Effect of Finger Moisture on Tactile Perception of Electroadhesion

Easa AliAbbasi, Muhammad Muzammil, Omer Sirin, Philippe Lefèvre, Ørjan Grøttem Martinsen, and Cagatay Basdogan

***Abstract*—We investigate the effect of finger moisture on the tactile perception of electroadhesion with 10 participants. Participants with moist fingers exhibited markedly higher threshold levels. Our electrical impedance measurements show a substantial reduction in impedance magnitude when sweat is present at the finger-touchscreen interface, indicating increased conductivity. Supporting this, our mechanical friction measurements show that the relative increase in electrostatic force due to electroadhesion is lower for a moist finger.**

***Index Terms*—Electroadhesion, electrical impedance, electrostatic force, tactile perception, psychophysics, finger moisture, touchscreen, surface haptics, mobile devices.**

I. Introduction

THE human haptic sense is a remarkable sensory system capable of detecting nano-scale wrinkles on seemingly smooth surfaces [1] and distinguishing between smooth surfaces with different material coatings [2] or even modified surface chemistries [3]. Despite the extraordinary capabilities of the human finger in discerning minute details, there remains a limited number of actuation technologies that can artificially replicate similar tactile sensations on touch surfaces. Surface haptics, an emerging field of research, aims to improve the way users interact with touch surfaces such as the touchscreens of mobile devices, enhancing the user experience by providing realistic and fine tactile feedback [4]. In this regard, electroadhesion (EA) via electrostatic actuation appears to be a promising technique for displaying frictional forces to the user's finger as it moves on the touchscreen. In this technique, a voltage signal is applied to the conductive layer of a capacitive touchscreen to generate an electrostatic attraction force between its surface and the finger sliding on it [5], [6], [7], [8]. This results in an increase in the frictional force acting against the finger, in the direction opposite to its movement. Although the technology for generating tactile feedback on a touchscreen via EA is already in place and straightforward to implement, our knowledge of the underlying contact mechanics, the nature of electrical interactions between the human finger and the touchscreen, and also our perception of tactile stimuli generated by EA are still limited. Unraveling the physics behind EA holds the promise of unlocking innovative technological applications. Beyond mobile devices, where the potential includes experiencing digital shapes and textures on touch surfaces [9], [10], [11], [12], [13] and interacting with them through finger/hand gestures [14], [15], these advancements are poised to extend into diverse domains such as robotics, automation, space missions, and textiles (see a more comprehensive review of EA applications in [16]).

In terms of contact mechanics, only a few studies have recently shed some light on the physics behind EA. The change in electrostatic forces between the human finger and a voltage-induced touchscreen was observed to be proportional to the square of the voltage amplitude ($F_e \propto V^2$) [6]. Although the change in friction coefficient between the human finger and touchscreen as a function of normal force follows a nonlinear curve for the applied voltage, the relative increase in steady-state friction coefficient due to EA was found to be 0.25% per volt (e.g. applying a sinusoidal voltage signal with an amplitude of 100 V at a frequency of 125 Hz results in a 25% increase in sliding friction coefficient) [17]. It was claimed that the increase in frictional force is due to an increase in the real contact area [18]. Despite the observed decrease in the measured apparent contact area during sliding under EA [19], the rise in the number of microscopic contacts at the interface due to EA leads to an increase in the real contact area. This hypothesis aligns well with the contact mechanics theory proposed for EA by Persson [20], [21], which considers the multi-scale nature of contacting surfaces.

Compared to the studies on contact mechanics, the number of studies investigating the electrical interactions between a human finger and a touch surface under EA is only a few. Shultz et

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al. [22] discussed that the electrical charges transfer through the contacting asperities of the finger and the touch surface and accumulate at the air gap regions. Since the magnitude of the electrostatic force is inversely proportional to the thickness of this gap, it can reach high values, an effect originally identified by Johnsen and Rahbek [23]. Shultz et al. [24] measured the electrical impedances of finger skin and touchscreen in isolation and subtracted them from the total electrical impedance measured while the finger slides on the touchscreen. They found that most of the applied voltage dropped across the air gap since its impedance dominated the impedances of the skin and the touchscreen. Later, Shultz et al. [25] argued that the impedance of the gap causes a volatile transition of force dynamics in the frequency range of 20–200 Hz. They demonstrated that using an amplitude modulation with a high-frequency carrier voltage signal reduces this transition regime and generates a constant friction force. In a recent study [26], we also performed electrical impedance measurements but extracted the air gap impedance from the remaining impedance by removing the effects of electrode polarization impedance. Our study showed that the remaining impedance is not just an air gap impedance as suggested by Shultz et al. [25], but composed of air gap and electrode polarization impedances in parallel. Earlier studies [24], [26], [27] also showed that the electrical impedance of the interfacial gap between the finger and the touch surface is significantly lower for the stationary finger compared to that of the sliding finger. It was suggested that when the finger remains stationary on the touchscreen, sweat accumulates at the interfacial gap and reduces the potential difference, decreasing the magnitude of the electrostatic forces. Our earlier study [8] highlighted the important role of charge leakage from the Stratum Corneum (SC), the outermost layer of skin, to the touch surface at low frequencies. The experimental results showed that the electrostatic force exhibits an inverted parabolic curve with a peak value at around 250 Hz. An electromechanical model based on the fundamental laws of electric fields and Persson's contact mechanics theory [28] was developed to estimate the frequency-dependent magnitude of electrostatic forces. The model revealed that the electrical properties of the SC and the charge leakage from it are the main causes of the inverted parabolic behavior.

In terms of tactile perception of EA, the number of studies is also limited. The sensitivity of the human finger to the polarity of the voltage signal was investigated and the results showed that the participants perceived negative or biphasic pulses better than positive ones [29]. The detection and discrimination threshold voltages across different frequencies were measured through psychophysical experiments, revealing a statistically significant relationship between absolute detection voltage and signal frequency. The results showed a U-shaped curve in detection threshold voltage, with the lowest value at 125 Hz, whereas the discrimination voltage remained constant at 1.16 dB against all tested frequencies [5]. The variation in tactile perception corresponding to the changing waveform of the applied voltage was investigated in [30]. The results showed that the participants were more sensitive to square voltage signals than sinusoidal ones for frequencies lower than 60 Hz. The analysis of the collected force and acceleration data in the frequency domain, by considering the human tactile sensitivity curve, suggested that the Pacinian channel was predominantly responsible for detecting EA stimuli. This was consistent across all square wave signals displayed at various frequencies. The interference of multiple tactile stimuli (tactile masking) under EA was also investigated [31]. The results showed that the sharpness perception of virtual edges depends on the masking amplitude and activation levels of frequency-dependent psychophysical channels. The tactile perception of a step change in friction due to EA was investigated by considering the influence of normal force and sliding velocity [32]. Participants perceived rising friction (EA is switched from OFF to ON during sliding) as stronger than falling friction (EA is switched from ON to OFF during sliding), and both the normal force and sliding velocity significantly influenced their perception.

Although finger moisture and environmental humidity are known to affect frictional forces under EA [19], their effect on tactile perception and the physics behind the change in electrostatic force intensity due to accumulated sweat at the interface has received less attention. One study investigated the effect of electrowetting, the change in the wettability of the liquid on the touchscreen under EA, and concluded that the increase in frictional forces between the finger and the touchscreen at higher humidity levels is mainly due to the increase in capillary forces [33]. It was also observed that the finger left more residue (primarily, sweat and sebum) in the areas of a touchscreen where EA was active [34]. The authors suggested that i) the electrohydrodynamic deformation of sebum droplets adhere to the finger valleys, which results in the creation of extra capillary bridges and leftover droplets on the screen's surface after they break, and ii) the electric field-induced stabilization of sebum capillary bridges exist between the finger ridges and the screen, which leads to the merging and formation of larger droplets.

In this study, we highlight the adverse effect of fingertip skin moisture on the tactile perception of EA by correlating the finger moisture of the participants measured by a Corneometer with their voltage threshold values, which was not investigated in our earlier studies. To understand and explain the outcome of our perception experiment, we utilize the electrical impedance and friction force measurements reported in our earlier studies [8], [17], [26], [32]. We show that the magnitude of electrostatic forces inferred from friction measurements is lower for a wet finger compared to a dry finger. Our electrical impedance measurements also suggest that the impedance drops drastically when liquid is at the interface. As a result, the voltage difference at the air gap and the magnitude of electrostatic forces decrease.

II. Material and Methods

A. Participants

The tactile perception experiment was conducted with ten adult participants (four females and six males) having an average age of 29.4 years (SD: 5.9). Due to its time-consuming nature, the electrical impedance and friction measurements were performed with one male participant (age: 32 years old) having relatively dry fingers. All participants provided written informed consent to undergo the procedure, which was approved by the

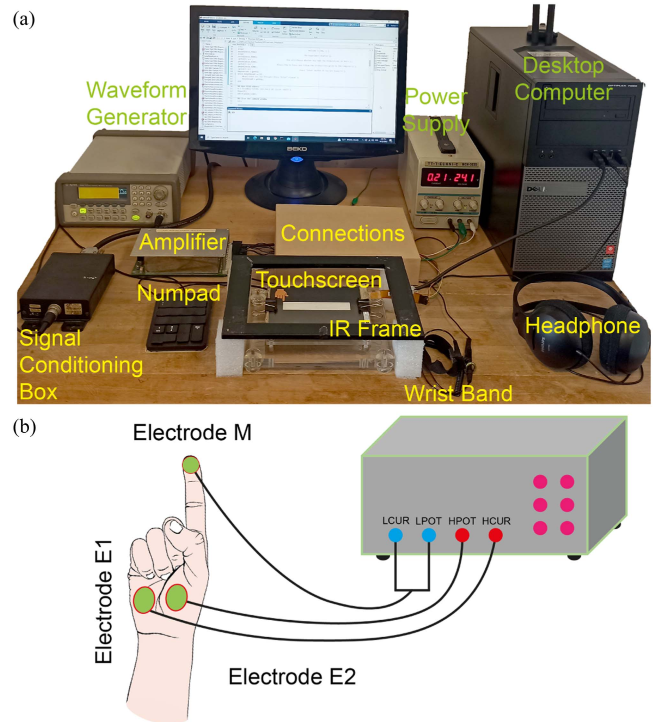

Fig. 1. (a) The setup used in our tactile perception experiments. (b) Schematic representation of skin moisture level assessment.

Ethical Committee for Human Participants of Koc University (Protocol Numbers: 2022.128.IRB2.020, 2023.280.IRB2.060). The investigation conformed to the principles of the Declaration of Helsinki and the experiments were performed by following relevant guidelines and regulations.

B. Tactile Threshold Experiments

We used the setup shown in Fig. 1(a) for the tactile perception experiment. In this setup, the input voltage signals were generated by a waveform generator (33220A, Agilent Inc.) connected to a PC via a TCP/IP protocol. The signals were then amplified by a piezo amplifier (E-413, PI Inc.) and applied to the conductive layer of a capacitive touchscreen (SCT3250, 3M Inc.) for displaying tactile stimulus to the participants. The touchscreen was rigidly fixed with holders to avoid undesired mechanical vibrations during the experiments. A DC power supply (MCH-303D, Technic Inc.) was utilized to provide 24 V DC voltage for operating the amplifier. A high-resolution force sensor (Nano 17-SI-12-0.12, ATI Industrial Automation Inc.) was placed below the touchscreen to measure contact forces. These forces were acquired by a 16-bit analog data acquisition card (PCI-6034E, National Instruments Inc.) with 10 kHz sampling frequency. An IR frame (IRTOUCH Inc.) was placed above the touchscreen to detect finger position.

Before the experiments, the participants washed their hands with soap, rinsed with water, and dried them at room temperature, and the touchscreen was cleaned with alcohol. Throughout the experiments, the participants were asked to wear an elastic strap on their stationary wrist for grounding and put on headphones playing white noise to prevent their tactile perception from being affected by any external auditory cue.

We conducted the absolute threshold detection experiment using the 2-Alternative Forced-Choice (2AFC) paradigm [35]. During the experiments, participants were asked to slide their index fingers on the touchscreen 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. Participants were asked to determine the pass (interval) in which they felt a tactile effect. To regulate their scan speed, a visual cursor moving at a speed of 20 mm/s was displayed on the computer monitor and the participants were asked to follow it with their index finger. To assist the participants with controlling their applied normal forces on the touchscreen, another visual feedback displayed the real-time magnitude of the applied normal force. The normal force and scanning speed were recorded in each trial. The average normal force and speed for all participants were 0.332 N (SD: 0.073) and 20.06 mm/s (SD: 0.87). If a participant's normal force or scan speed 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. Before starting the experiments, participants were given verbal 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 the voltage signal applied to the touchscreen (and hence the magnitude of the tactile stimulus) was altered using the three-down/one-up adaptive staircase method [31]. To determine the detection thresholds for the sinusoidal AC signal at 125 Hz, the experiment started with a voltage amplitude of 200 V_{pp}. It is worth noting here that the initial voltage amplitude provided sufficiently high intensity for all participants. 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 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. The threshold was calculated as the mean of the last five reversals. The moisture level of each participant's skin was measured by a Corneometer (CM 825, Courage - Khazaka Electronic) four times just before and right after the experiment and an average of eight measurements was reported for each participant.

C. Electrical Impedance Experiments

We selected the two-electrode method for all our electrical impedance measurements performed by the impedance analyzer (MFIA, Zurich Instruments Inc.) except for the assessment of skin moisture level, in which we utilized three electrodes (Fig. 1(b)).

The contact area of the electrodes in all electrical impedance measurements was 130 mm^2. In measuring skin impedance, an additional electrode of approximately ten times the size of the measuring electrode was attached to the ventral forearm [26]. Before each measurement session, the impedance analyzer was calibrated with the short-open-load option of the device to compensate for the residual impedances in the system.

The reader can refer to [26] regarding the procedures for measuring the electrical impedance of human skin, touchscreen, and the total sliding impedance of the finger on the touchscreen. In this study, obtaining consistent data with a moist finger proved more challenging when measuring the total sliding impedance, attributed to variations in moisture level, stemming from the prolonged duration of the experimentation due to the frequency sweep procedure. For this reason, four droplets of 5 μL 0.9% Isotonic Sodium Chloride (NaCl) were applied at four different locations on the touchscreen (a total of 20 μ L) to imitate a moist finger (called 'wet' condition in the text).

In addition to the impedance measurements, we measured the low-frequency susceptance of the skin, an indicator of skin moisture [36], [37], [38], using the impedance analyzer (MFIA, Zurich Instruments Inc.) and three electrodes (Fig. 1(b)). Electrode M in Fig. 1(b) is a custom-made metal electrode attached to the participant's fingertip. Electrodes E1 and E2 are electrocardiogram (ECG) electrodes (Red Dot 2228, 3M Inc.), which were attached to the palm of the same hand. Using a custom-made circular tube, a weight of 100 grams was placed on top of Electrode M and kept vertically aligned. The weight was equivalent to a normal force of 1N. A current was applied between two electrodes (M and E1), and the resulting differential voltage was measured between electrode M and the third electrode (E2). This results in a monopolar measurement, where the impedance between the electrode M and the third electrode (E2) can be measured. Since the viable skin is relatively well-conducting, the measured impedance is dominated by the SC beneath electrode M [39]. The magnitude and phase of this impedance were measured at 125 Hz for 10 seconds, with a sampling frequency of 2.5 kHz.

Once the magnitude and phase of the electrical impedance are known, one can calculate the real and imaginary parts of the impedance as:

$$Re\{Z\} = |Z| \cos\Phi \tag{1}$$

$$Im\{Z\} = |Z| \sin\Phi \tag{2}$$

where, $|Z|$ and Φ are the magnitude and phase of the measured electrical impedance, respectively. Hence, the susceptance can be calculated as:

$$B = -\frac{Im\{Z\}}{Re\{Z\}^2 + Im\{Z\}^2} \tag{3}$$

The susceptance measurements were performed under nominal and moist finger conditions. In the nominal finger condition, the participant waited for five minutes in the experiment room, allowing his body to reach normal hydration levels. Conversely, in the moist finger condition, the participant wore thick clothing and waited for fifteen minutes in the experiment room to induce sweating and achieve an elevated level of skin moisture.

D. Friction Force Experiments

The details about the setup for friction measurements can be found in our earlier publications [8], [32]. The experiment aimed to measure the friction force between the finger and the touchscreen under EA = OFF (no voltage was applied to the touchscreen) and EA = ON (an AC voltage signal of 120 V at a frequency of 125 Hz was applied to the conductive layer of the touchscreen) for two distinct moisture conditions of the fingerpad: a) nominal and b) moist. The experiments for the nominal finger condition were conducted early in the morning from 7 a.m. to 9 a.m., while the participant was fasting to minimize sweat generation. In contrast, the experiments for the moist finger condition were carried out in the afternoon between 2 p.m. to 5 p.m. During this time, the participant wore thick warm clothes to raise body temperature, inducing increased sweat generation. It is imperative to note that no artificial liquid was introduced to the interface in either of the two experimental conditions. Before the experiments, the touchscreen was cleaned with alcohol. During the experiments, the index finger of the participant's right hand was placed in a custom-made hand support to ensure consistent contact with the touchscreen at an angle of 20 degrees. An electrical grounding strap was wrapped around the participant's wrist to keep him grounded when the voltage was applied to the touchscreen. The participant was advised to maintain a stable and stationary position throughout the experiments. The normal force applied to the touchscreen by the finger of the participant was maintained at 1N via the PID controller in all trials. In each trial, the touchscreen was translated under the fingerpad of the participant in the tangential direction for a distance of 60mm at a constant speed of 20mm/s.

There were a total of 108 trials in the experiment, performed in 3 days. Hence, there were 36 trials on each day (2 moisture conditions: nominal and moist $\times$ 2 EA states: OFF and ON $\times$ 3 trials / session $\times$ 3 sessions). For each trial, the coefficient of friction (CoF) was calculated by dividing the recorded tangential force by the corresponding normal force. The electrostatic force acting on the finger was then inferred from the experimental CoF data [17]:

$$F_e = \left(1 - \frac{\mu^{OFF}}{\mu^{ON}}\right) F_n \tag{4}$$

where, F_n indicates the normal force acting on the touchscreen by the finger and μ^{ON} and μ^{OFF} represents measured CoF when EA = ON and EA = OFF, respectively.

III. Results

A. Tactile Threshold Measurements

Fig. 2 presents the threshold voltages and fingertip skin moisture level of each participant. The average threshold value ($30.41V_p$) is consistent with the threshold value reported in our earlier study for the stimulation frequency of 125 Hz [30]. The Pearson correlation showed a positive and strong correlation between threshold voltages and moisture level ($r = 0.81$, $p < 0.01$). This finding is consistent with the results of our earlier study [19] and supports our claim that moisture adversely affects the capacity of electrostatic actuation (EA) to modulate friction, which in turn influences the tactile perception of EA.

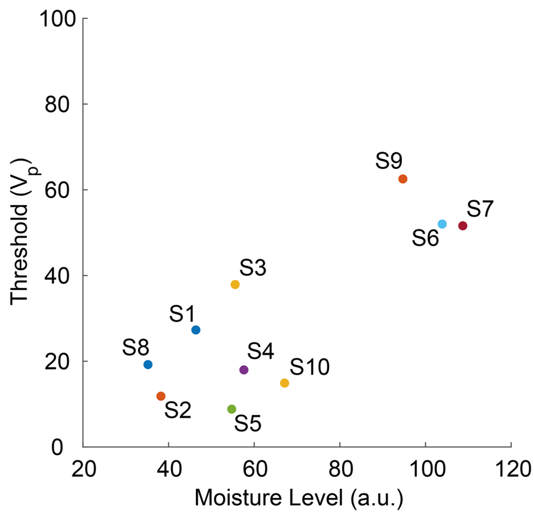

Fig. 2. The threshold voltage versus moisture level of each participant. Moisture measurements are given in arbitrary units (a.u.) that range from 20 (dry skin) to 120 (very wet skin).

B. Friction Force Measurements

Fig. 3(a) and (b) display the change in CoF as a function of displacement for the nominal and moist finger conditions, respectively, where each curve represents the mean values of 27 trials. Blue and red-colored curves depict the CoF for EA = OFF and EA = ON, respectively. The shaded regions around the curves represent the standard deviations. Fig. 3(c) depicts the steady-state values of CoF computed by averaging the data within the interval between 35 mm to 45 mm of displacement. In the nominal finger condition, the mean values for EA = OFF and EA = ON were 0.29 ± 0.05 and 0.38 ± 0.04, respectively. For the moist condition, the mean values for EA = OFF and EA = ON were 1.47 ± 0.11 and 1.58 ± 0.10, respectively.

The relative differences in CoF between EA = ON and EA = OFF for the nominal and moist conditions are given in Fig. 3(d). There was a contrast of 31% in the nominal condition, whereas a relative difference of around 7% was observed in the moist condition. The electrostatic force under the nominal and moist conditions is given in Fig. 3(e). Fig. 3(f) presents the mean values of the fingerpad's susceptance under the nominal and moist conditions. This bar graph shows that the susceptance of the moist finger was significantly higher than that of the nominal finger, suggesting that the moist finger had a relatively higher moisture level than that of the nominal finger, as anticipated. We conducted Wilcoxon signed-rank tests instead of t-tests to assess statistical differences due to the violation of the normality assumption. The results indicate statistically significant differences between the EA = ON and EA = OFF conditions for both the steady-state coefficient of friction (CoF) ($p < 0.001$) and the susceptance ($p < 0.001$).

C. Electrical Impedance Measurements

Fig. 4(a) and (b) present the average magnitude and phase of the electrical impedance measurements as a function of frequency, respectively. The shaded regions around the curves represent the standard error of means. Green, black, magenta and cyan-colored curves show the electrical impedance measurements for skin, touchscreen, sliding finger in nominal condition, and sliding finger in wet condition, respectively.

As shown in Fig. 4(a), the summation of the magnitudes of skin and touchscreen impedances is not equal to the magnitude of the total sliding impedance for both the nominal and wet conditions. Hence, another impedance must be in series with the skin and touchscreen impedances, which we name the "remaining impedance". We subtract the skin (Z_{Skin}) and touchscreen (Z_{TS}) impedances from the total sliding impedance ($Z_{Sliding}$) to obtain the remaining impedance [24], [26]:

$$Z_R = Z_{Sliding} - Z_{Skin} - Z_{TS} \tag{5}$$

The magnitude (solid curves) and phase (dashed curves) of the remaining impedance for the sliding finger under the nominal (magenta-colored curve) and wet (cyan-colored curve) conditions are presented in Fig. 4(c) as a function of frequency. The magnitude of the remaining impedance for the nominal condition was significantly higher than that of the wet condition. In other words, the liquid at the interface of the finger and the touchscreen caused a drop in impedance magnitude of more than tenfold compared to the nominal condition. As shown in Fig. 4(c), the phase angles of the remaining impedances for the nominal and wet conditions showed a resistive behavior at lower frequencies. This resistive behavior was followed by purely capacitive behavior after approximately 30 Hz for the nominal condition (i.e. the phase angle is around -90 degrees after 30 Hz). However, the phase angle of the wet condition showed a capacitive behavior for a narrow range of frequencies, followed by a sharp return to the resistive behavior.

Fig. 4(d) shows the remaining admittances for the nominal and wet conditions. A one-decade-per-decade line (dashed purple-colored) fits well to the admittance curve of the nominal condition after 30 Hz, suggesting a constant capacitance after that frequency (Fig. 4(e)). Hence, the remaining impedance of the nominal condition can be modeled by a single capacitance (C_{gap}) at higher frequencies, representing the air gap between the finger and the touchscreen [26]. At frequencies lower than 30Hz, there is a parasitic capacitance. This capacitance occurs due to the electric double layer at the interface between the finger and the touchscreen [40]. Similar to our susceptance measurements in Fig. 3(f), Martinsen et al. [38] measured the susceptance of skin and verified the existence of water in the SC layer of skin. Hence, electric double layer can build up between the solid surface of the touchscreen and the water contents in the SC. The formation of the electric double layer at the interface of the finger surface underlies the phenomenon of electrode polarization [41]. Upon contact with the voltage-induced touchscreen, the human finger triggers the movement of ions in the finger tissue toward the surface of the touchscreen, causing the formation of a first layer on the inner finger surface. This primary layer consists of ions carrying electric charges opposite to those of the touchscreen, while the subsequent layer comprises loosely anchored ions bearing similar charges. The presence of free ions in the finger, possessing charges contrary to those of the touchscreen, results in their attraction towards the touchscreen,

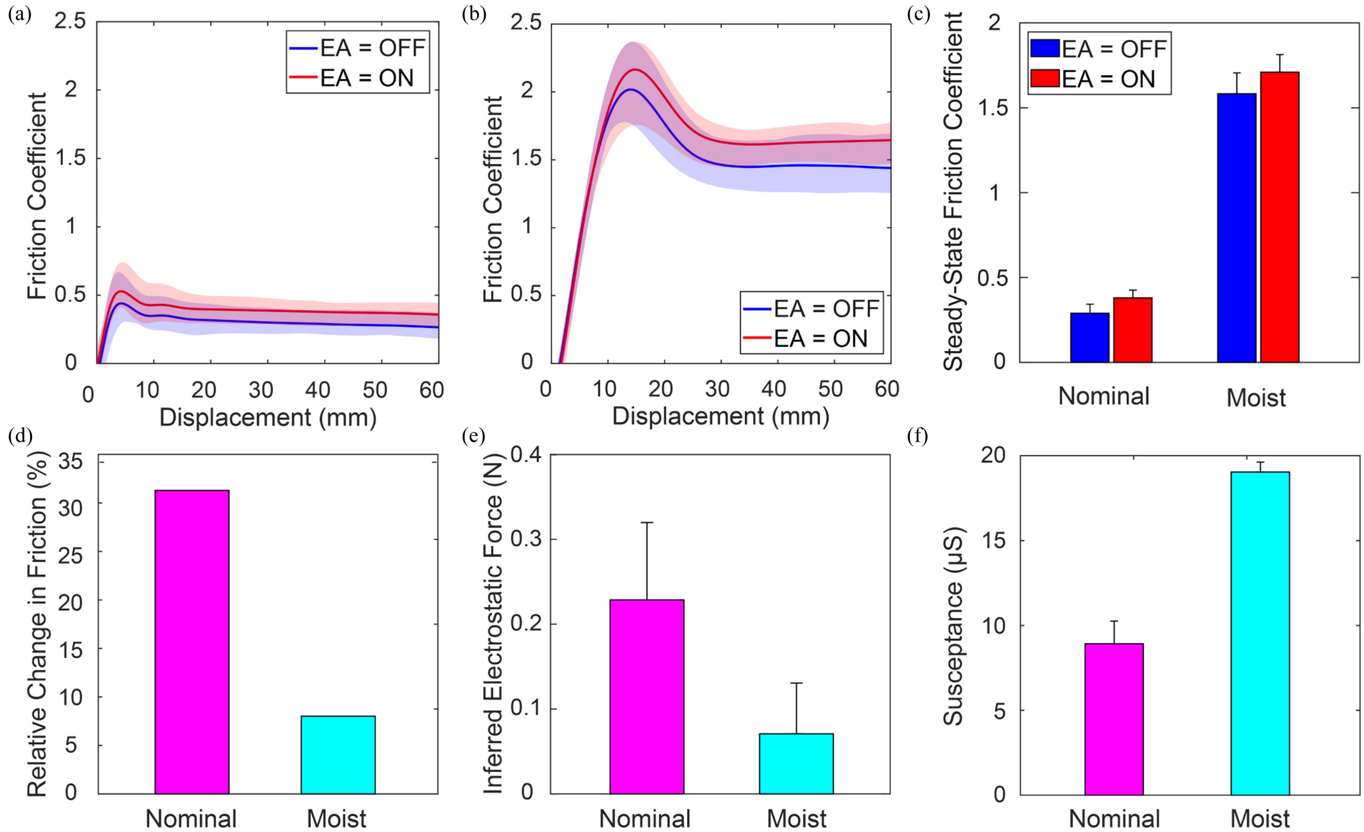

Fig. 3. Coefficient of friction (CoF) as a function of displacement with and without EA for (a) nominal and (b) moist finger conditions. The solid curves show the mean values and the shaded regions around them are the standard deviations for all trials. (c) Mean values of steady-state CoF under nominal and moist finger conditions with and without EA. (d) Relative difference in CoF between EA = ON and EA = OFF for the nominal and moist finger conditions. (e) Electrostatic forces inferred from the friction measurements for the nominal and moist finger conditions. (f) Mean values of the susceptance, an indicator of skin moisture, measured under the nominal and moist conditions.

displacing the ions in the first layer and leading to the leakage of electrons from the finger to the touchscreen surface. It is worth noting that the transfer of ions from the finger to the touchscreen is restricted because the touchscreen has only electronic charge carriers rather than ionic ones. Particularly at lower frequencies, the sufficient duration allows the free ions to displace those in the first layer more effectively, leading to an increased rate of charge leakage and, subsequently, a reduction in the strength of the electric field at the interface (a conduction path builds up between the finger and the touchscreen as emerged in the remaining resistance curve in Fig. 4(f)). Hence, a capacitance (C_{EP}) in parallel with a resistance (R_{EP}) can be used to model the behavior of the electrode polarization impedance as suggested in [26] (see Fig. 4(g) for our proposed circuit model).

Similar to the nominal condition, a one-decade-per-decade line fits well to the admittance curve of the wet condition in Fig. 4(d) for frequencies ranging from 100 Hz to 10 kHz. Hence, the remaining impedance of the wet condition can be modeled by a set of parallel capacitances for the air gap (C'_{gap}) and NaCl (C_{NaCl}) at frequencies ranging from 100 Hz to 10 kHz. At frequencies lower than 100 Hz, there is a parasitic capacitance due to the electric double layer (C'_{EP}) in parallel with a resistance (R'_{EP}). As shown in Fig. 4(f), the resistance of the wet condition is lower than that of the nominal condition. This indicates that NaCl fills the air gap and creates a conduction path between the finger and the touchscreen, which can be modeled by a resistance (R_{NaCl}). Fig. 4(h) shows our proposed circuit model for the wet condition. Note that the values of C'_{gap}, C'_{EP}, and R'_{EP} differ from the corresponding ones used for the nominal condition.

Using the circuit models given in Fig. 4(g) and (h), the remaining impedances for the nominal (Z_R) and wet (Z'_R) conditions can be expressed respectively in the Laplace domain as:

$$Z_R = \frac{R_{EP}}{1 + R_{EP}\left(C_{EP} + C_{gap}\right)s} \quad (6)$$

$$Z'_R = R_{NaCl} + \frac{R'_{EP}}{1 + R'_{EP}\left(C'_{EP} + C'_{gap} + C_{NaCl}\right)s} \quad (7)$$

At low and high frequencies, (6) and (7) reduce to (8) and (9), respectively.

$$\lim_{\omega \to 0} Z_R \approx R_{EP}$$
$$\lim_{\omega \to \infty} Z_R \approx 0 \quad (8)$$

$$\lim_{\omega \to 0} Z'_R \approx R'_{EP} + R_{NaCl}$$
$$\lim_{\omega \to \infty} Z'_R \approx R_{NaCl} \quad (9)$$

This limit analysis shows that under the nominal moisture condition, the capacitances C_{EP} and C_{gap} become effectively

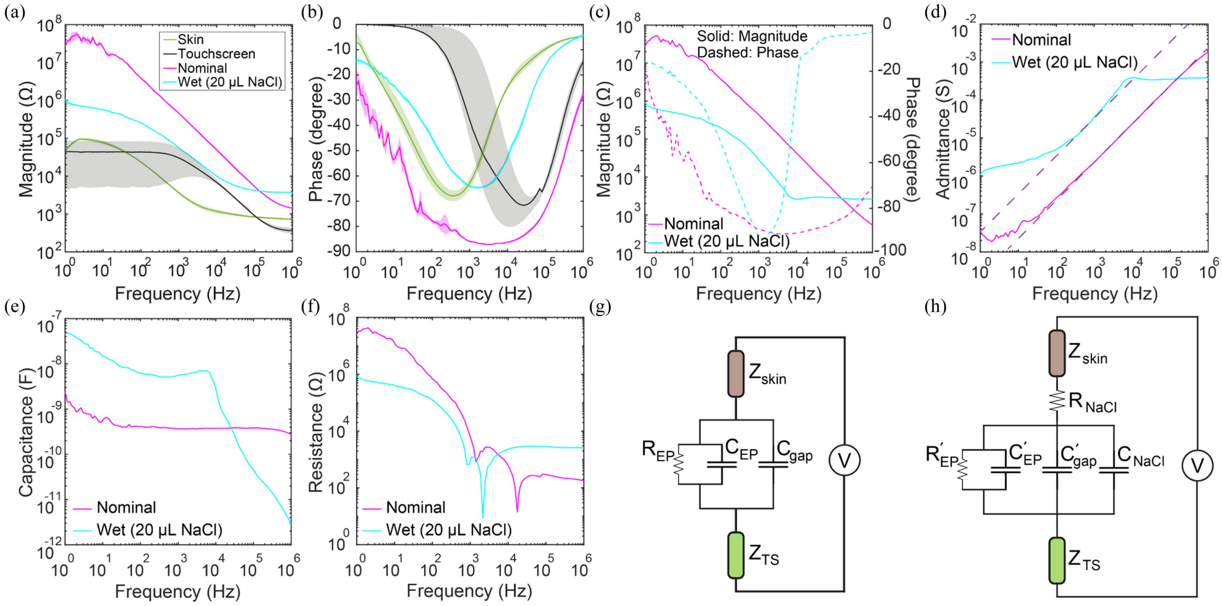

Fig. 4. The change in average electrical impedance (a) magnitude and (b) phase as a function of frequency for finger skin (green), the touchscreen itself (black), sliding finger on the touchscreen under the nominal (magenta) and wet (cyan) conditions. (c) The magnitude (solid curves) and phase (dashed curves) of the remaining impedance as a function of frequency for the sliding finger under the nominal (magenta) and wet (cyan) conditions as a function of frequency. (d) The change in the remaining admittance as a function of frequency for the sliding finger under the nominal (magenta) and wet (cyan) conditions. The dashed purple-colored lines are the one-decade-per-decade lines fitted to the admittance curves. The change in the (e) capacitance and (f) resistance at the interface between the finger skin and touchscreen under the nominal and wet conditions as a function of frequency. Our proposed circuit model for the finger in contact with a voltage-induced touchscreen under the (g) nominal and (h) wet conditions.

shunted as the stimulation frequency tends towards zero, equivalent to a DC stimulation, diverting all the current flow towards the resistance R_{EP}, consequently leading to a higher amount of charge leakage through SC in comparison to that observed under a typical AC stimulation at high frequencies. In other words, the interface of the finger and touchscreen is more conductive at lower frequencies due to the leakage of electrical charges from the finger to the surface of the touchscreen. At higher frequencies, the charge leakage diminishes and the behavior of the interface becomes more capacitive. Similarly, under the wet condition, the capacitances C'_{EP}, C'_{gap}, and C_{NaCl} short out as the stimulation frequency reaches zero and all the current flows through the resistances R'_{EP} and R_{NaCl}. However, the resistance of the NaCl (R_{NaCl}) remains effective even at higher frequencies, creating a conduction path between the finger and the touchscreen. At low frequencies, $R'_{EP} + R_{NaCl} < R_{EP}$ since NaCl fills in the air gap between the finger and the touchscreen and reduces the resistivity as shown in Fig. 4(h). This overall understanding further clarifies the weaker electric field observed during a DC stimulation compared to an AC stimulation.

IV. Discussion

In this study, we investigated the effect of moisture on the tactile perception of EA with 10 participants. We observed that the participants with very moist fingers (S6, S7, S9) had significantly higher threshold levels than the other participants (Fig. 2). For those participants, we argue that the introduction of finger sweat into the interface reduces the strength of the electric field as demonstrated by our electrical impedance measurements (Fig. 4(a)). Furthermore, if the friction force acting on the subject's finger was already high due to moisture, then a relatively small increase in the same force due to EA did not contribute much to his/her tactile perception (Fig. 3(d)). We performed experiments with one participant having relatively dry fingers and measured the friction forces between his right hand's index finger and the touchscreen under nominal and moist conditions with and without EA (Fig. 3(a)–(c)). Our results showed that, even in the absence of EA, the CoF experiences a five-fold increase when transitioning from the nominal to moist condition. Earlier studies in tribology literature have also reported a variation in CoF between dry and wet conditions by a factor of 1.5 to 7 [42], [43], [44]. The increase in CoF was explained by the softening of the finger due to the absorption of water, also known as plasticization, which increases the contact area and, thus, the tangential frictional force. Others attributed this change to capillary adhesion due to meniscus formation [45], [46], viscous shearing of liquid bridges formed between the skin and the surface [47], and the work of adhesion due to absorbed moisture [48], [49].

Our friction measurements showed that the magnitude of electrostatic forces due to EA is higher for the nominal condition compared to the moist condition (Fig. 3(e)). In the presence of moisture, the water particles bridge the air gap between the fingertip and the touchscreen surface. This bridging effect shortens the conduction path between the finger and the touchscreen, resulting in a diminished or lowered potential difference across the gap, causing a reduction in the electrostatic force. This observation was verified by comparing the electrical impedance measurements performed with the sliding finger under the nominal and wet conditions (Fig. 4(a) and (b)). In the wet condition, we intentionally added some liquid (NaCl) to the interface between the finger and the touchscreen so that the interface remains lubricated throughout the frequency sweep. As shown in Fig. 4(a), the magnitude of the electrical impedance for the wet condition dropped by more than an order of magnitude, compared to the nominal condition. This result suggests that in the presence of sweat at the interface between the finger and the touchscreen, the electrical charges can move between the finger and the touchscreen more easily, reducing the magnitude of the strength of the electric field at the gap.

V. Conclusion

Our future studies will investigate the effect of controlled hydration of the interface on friction between the finger and touchscreen with and without EA. Previous research in tribology, conducted without employing EA, observed an initial rise in the coefficient of friction, which subsequently decreased as the level of moisture or liquid present at the contact interface increased [43], [46], [50], [51]. The underlying physics driving this transformation is not fully elucidated, given the intricate nature of the transition phases between dry and fully lubricated states. This complexity is particularly pronounced in the context of contacts involving nonlinear and viscoelastic materials, such as the human finger skin, which also exhibits multi-scale surface roughness. Moreover, our understanding of the impact of EA on this lubrication transition is currently limited, with only a handful of studies touching this subject to date [19], [33], [34].

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