where $P(p, u)$ is the probability distribution for the interfacial separation u , which depends on the squeezing pressure p (see below).

Assume that we squeeze the upper solid against the substrate with a force F_0 . When an electric potential is applied between the solids, there will be an additional electric force acting on them. In the simplest approach, one includes the electric attraction $p_a = \langle \sigma_{zz} \rangle$ as a contribution to the external load. Thus we write the effective squeezing or loading pressure as

$$p = p_0 + p_a, \quad (4)$$

where $p_0 = F_0/A_0$ is the applied pressure. Intuitively, one expects this approach to be accurate when the interaction force between the surfaces is long-range. A similar approach has been also successfully used for modeling the attraction resulting from capillary bridges [Persson, 2008, Persson and Scaraggi, 2014].

To calculate $p_a = \langle \sigma_{zz} \rangle$, we need to know the probability distribution $P(p, u)$. For randomly rough surfaces, the function $P(p, u)$ has been approximately calculated [Almqvist et al., 2011, Afferrante et al., 2018]. Using eqn (3) and (4) the time (and space) average of the effective pressure is obtained as

$$p = p_0 + \frac{1}{4} \epsilon_0 V_0^2 \int_0^\infty du P(p, u) \frac{1}{|u + h_0|^2}. \quad (5)$$

For a homogeneous elastic solid, the relative contact area A/A_0 can be obtained by using [Persson, 2001]

$$\frac{A}{A_0} \approx \frac{\sqrt{\pi}}{2} \operatorname{erf} \left(\frac{2p}{h'E^*} \right), \quad (6)$$

where h' is the rms slope of the combined surface roughness profile and $E^* = E/(1 - \nu^2)$ (where E and ν are the Young's modulus and Poisson ratio of the elastic solid, respectively). This equation is valid for the contact between homogeneous elastic solids with random surface roughness. When $A/A_0 \ll 1$, eqn (6) reduces to

$$\frac{A}{A_0} \approx \frac{2p}{h'E^*}. \quad (7)$$

The human skin is a layered material and hence h' is not the rms-slope of the combined surface roughness, but a quantity which depends on the surface roughness power spectrum as well as the elastic modulus and thickness of the layers [Persson, 2012]. In addition, for dry skin, the local contact pressures are typically so large that plastic deformation may occur, and in this case one cannot use eqn (6) or (7) directly to calculate the contact area but the full theory described elsewhere [Persson, 2012, Persson, 2001] must be used.

From the knowledge of A , we obtain the friction force from

$$F_f = A\tau_f. \quad (8)$$

The frictional shear stress τ_f is independent of the asperity contact pressure $p^* = pA_0/A$ as long as p^* is less than a few MPa. As an example, which is of interest for grippers in robotics applications, for silicone rubber (PDMS) sliding (in complete contact) on a smooth glass surface with a speed of $v \approx 1$ mm/s, the experiments have shown that $\tau_f \approx 0.1$ MPa [Chateauminois and Fretigny, 2008]. At the same sliding speed, for other types of rubber $\tau_f \approx 1 - 10$ MPa [Rowe et al., 2013, Lorenz et al., 2015], and for the human skin, which is of interest for touchscreens, $\tau_f = 5 - 13$ MPa [Persson et al., 2013, Kovalev et al., 2014]. This is also similar to what is observed for plastics (polymers below the glass transition temperature) [Whitten and Brown, 2007].

In Figure 3.2, we schematically show the physical processes and related length scales leading to tactile sensing in the contact between finger and electrostatically actuated touchscreen. The skin shows graded mechano-biological properties with specific nerve receptors placed at specific depths from the outermost surface, Figure 3.2b. The latter is characterized by the stratum corneum (SC), which consists of corneocytes (dead cells) with high keratin content embedded in a lipid medium. The SC is characterized by a peculiar papillary ridge patterning, and at shorter length scales (higher magnification) by a random surface roughness [Persson et al., 2013, Kovalev et al., 2014], whose spectral characteristics and three-dimensional roughness map (corresponding to a realization of the power spectral density (PSD)) are shown

in Figure 3.2c.

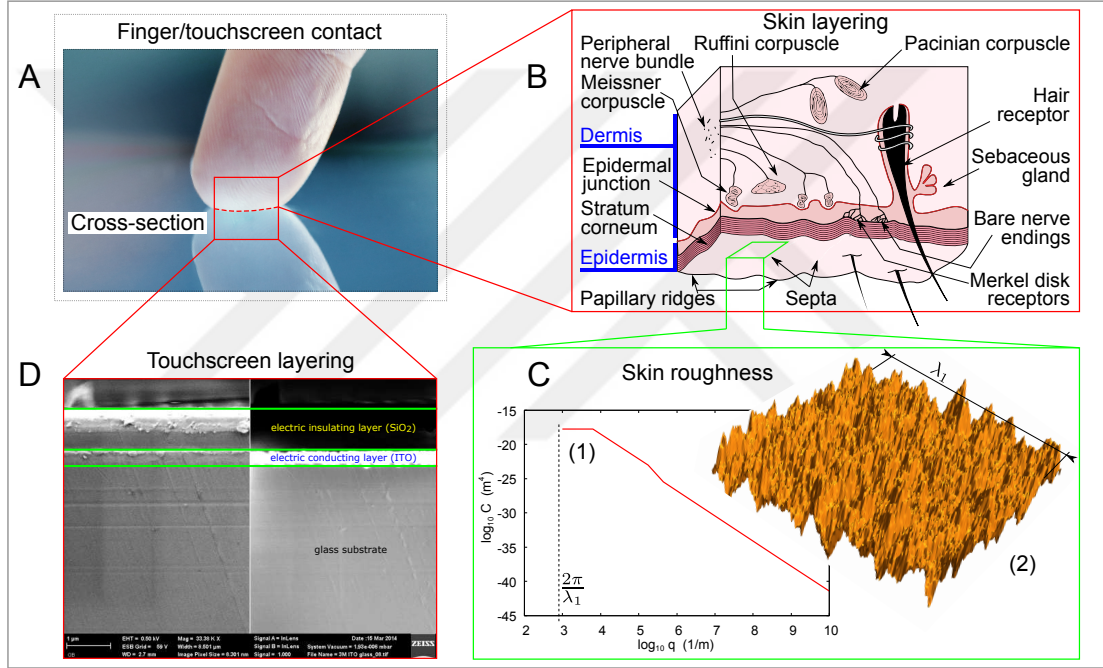


Figure 3.2: **(a)** Physical processes and related length scales leading to tactile sensing during contact between finger and touchscreen under electroadhesion. **(b)** Schematic of the layered structure of the generic human skin with indication of the relevant biological clues and nerve receptors. **(c)** The surface roughness PSD as a function of the wavenumber (log-log scale) calculated from the skin surface topography reported in Refs. [Persson et al., 2013, Kovalev et al., 2014]. The PSD has the rms roughness amplitude $22 \mu\text{m}$ and the rms slope 0.91. The linear region for $q > 4 \times 10^5 \text{ m}^{-1}$ corresponds to a Hurst exponent $H = 0.86$. The three-dimensional surface roughness corresponds to a realization of the PSD. **(d)** Left-side, cross section image of a capacitive touchscreen (Model: SCT-3250, 3M) obtained by field emission scanning electron microscopy (FESEM, Zeiss Ultra Plus). On the right side, the same image is reported with an improved contrast to highlight the different layers of the cross section: an electric insulator layer (SiO₂) with a thickness of $\approx 1 \mu\text{m}$, an electric conducting layer (ITO) with a thickness of $\approx 250 \text{ nm}$, and glass substrate.

3.3 Methods

3.3.1 Set-up

The major components of our set-up include a high-torque step motor moving a slide on a power screw and a force sensor attached to the base of the touch screen (Figure 3.3). The step motor (MDrive23Plus, Intelligent Motion Systems Inc.) was programmed to translate the slider forward and backward in horizontal direction at the desired sliding velocity. The experimenter's hand was placed on the slider such that the phalanges of index finger were aligned with a constant angle of approximately 30° with respect to the touchscreen, and the tip of the index finger was always in contact with the touchscreen during the sliding. A sinusoidal voltage signal with each of the following amplitudes 25 V, 50 V, 75 V, 100 V, 125 V, 150 V, 175 V, and 200 V at 125 Hz was applied to the touchscreen. As the experimenter's finger was moving on the touchscreen, the force response was measured using a force transducer (Nano 17, ATI Industrial Automation Inc.) placed under the touchscreen. The normal and tangential forces were acquired by a 16-bit analog data acquisition card (NI

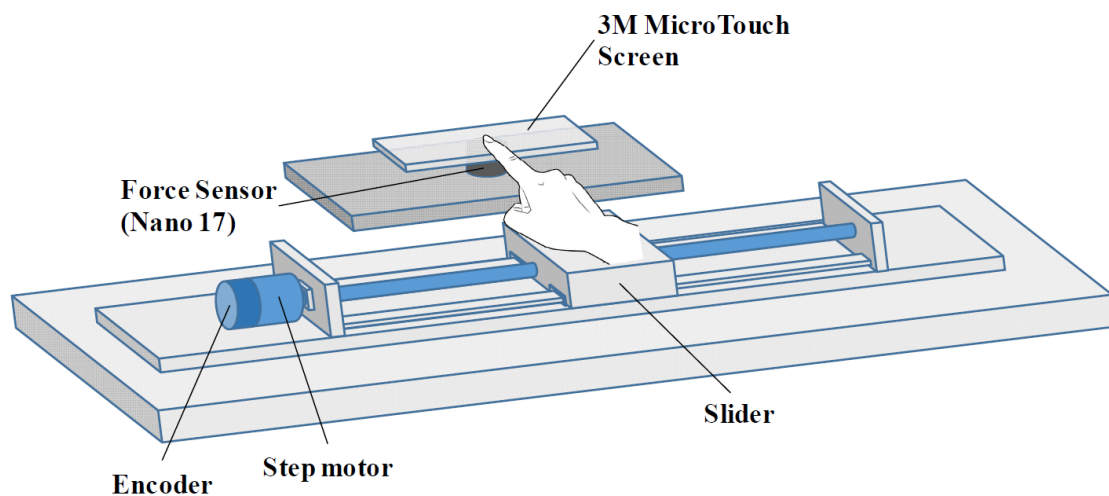


Figure 3.3: Schematic of the experimental setup for measuring the force responses of the index finger in the normal and tangential directions, when subjected to a relative sliding motion with respect to the touchscreen.

PCI-6034E, National Instruments Inc.) with a sampling rate of 10 kHz. Note that the electric stress oscillates between zero and a value twice as large as the average electric stress, although the voltage applied to the touchscreen takes negative and positive values, and oscillates around zero. If we assume that the friction force F_f is proportional to the sum of the applied stress p_0 and the adhesive stress (3), then we expect the friction force to oscillate with the frequency $2\omega_0$, where ω_0 is the frequency of the voltage signal applied to the touchscreen. To illustrate that this is indeed the case, in Figure 3.4 we show the measured friction force F_f as a function of time. The

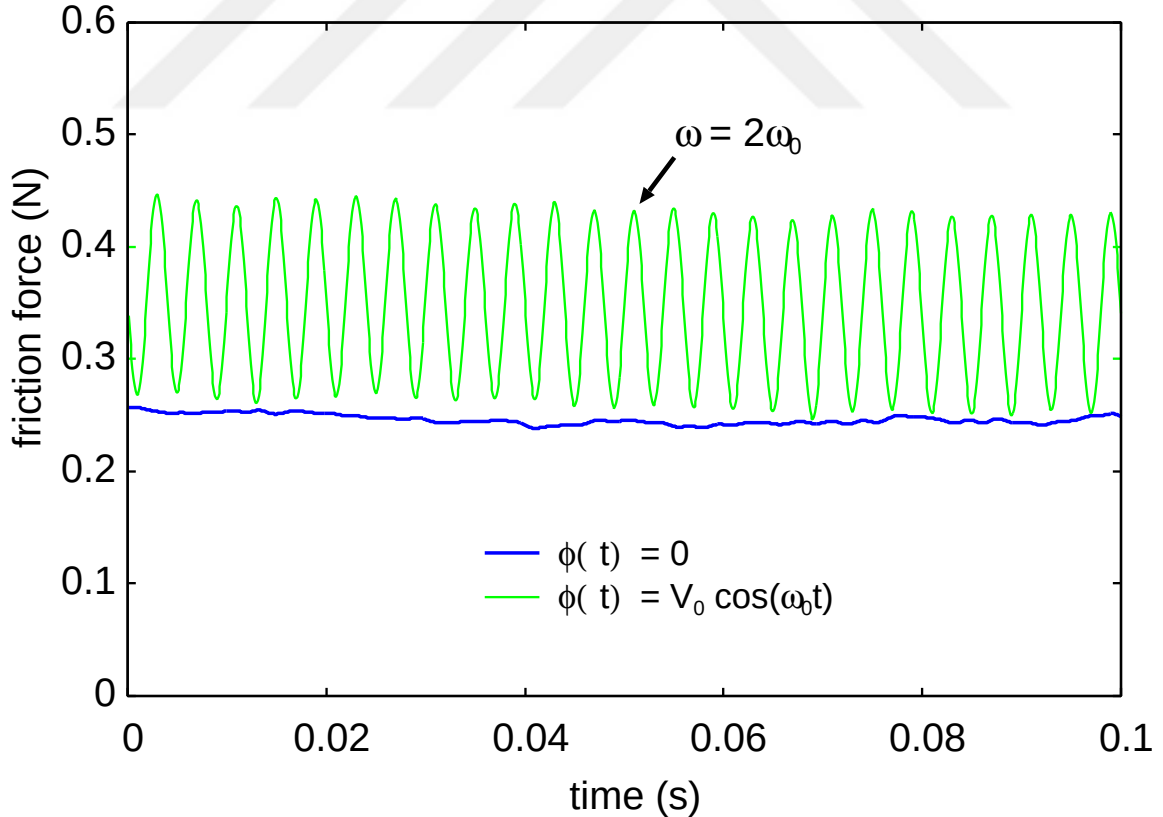


Figure 3.4: The friction force F_f as a function of time. Green-colored data: with an applied oscillating electric potential $\phi(t) = V_0 \cos(\omega_0 t)$ ($V_0 = 100$ V and $f_0 = \omega_0/(2\pi) = 125$ Hz). Blue-colored data: without an applied electric potential. The normal force is $F_N = 1$ N in both cases. Note that there are 25 oscillations in the green-colored data, i.e., the frequency of oscillations in the electric stress is $25/0.1 = 250$ Hz, i.e., twice the frequency of the applied electric potential.

green-colored data is with the applied oscillating electric potential $\phi(t) = V_0 \cos(\omega_0 t)$ ($V_0 = 100$ V and $\omega_0 = 2\pi f_0$ with $f_0 = 125$ Hz) while the blue-colored data is the friction force without an applied electric potential. The blue-colored data is slightly below the green one because the applied normal force was slightly lower in the case of no applied voltage.

3.3.2 Participants

The experiments were conducted with one male adult subject 29 years old. The subject used the index finger of his right hand during the experiments. The subject read the consent form and approved it before the experiments. The form was approved by Ethical Committee for Human Participants of Koc University.

3.3.3 Experimental Procedure

The finger of the experimenter moved forward and backward on the touchscreen for a total displacement of 80 mm in one cycle. The sliding velocity was selected as 50 mm/s based on the preliminary experiments such that full slip behavior was observed between the fingertip and the touchscreen. For each applied voltage, the experimenter aimed to increase his normal force from 0.2 N to 2 N with an increment of 0.2 N after every other 4 cycles. In order to keep the normal force constant, the test person visually tracked his force response from a large screen oscilloscope and trained himself in advance of the experiments. However, it is important to emphasize that keeping the normal force at a constant value was not easy even for a trained experimenter and some deviations occurred. The electrovibration was turned on and off after every other cycle. Hence, the experimenter made a total number of 320 cycles (8 different applied voltages $\times$ 10 increments of normal force per applied voltage $\times$ 2 cycles per force increment $\times$ 2 experimental condition (i.e., electrovibration on versus off)).

The experimenter washed his hand with soap, rinsed with water, and dried them in room temperature before the experiments. Moreover, the touch screen was cleaned by alcohol before each experiment. An external fan, placed near the sliding mechanism,

was used to hinder the accumulation of moisture on the fingerpad.

3.4 Results

3.4.1 Mean Field Contact Mechanics

The mean field theory taking into account the surface roughness, surface plasticity, and finger layering, is validated against deterministic contact electro-mechanics simulations for dry skin performed by BEM [Persson and Scaraggi, 2014]. Figure 3.1*b* shows the roughness PSD employed in the comparison, whereas the remaining electro-mechanics parameters are reported in Figure 3.6. Figure 3.5*a* shows, for one roughness realization, the BEM-predicted finger roughness upon reaching a normalized contact area of $A/A_0 \approx 10^{-3}$, with a magnified view of the surface (and its contact spot). In Figure 3.5*b*, we report the BEM-predicted skin micro-contact map (white is for non-contact), with magnified view of the map. In the magnification, the black and red contour lines show the complex patterns produced by the electroadhesive iso-stress curves around the true contact areas, revealing that an important contribution to electroadhesion, which is more effective in the contact domains (where interface separation is zero), is definitely provided by non contact areas as well. Finally, in Figure 3.6, we report the normalized contact area A/A_0 as a function of the contact pressure p_0 for different values of applied voltage difference across the interface. The markers are the outputs of the BEM simulations for two realizations of the PSD given in Figure 3.1*b*, whereas the solid lines are the outputs of the mean field theory. The comparison has been limited to a range of normalized contact areas which is of interest for the application. We observe a very good agreement between the results of the stochastic and deterministic contact models.

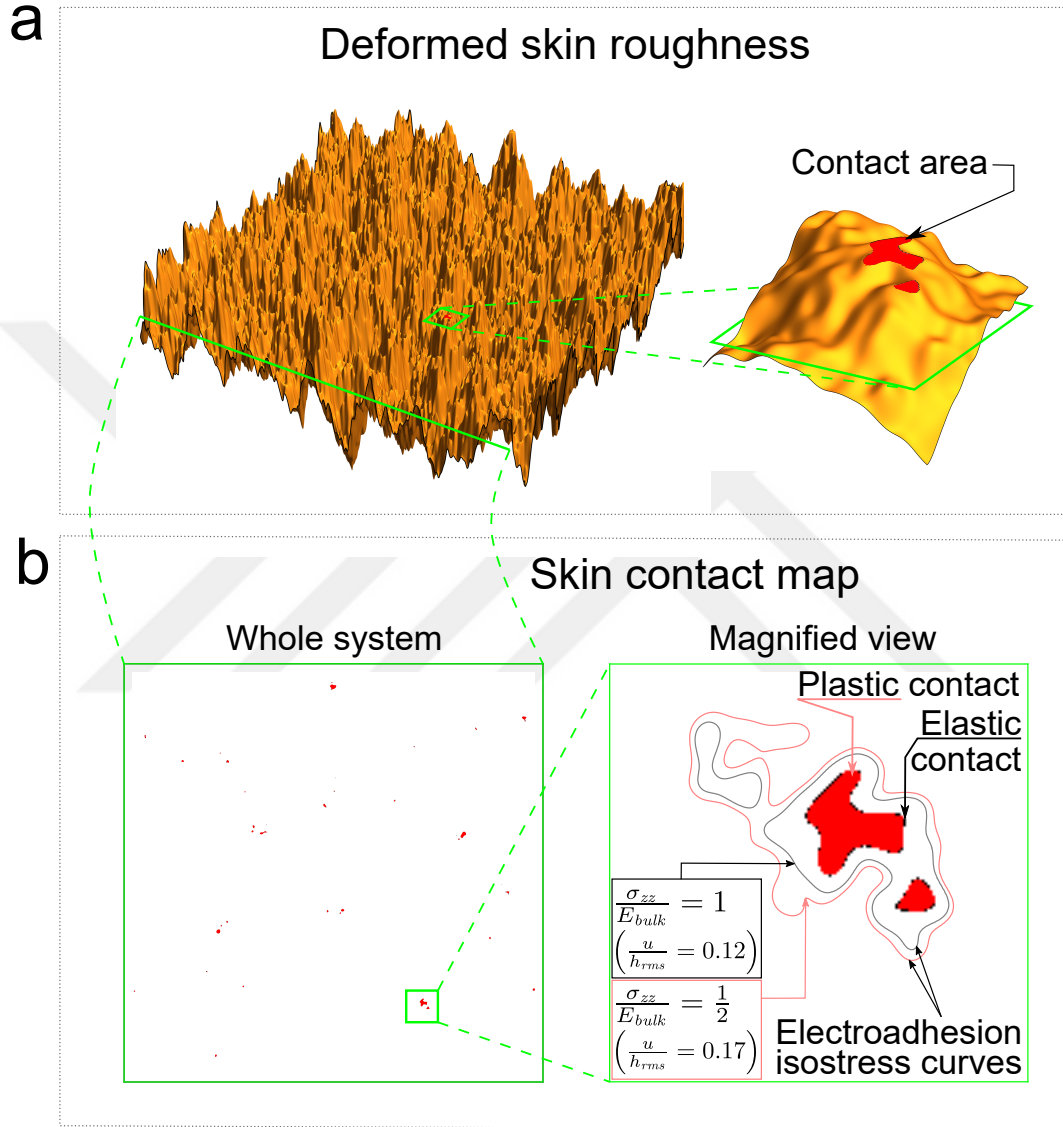


Figure 3.5: (a) BEM-predicted roughness upon contact, with a magnified view of the surface and representation of the contact domain. The rough contact is simulated with 16 divisions at the small roughness wavelength. (b) BEM-predicted skin micro-contact map, with magnified view of the map and indication of the contact domain. The black and red contour lines show the electroadhesive iso-stress curves around the true contact areas (h_{rms} is the root mean square surface roughness).

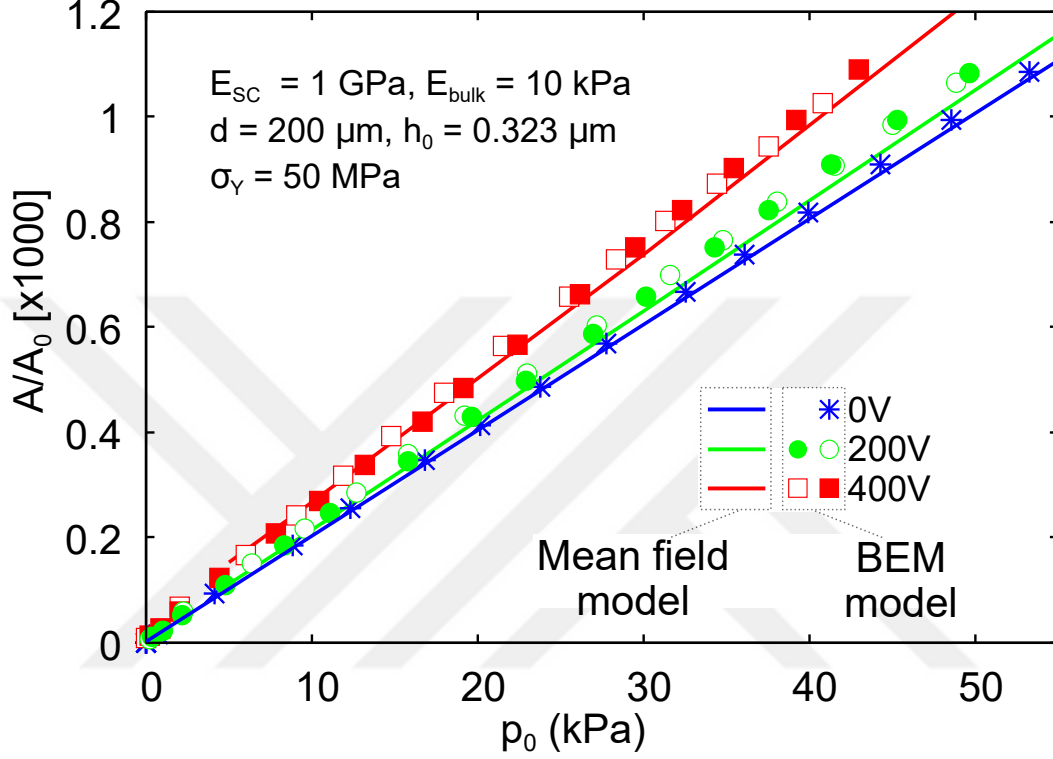


Figure 3.6: Comparison between the normalized contact area as a function of the contact pressure, at different values of applied voltage difference across the interface. The markers are the outputs of the RMD model (from two realizations of the PSD), whereas the solid lines represent the outputs of the mean field theory.

3.4.2 Comparison with Experiments

We found that the apparent contact area A_0 depends weakly on the normal force, where in our experiments the nominal contact pressure $p_0 = F_N/A_0$ varies between 3 kPa and 20 kPa. We report the typical friction force measured in our setup as a function of time in Figure 3.4. The green line is obtained by an oscillating electric potential $\phi = V_0 \cos(\omega_0 t)$ (with $V_0 = 200 \text{ V}$ and $f_0 = \omega_0/(2\pi) = 125 \text{ Hz}$) applied to the touchscreen. The blue line is for the case without the applied electric potential. The normal force applied by the finger is $F_N = 1 \text{ N}$ in both cases. We note that (in the green curve) the main frequency of the friction signal is 250 Hz, exactly twice the frequency of the applied electric potential, as expected from the theory (see Eq. (1)).

In Figure 3.7, we compare the friction coefficient estimated from the experimental data (markers) with the one predicted by theory (solid lines). In the calculation we used the SC Young's modulus $E = 40$ MPa, corresponding to semi-wet skin. The frictional shear stress τ_f , used to obtain the friction force from $F_f = A\tau_f$, was adjusted to obtain the best agreement with the measured data, and the used value $\tau_f = 8$ MPa is similar to $\tau_f = 13$ MPa in the dry state and $\tau_f = 5$ MPa in the wet state, reported in Ref. [Kovalev et al., 2014] (see also [Persson et al., 2013, Kovalev et al., 2014, Adams et al., 2007b]). We observe that the frictional shear stress τ_f is usually independent of the asperity contact pressure $p^* = pA_0/A$ as long as p^* is less than a few MPa. As an example, which is of interest for robotic or surgical grippers, for silicone rubber

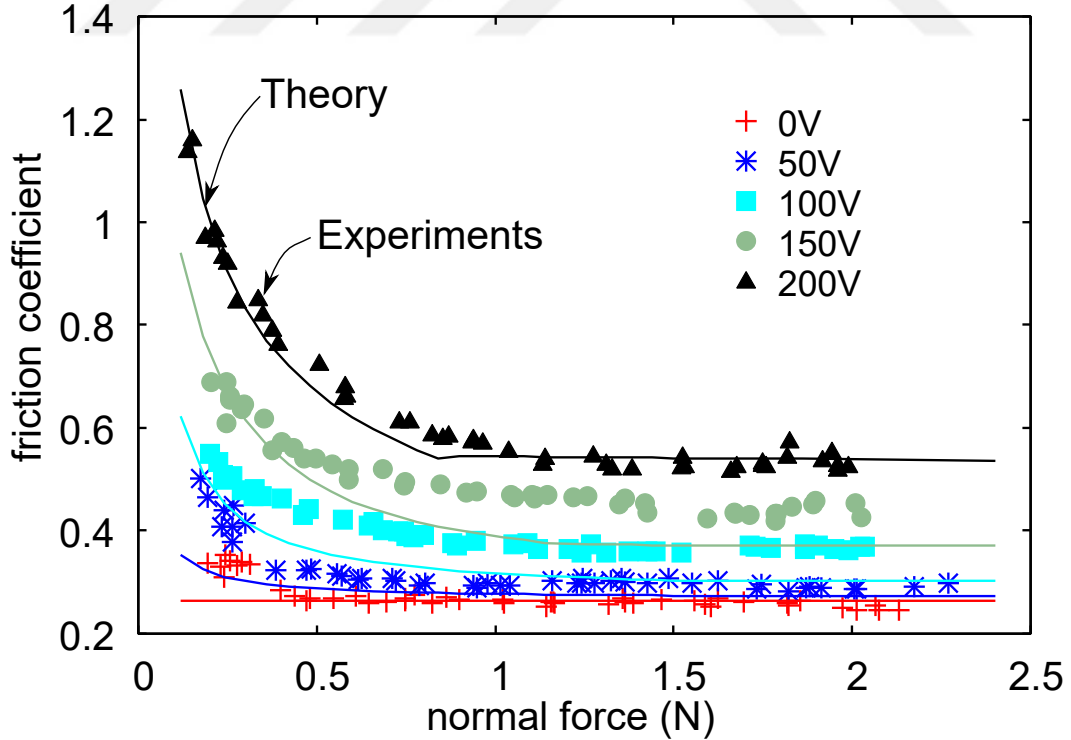


Figure 3.7: The friction coefficient μ obtained from the theory (solid lines) and the experiments (markers) as a function of the applied normal force F_N . The amplitude of the voltage applied to the touchscreen is varied between 0 V (red) and 200 V (black), with an increment of 50 V, at 125 Hz. The relative sliding speed in the experiments was 50 mm/s. In the calculations, we used $E_{SC} = 40$ MPa, $d = 200$ μm , $E_{\text{bulk}} = 10$ kPa and $h_0 = 0.2$ μm .

(PDMS) sliding (in complete contact) on a smooth glass surface at the sliding speed $v \approx 1$ mm/s, experiments have shown that $\tau_f \approx 0.1$ MPa [Chateauminois and Fretigny, 2008]. At the same sliding speed, for other types of rubber [Rowe et al., 2013, Lorenz et al., 2015] $\tau_f \approx 1 - 10$ MPa. This is also similar to what is observed for plastics (polymers below the glass transition temperature) [Whitten and Brown, 2007], and also as expected from molecular dynamics calculations [Sivebæk et al., 2008].

Note that the friction coefficient increases when the applied normal force decreases, as typical when adhesion is important. Note also that a small increase in the friction coefficient is also observed when the applied voltage is turned off. This has been observed also in earlier studies [Derler et al., 2009], and must be due to some additional adhesion process, e.g., due to the van der Waals interaction, or due to capillary bridges formed by water or from oil on the fingers [Persson, 2008].

Finally, Figure 3.8 shows the influence of the thickness of the effective insulating layer h_0 on the normalized contact area A/A_0 as a function of the applied voltage V . Note that $h_0 = d_1/\epsilon_1 + d_2/\epsilon_2$, however, its value is mainly determined by the thickness of the touchscreen insulating layer. In the figure, the Young's modulus of the SC is $E_{SC} = 100$ MPa, and the applied pressure is $p_0 = 10$ kPa. The results suggest that the thickness of the touchscreen insulating layer has a large impact on the normalized contact area, and thus on the magnitude of the electroadhesive friction.

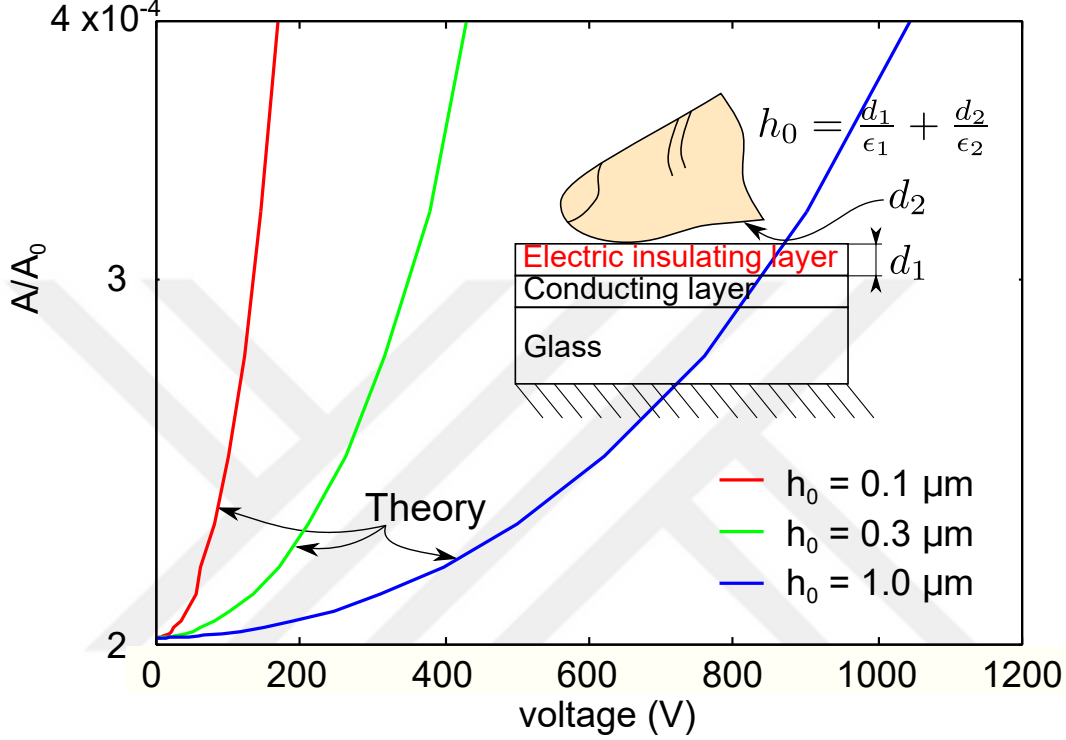


Figure 3.8: The normalized contact area A/A_0 as a function of the applied voltage V and the thickness of the effective insulating layer $h_0 = d_1/\epsilon_1 + d_2/\epsilon_2$. The applied pressure is $p_0 = 10$ kPa.

Discussion

3.4.3 The effect of electrovibration frequency on electroadhesion force

Let us discuss on how the frequency, ω , of the oscillating electric potential influences the electroadhesion force. Yamamoto and Yamamoto [Yamamoto and Yamamoto, 1976] have shown that SC has a finite electric conductivity. Thus, if the frequency is very small, charges can drift through the SC and to its outer surface. The theory described above is still valid in this limiting case: If ω is very small, the dielectric function of the SC is very large, and in fact $\epsilon_2(\omega) \rightarrow \infty$ as $\omega \rightarrow 0$. It follows that as $\omega \rightarrow 0$ we have $d_2/\epsilon_2 \rightarrow 0$, as if the insulating SC layer would not exist at all. This results in a shorter separation between the positive and negative charge distributions,

and in order for the applied voltage to stay constant, the electric field in the air gap must increase. Clearly, in this case, the electroadhesion force would be maximal. Figure 3.9 shows the calculated dependency of the contact area on the frequency $f = \omega/(2\pi)$ of the oscillating electric potential $\phi = V_0 \cos(\omega t)$.

The ratio $A_{\text{on}}/A_{\text{off}}$ between the real contact area with electroadhesion to that without electroadhesion was obtained using (3) with the dielectric function $\epsilon_2(\omega)$ of the SC given by (4) with $\epsilon_{\text{SC}}(\omega)$ and $\rho_{\text{SC}}(\omega)$ from Ref. [Yamamoto and Yamamoto, 1976]. We have used the normal force $F_N = 0.5$ N and $V_0 = 100$ V, $d_1 = 1$ μm , $d_2 = 200$ μm , and $\epsilon_1 = 8$. At low frequencies the charge on the skin surface can drift out on the touchscreen. This effect depends on the surface and bulk electric conductivity of the touchscreen, and on liquids (e.g. oil and sweat) which may occur in some fraction of the non-contact area. To take this into account we also show calculated results in Figure 3.9 where we assume the airgap is filled with a material

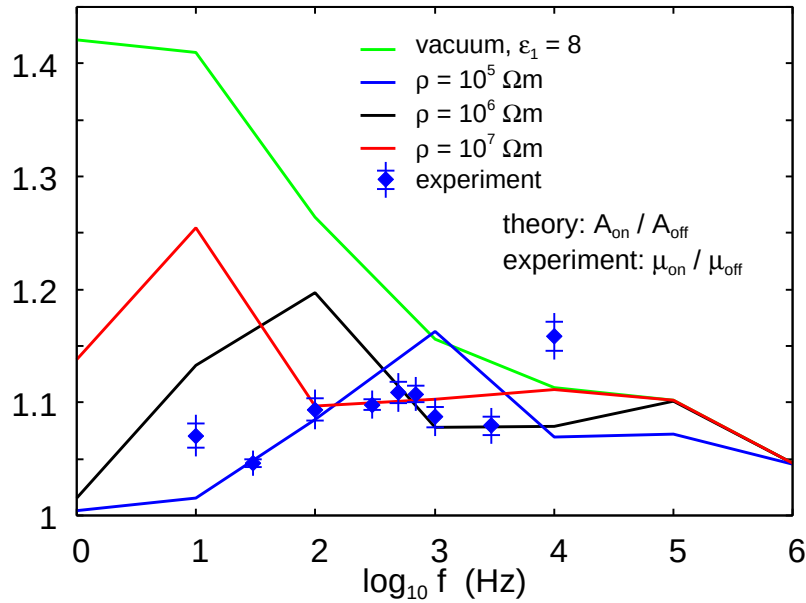


Figure 3.9: Solid lines: The calculated dependency of the contact area on the frequency $f = \omega/(2\pi)$ of the oscillating electric potential $\phi = V_0 \cos(\omega t)$. The $A_{\text{on}}/A_{\text{off}}$ is the ratio between the real contact area with electroadhesion to that without electroadhesion.

with the resistivity ρ equal to 10^5 , 10^6 and $10^7 \Omega \text{ m}$.

If we assume that the friction force is proportional to the area of real contact, then the ratio $A_{\text{on}}/A_{\text{off}}$ equal the ratio $\mu_{\text{on}}/\mu_{\text{off}}$ between the friction coefficient with electroadhesion to that without electroadhesion.

3.4.4 Tactile perception of electrovibration

One interesting observation is that the electroadhesion between a finger and a touchscreen can be felt only indirectly as a change (increase) in the sliding friction force when an alternating voltage is applied to the touchscreen (also called electrovibration). That is, when a stationary finger is pushed against the touchscreen displaying electrostatic forces, the electrovibration cannot be perceived. The reason for this is the difference in the finger deformations between the conditions when the voltage is off and on, and accordingly, about the mechanoreceptors stimulated when the finger is stationary and moving.

For stationary contact, most of the electrovibration induced deformations of the skin is localized to the SC. Hence, no mechanoreceptors experience stress to simulate the spiking response to convey information through nerve fibers to the brain. For sliding contact, instead, the additional friction force due to electroadhesion will result in a fluctuating shear deformation of the finger. Hence, the Pacinian corpuscles (FA II receptors), which are most sensitive to vibrations at 250 Hz (main frequency of the friction signal was 250 Hz, see Figure 3.4) will be deformed and emit neural signals [Saal et al., 2017]. The discussions made by Vardar et al. [Vardar et al., 2017] are in agreement with our arguments given above where they suggested that the Pacinian corpuscle is the primary mechanoreceptor responsible for the detection of the electrovibration stimuli. This is in line also with the study of Scheibert et al. [Scheibert et al., 2009], which emphasize the role of fingerprints in stimulating the Pacinian receptors.

3.4.5 Limitations of the study

In this study, we have assumed that the only attraction between the finger and the touchscreen is the electrostatic force due to the applied potential. In reality, there will be always other attractive interactions between two contacting solids, e.g. the Van der Waals interaction will operate between all solids and capillary bridges can be very important for the human skin. Furthermore, we have neglected electrical breakdown across the narrow gap between the contacting solids [Strong et al., 2006]. When a large electric potential is applied between narrowly separated surfaces, a very large electric field can prevail, in particular close to high and sharp asperities. If the local electric field becomes larger than some critical value, breakdown occurs. For gap separations that are typical in many applications ($\approx 1 \mu\text{m}$ or less), the breakdown voltage is typically a few hundred volts. The relative importance of these additional effects will be evaluated in a future study.

The theory presented above focuses on the change in the contact area due to electroadhesion. It is true that the nominal (or apparent) contact area changes significantly (it decreases) with increasing tangential force, which we attribute to a large-strain nonlinear effect, but one expects from theory that the real contact area is nearly independent of the apparent contact area if the applied normal force is constant (and not too high). It is also known that the true contact area may decrease at the onset of sliding but this is mainly the case when the surface roughness occurs on the harder surface and where the asperity contact regions renew during sliding. In any case, these “higher-order” effects are not covered by our model.

Chapter 4

CONCLUSION

Displaying tactile effects through a touch screen has several potential applications in consumer electronics, white goods, and mobile devices. One of the approaches in this regard is electrovibration. The contact mechanics behind the electrovibration is currently under investigation. In this thesis, we investigated the cause of an increase in tangential frictional forces under electrovibration.

In Chapter 2, we investigated the contact mechanics between the human finger and a touchscreen under electrovibration using a robotic set-up and an imaging system. For this purpose, an experimental study was conducted. The frictional forces acting on subjects' index finger pad and its apparent contact area were measured at a constant sliding speed during transition from stick to full slip for different normal loads and when electrovibration (EV) was OFF and ON. Results suggest that although the contact mechanics of OFF and ON EV conditions are quite similar before full slip, they are distinct during sliding. In particular, we observed an increase in the coefficient of friction during slip (and hence the friction force) as expected, but surprisingly a larger decrease in apparent contact area under electrovibration. Based on the adhesive friction model suggested in the literature [Adams et al., 2007a], we proposed that the increase in friction force under electrovibration is actually due to an increase in the real contact area. Moreover, the moisture appears to have an adverse effect on electrovibration. The relative increase in coefficient of friction was smaller for the subjects having higher levels of fingertip skin moisture (Figure 2.8). We speculate that high moisture decreased the electrical impedance of the interfacial gap between the finger and the touchscreen, leading to a smaller increase in frictional force under electrovibration.

In Chapter 3, we proposed a mean field theory based on multiscale contact mechanics to analyze the effect of electroadhesion on sliding friction. We performed experiments to measure how the friction between a finger and a touchscreen changes with the applied contact pressure and voltage under electroadhesion. We validated the proposed theory against the results of full-scale contact mechanics simulations and the experimental data. The results showed that the friction force increases as a function of the applied normal force and the potential difference between the finger and the touchscreen. The proposed theory showed that electroadhesion produces an increase in real contact area, resulting in an increase in tangential frictional force. Also, we found that in order to further augment the friction force, and thus the human tactile sensing, a thinner insulating film could be used on the touchscreens. Finally, we explained the reason why haptic effects are not perceived when the finger is stationary, but only when it is moving.

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