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Preferential Contamination in Electroadhesive Touchscreens: Mechanisms, Multiphysics Model, and Solutions

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Electroadhesive surface haptic touchscreens can help augment user experiences by providing tactile effects. The electrode layout in current commercialized designs has separated electrodes for the sensing and actuating functions. During regular use, it is observed that fingerprint residue preferentially deposits on the actuating electrodes far more than the sensing electrodes, which makes the underlying electrode pattern apparent and is highly undesirable for touchscreen users. To address this issue, various physical phenomena (electrohydrodynamic deformation, capillary bridge stabilization, electrowetting, and electrophoretic deposition) are investigated to understand the mechanism. Through experimentation, multiphysics modeling, and surface characterization, it is found that the root cause can be attributed to two mechanisms occurring in the actuating regions: 1) electrohydrodynamic deformation of sebum droplets attached to the finger valleys leading to the formation of additional capillary bridges and residual droplets on the screen surface after their rupture, and 2) electric field-induced stabilization of sebum capillary bridges existing between the finger ridges and the screen, leading to the coalescence and formation of larger-sized droplets. The developed model can then be used to address the issue during the screen design process. An example of using the model to explore the impact of changes in screen oleophobicity is shown.

1. Introduction

Surface haptic devices can be used to generate tactile effects on touch surfaces such as cellphones, tablets, kiosks, and information displays. The integration of haptics into touch surfaces has enabled the rendering of textures and control devices, such as knobs and slides, on touchscreens, and has widespread applications in entertainment, education, and e-commerce.

A popular mode of actuation in surface-haptic displays is electroadhesion.[1] This involves modulating the friction between the finger and the screen through the application of electrostatic forces across the air gap between the fingertip and the touchscreen.[2] Extensive research has been carried out by several research groups[3] to model friction force modulation in electroadhesive screens. The effects of electrowetting,[4] nanotexture,[5] and temperature[6] on electroadhesion have also been studied.

Current commercial electroadhesive touchscreens, such as Tanvas MimoVue, have transparent electrodes laid out in a specific pattern underneath a dielectric layer on the top glass surface. The screen surface can be broadly categorized into two groups depending on the functionality that the underlying electrodes serve—regions that we refer to as "haptic" regions where the actuating electroadhesive forces are applied, and regions that

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we refer to as "sensing" regions which sense where the finger is on the screen. A schematic showing the generic layout of such haptic and sensing regions on an electroadhesive screen is shown in **Figure 1**a. The haptic and sensing electrodes are physically separated and electrically isolated from each other and the voltage is applied only to the electrodes in the haptic regions. This results in a high electric field across the air gap in the haptic regions and an almost negligible electric field in the sensing regions.

During daily use, the surface of the finger has contaminants such as dust, sweat, and sebum (from contact with sebum-rich areas such as the scalp and face). When we use touchscreen devices, some of these contaminants get transferred to the surface, which is visible to the naked eye as fingerprint residue. It has been observed that electroadhesive touchscreens attract more contamination from the finger surface than the non-electroadhesive screens (Figure 1b), and this contamination is preferentially deposited (Figure 1b), meaning far more is deposited on the haptic regions relative to the sensing regions. This preferential contamination of the haptic regions of electroadhesive screens is visible to the naked eye (Figure 1b) and can be confirmed using optical microscopy and atomic force microscopy (AFM), which show increased numbers of droplets on haptic regions (Figure 1c). The preferential deposition of fingerprint residue makes the layout of the underlying haptic and sensing electrodes apparent to users, which is undesirable in a consumer product, particularly high-resolution displays. To the best of our knowledge, this is the first report of this significant issue in commercial electroadhesive screens. It is essential to fundamentally understand the mechanism to address and solve the issue in future screen designs.

In this study, we aim to find the root cause of this issue by answering the following question: what are the underlying physics governing the increased and preferential deposition of fingerprint residue at the finger-device interface in electroadhesive touchscreens? We start by formulating and investigating several hypotheses (electrohydrodynamic(EHD) deformation, capillary bridge stabilization, electrowetting, and electrophoretic deposition). Based on our experimental findings, we propose two mechanisms for the observed preferential contamination: 1) electrohydrodynamic deformation of sebum droplets attached to the finger valleys leading to the formation of additional capillary bridges and residual droplets on the screen surface after their rupture, and 2) electric field-induced stabilization of sebum capillary bridges existing between the finger ridges and the screen, leading to the coalescence and formation of larger-sized droplets. Thereafter, a multiphysics numerical model is built to study the interface and it is validated through experimental characterization. This model can be used by electroadhesive device designers to address this issue during the design process. As an example of its application, we explore oleophobic surfaces with higher contact angles as a possible design solution.

2. Results and Discussion

2.1. Mechanistic Study

During regular use, the finger may be contaminated with biological secretions and entities that it comes in contact with—sweat, sebum, or keratins from the stratum corneum of the skin. The human body contains three major types of secretion glands, each producing a different type of sweat—eccrine, sebaceous, and apocrine.[7] The palm has eccrine glands, and hence eccrine perspiration is a potential constituent of the fingerprint residue.[8] Apocrine glands located close to hair follicles secrete a viscous, milky fluid containing proteins, carbohydrates, cholesterol, and iron.[8] However, since apocrine glands are mainly present in parts of the body (armpit, groin, nipples) that are not normally in contact with the finger during daily use, apocrine secretion is not a likely constituent of the fingerprint residue. Latent fingerprint residues have also been observed to contain proteins,[7] possibly originating from eccrine sweat or the cells of the stratum corneum.[9] Sebaceous glands abundantly excrete sebum, which is mainly comprised of squalene, wax, and saturated fats,[7] and are in locations of frequent finger contact such as the face. Hence, the main possible constituents contributing to the contamination are eccrine perspiration, sebum, or a combination of both. The electric field can affect the behavior of all of these potential contaminants, which, in turn, can also affect the electric field distribution. Therefore, it is necessary to first identify the major constituents present in the fingerprint residue that cause preferential contamination in the haptic regions. Since the electric field at the interface is much higher in the haptic regions than the sensing regions and is thus a key contributor to the preferential contamination observed, it is necessary to explore how the electric field might give rise to different multiphysics phenomena at the interface.

Three commercial liquids (Pickering Laboratories and Biochemazone) were used to contaminate the screen artificially by placing a small amount of liquid on the screen and swiping with the finger after it was cleaned: the first was artificial eccrine perspiration, the second was artificial sebum, and the third was an emulsion of artificial eccrine perspiration and artificial sebum. The contamination pattern formed with each artificial fluid was compared to the pattern formed after regular usage with a naturally contaminated finger. It was found that only artificial sebum replicated the preferential pattern formed by natural contaminants (Figure S1a, Supporting Information). In addition, AFM scans showed that the contaminants showed negligible loss of volume even after 1 week of exposure to the open atmosphere (Figure S1b, Supporting Information), suggesting a negligible lack of evaporation. Thus, we can conclude that the preferential contamination observed primarily consists of sebum (Section S1, Supporting Information). Although the sebum deposited on the screen can be cleaned using acetone, isopropyl alcohol, and deionized water, it is inconvenient to do so regularly in a consumer electronic device. To tackle this issue, we need a better understanding of the behavior of sebum at the finger-device interface in electroadhesive haptic touchscreens. Thus, we next aimed to study the various electrokinetic and electrohydrodynamic phenomena that may cause the sebum to preferentially deposit on the haptic regions of the screen.

Electrohydrodynamics (EHD) refers to the study of the mutual effect of electrical and hydrodynamic forces on each other in systems containing fluids and subjected to electric fields. It has been observed that electric forces on spherical liquid droplets cause them to deform, and the deformations can be prolate or oblate, depending on the permittivity, conductivity, and viscosity ratios of the fluid droplet and the surrounding medium.[10] The shape evolution of small droplets in the presence of electric fields

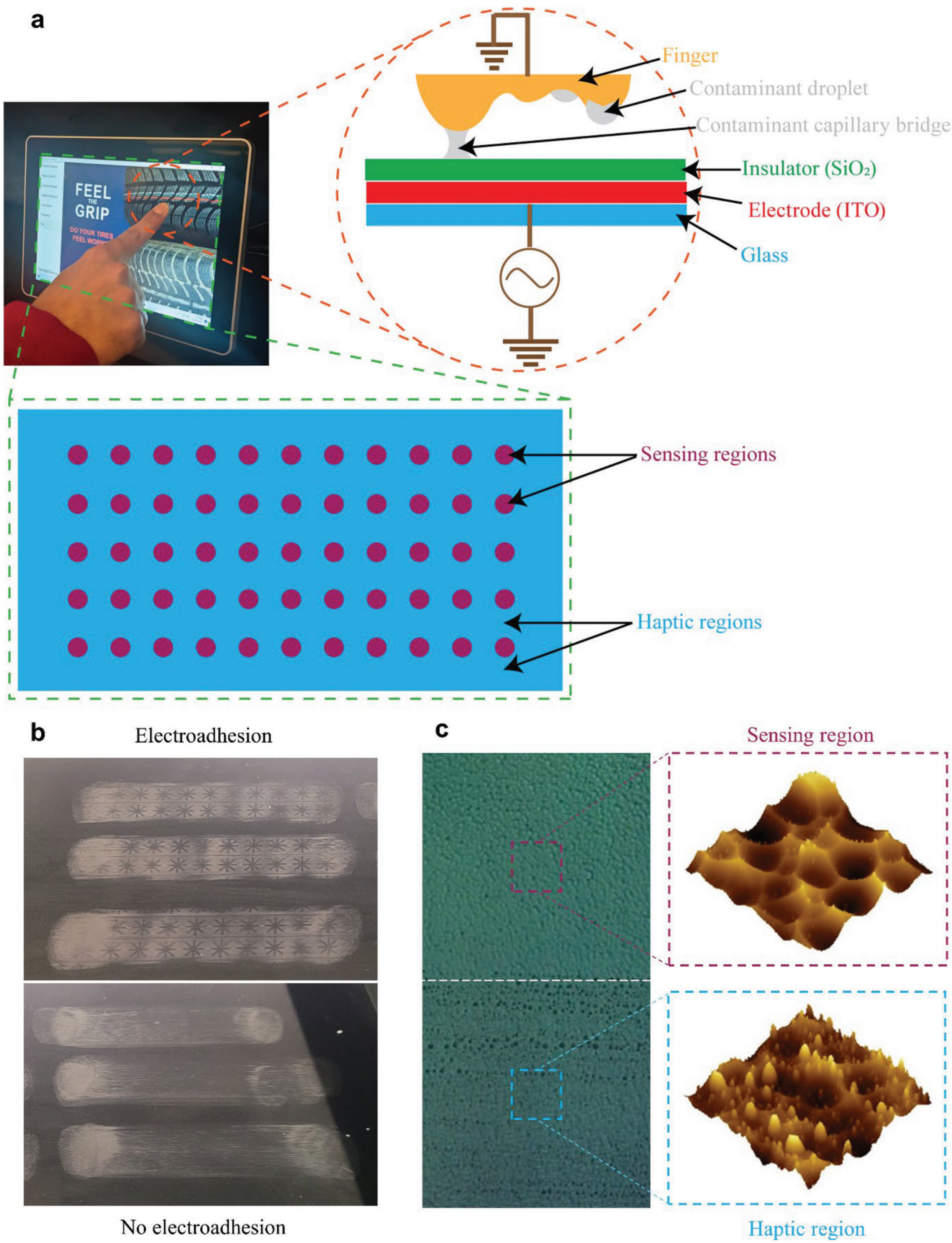

Figure 1. a) Schematic of the finger-device interface showing the contaminants present as a pendant droplet or a capillary bridge and a typical layout of a commercial electroadhesive haptic screen with underlying haptic and sensing regions. b) Visible increased and preferential contamination (electrode patterns visible) when electroadhesion is turned on; less and no preferential contamination (electrode patterns not visible) when electroadhesion is absent. c) Optical microscopy images and atomic force microscopy scans of the haptic and sensing regions of a textured electroadhesive screen showing

depends on the relative strength of the electric force in comparison to the surface tension force.[11] EHD has also been used as a drop-generation mechanism.[12] It has also been observed that in a multiphase system involving fluids with different dielectric permittivities, the application of an electric field stabilizes the liquid bridge.[13] This happens because the normal stresses generated by the induced polarization at the interface counteract the capillary forces causing perturbations and instability of the bridge.

Sebum is present on both the ridges and valleys of the skin fingerprint structure. While the droplets attached to the ridges readily form capillary bridges upon coming into contact with the screens, the droplets in the valleys remain attached to the finger in a pendant configuration with an air gap between the droplet and the screen.

If we have a sebum droplet attached to the fingerprint valley, a sufficiently high electric field might cause EHD deformation of the droplet. If the deformation is prolate in nature and the magnitude of deformation is large enough, it will come into contact with the touchscreen surface, thus forming a capillary bridge. When the finger slides across the screen, shear forces will cause the bridge to rupture, leaving behind additional sebum droplets on the surface of the screen. To test this hypothesis, we studied the EHD deformation of a grounded pendant sebum droplet subjected to an electric field. It was observed that the droplet deformation increases with increasing voltage, and ultimately forms a capillary bridge between the top plate and the bottom glass screen (**Figure 2**a). This suggests that EHD deformation of sebum droplets might cause additional capillary bridge formation and residual droplets being left behind in the regions of the high electric field upon rupture, thus leading to a visibly increased preferential contamination in the haptic regions of the screen.

If we have a capillary bridge already formed between the ridges of the fingertips and the screen, the increased stability of the bridge due to the electric field will allow it to stretch and travel further without breaking under the application of a shear force during sliding. Over multiple swipes, the bridge is more likely to come into contact with residual sebum droplets from previous swipes, thus coalescing and leaving behind progressively larger droplets upon rupture. To test this hypothesis, we conducted an experiment to see if capillary bridges are more stable in the presence of electric fields. We found that the neck diameter of the bridge increases with increasing voltage, thus increasing its thickness ratio (ratio of bridge diameter to bridge height) and making it more stable (**Figure 3**a and Figure S2b, Supporting Information). This suggests that electric fields have a stabilizing effect on capillary bridges, which might allow them to travel further and coalesce with other residual droplets before rupturing, leading to the formation of larger-sized droplets on the haptic regions of the screen.

We also investigated the possible contribution of electrowetting (Figure S2c, Supporting Information) and electrophoretic deposition (Figure S2d, Supporting Information) to preferential contamination, but our experimental results showed that these phenomena were not major contributors to preferential contamination (Section S2, Supporting Information).

2.2. Multiphysics Numerical Model

To further validate our hypotheses, a multiphysics numerical model was developed to simulate the finger-device interface in electroadhesive touchscreens. Electrical and fluid flow equations with appropriate assumptions were used to calculate the electric field distribution at the finger-device interface, while an interface tracking formulation was used to track the interface between the two fluids (sebum and air). Details of the numerical model are presented in Section S3, Supporting Information.

COMSOL Multiphysics (v 5.6) was used to couple the multiphysics multiphase system using the electrostatics and two-phase laminar flow, level set physics. A schematic of the model setup is shown in Figure S3, Supporting Information. The finger-device interface was approximated as a rectangular domain. The top wall of the domain represents the finger surface, and the bottom wall represents the screen surface. Because sebum has a low contact angle on the finger skin and a high contact angle on the glass surface, a capillary bridge subjected to a shear force is pinned to the more wetting surface (finger) and slides on the less wetting surface (glass). The bridge dynamics are mainly governed by the texture of the surface on which it slides, which is the glass surface in our case. Therefore, in our model, the finger has been modeled as a flat surface. This also makes it convenient to apply the relative motion using the "Wetted Wall" boundary condition since the velocity component at all points is parallel to the surface tangent. To capture any surface-texture-related effects of contact angle hysteresis on the sliding dynamics of the capillary bridge, the screen has been modeled as a rough surface based on the AFM topographical scans of the textured glass. In Figures 2, 3, and 5, sebum in different configurations (pendant droplet, sessile droplet, and capillary bridges) represents one phase (dark blue), while the surrounding medium representing atmospheric air represents the second phase (light blue).

The electric potential in the system was solved using the "Electrostatics" physics interface. A sinusoidal electric potential and ground were used as the boundary conditions for the bottom and top walls of the domain, respectively. A zero-charge boundary condition was imposed on the two side walls. At the finger-screen interface, both the fluid (sebum droplet) and the surrounding medium (air) have low electrical conductivities and can be considered as perfect dielectrics. The volumetric free charge density in such a system can be assumed to be zero.

The pressure and velocity in the system were solved using the "Laminar Flow" physics interface. Wetted wall boundary conditions with Navier slip wall condition and suitable contact angles were applied to the top and bottom walls. Additionally, a translational velocity was applied to the top wall to represent the swiping motion of the finger relative to the screen. An open boundary was used as the boundary conditions for the two side walls. The

preferential contamination; the underlying surface texture of the screen can be seen in the sensing regions (which have only a few small contaminant droplets), while multiple large contaminant droplets can be seen on the haptic regions.

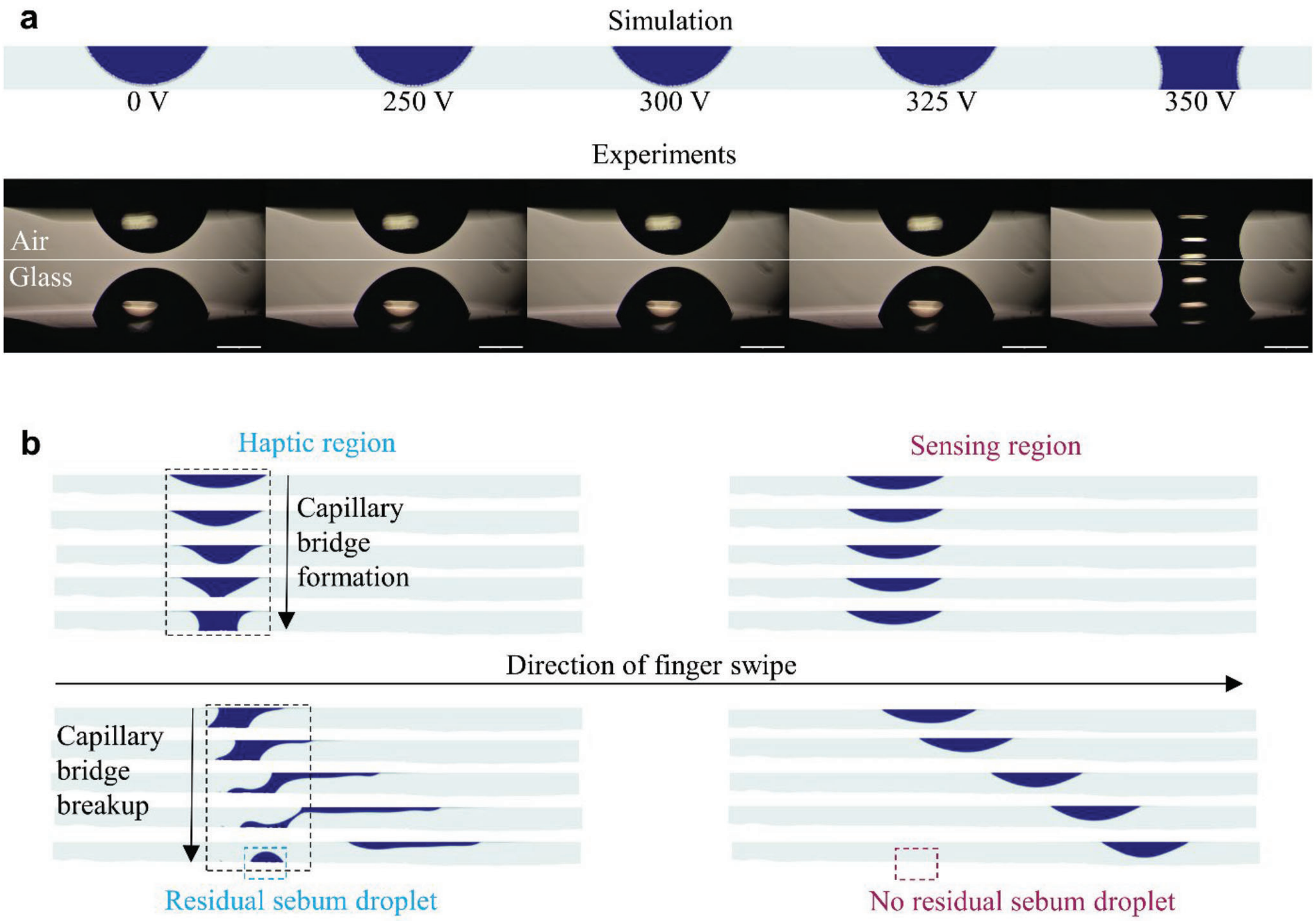

Figure 2. a) Multiphysics numerical model and large-scale experimental validation showing a pendant sebum droplet forming a capillary bridge due to EHD deformation in the presence of an electric field (scale bar = 375 µm). The deformations at 0, 250, 300, 325, and 350 V (left to right) are shown. b) Actual-scale simulation of a sebum droplet at the finger-device interface on a haptic region of an electroadhesive touchscreen showing that the electric field is strong enough to form a capillary bridge due to EHD deformation and eventually rupture due to shear forces generated during a finger swipe. This leaves behind additional residual droplets in the haptic regions; no such phenomenon occurs in the sensing regions due to the absence of an electric field.

electrostatic force given by the divergence of the Maxwell stress tensor was added as a volume force over the entire domain.

The "Level Set" physics interface was used to solve for the level-set variable and track the moving interface of the sebum-air multiphase system.

2.3. Mechanism of Preferential Contamination

As a first step, the multiphysics model was validated by carrying out experiments at a larger (mm) scale due to difficulties with illuminating and imaging across a micrometer-sized gap. They showed very good agreement with our numerical model (Figure 2a and Figure S2a, Supporting Information). The slight differences between the modeling and experimental results (Figure S2a, Supporting Information) can be attributed to the fact that the values of the physical properties of artificial sebum were approximated to be equal to those of natural sebum, while in reality there might be small differences between them.

Next, the model was used to simulate the finger-device interface at the actual (µm) scale and check if the electric forces are strong enough to show the same behavior as observed in our large-scale experiments. Previous studies[14] have shown that the continuum approximation holds well for the length scales greater than 10 nm, and the model can thus be extended to make predictions of the phenomena occurring at the finger-device interface, which have much larger length scales (close to 1 um). As mentioned previously, there may be two possible configurations that the sebum at the interface might be in—either as a pendant drop attached to the finger surface if it is on the valleys of the fingerprint, or as a capillary bridge between the finger and the screen surface if it is on the ridges of the fingerprint.

The modeling results in Figure 2b show that when the finger is in a haptic region, the EHD deformation of a pendant sebum droplet attached to the fingerprint valley is sufficient to touch the surface of the screen and form a capillary bridge. Upon shearing, this bridge ruptures, leaving behind a residual sebum droplet on the screen. Thus, the formation and rupture of additional capillary bridges leave behind a higher volume of sebum in the haptic

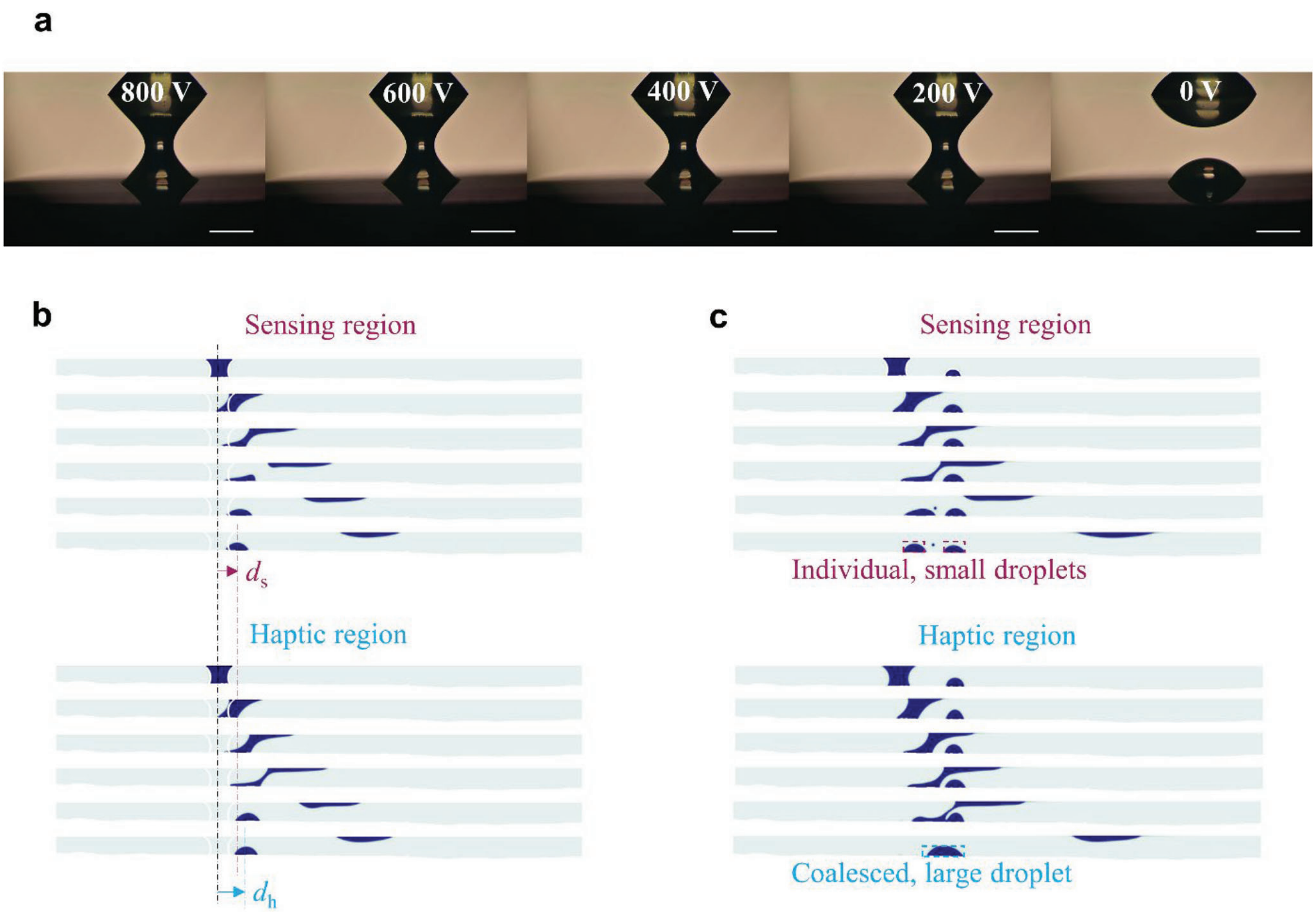

Figure 3. a) Experimental verification of the electric field-induced stabilization of a sebum capillary bridge. The neck diameter of the bridge at 800, 600, 400, and 200 V (left to right) decreases with decreasing voltage until it eventually breaks off at 0 V (scale bar = 375 µm). b) Multiphysics simulation showing that the increased stability of the capillary bridge allows it to travel a greater distance over the haptic regions (d_h) as compared to the sensing regions (d_s) (i.e., $d_h > d_s$) before rupturing under the action of shear forces. c) Multiphysics simulation showing that the larger distance traveled on the haptic regions causes the bridge to coalesce with a residual droplet before rupture, ultimately leaving behind a larger sebum droplet upon breakup.

regions. When the finger is on the sensing region, no electric field is present, and the droplet does not undergo deformation. Thus, no additional capillary bridges are formed in the sensing regions, predicting a lower volume of residual sebum in the sensing regions.

The modeling results in Figure 3b show that the electric field-induced stabilization of the capillary bridge allows it to travel a larger distance (d_h) laterally before it ruptures, as compared to the sensing region (d_s) where the electric field is absent. Here, d_h and d_s represent the distance between the initial position of the bridge (before rupture) and the final position of the residual droplet (after rupture) on the haptic and sensing regions, respectively. Due to its ability to travel a larger distance, a capillary bridge on the haptic region has a higher likelihood of coming into contact with a residual sebum droplet from an earlier swipe and coalesce. This coalescence increases the total volume of sebum in the capillary bridge, which ultimately leaves behind a larger residual drop on the screen upon rupture (Figure 3c). In the absence of any electric field, there will be no coalescence, and smaller, less visible individual drops would be left behind on the sensing regions of the screen.

For both possible sebum configurations at the finger-device interface (pendant droplet and capillary bridge), our model predicts that the haptic regions would show both an increased amount of contamination due to the EHD deformation of pendant droplets and larger-sized droplets due to the stabilization and coalescence between capillary bridges and residual droplets. To verify this prediction, a finger contaminated by touching sebum-rich areas of the scalp and the face was swiped on the electroadhesive screen. Optical microscopy images show that the total volume of residual contaminants increases with increasing voltage (Section S5, Supporting Information). AFM was used to scan the surface topographies of the screens and quantify the contamination distribution in the haptic and sensing regions as shown in **Figure 4**a, where the large wavelength features correspond to the surface texture of the screen and droplets appear as smaller, bright spots. Analysis of the scans across three different haptic and sensing regions confirm that the haptic regions have a statistically significantly larger total volume of sebum (p-value = 0.0089 using Student's t-test) as compared to the sensing regions (Figure 4b). It can also be observed that a much larger fraction of the sebum droplets in the haptic regions is larger in size as compared to the sensing

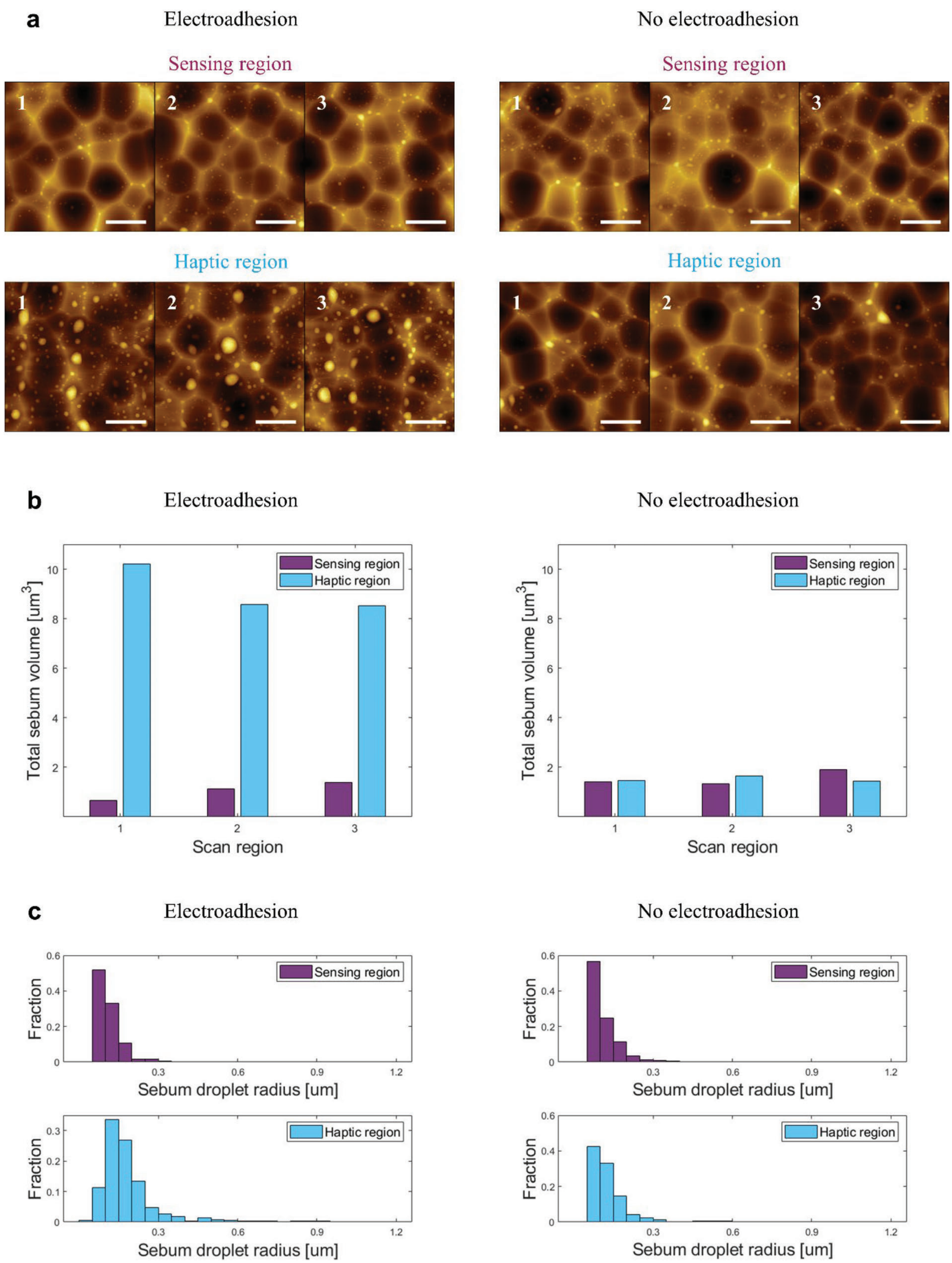

Figure 4. Surface characterization of contaminated haptic touchscreens. a) AFM scans showing preferential contamination on haptic regions in the presence of electroadhesion (scale bar = 5 µm). The haptic regions show b) a larger total volume of residual sebum and c) a greater fraction of residual sebum droplets of larger radii.

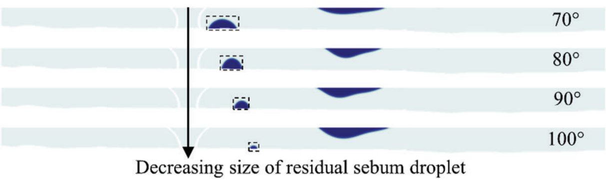

Figure 5. Proposed solution showing a lesser volume of residual sebum droplets on screens with higher sebum-glass contact angle.

regions in the presence of electroadhesion (Figure 4c). Both the larger volume and larger size of residual sebum visually appear as preferential contamination on the haptic regions of electroadhesive touchscreens. No such effect is observed when electroadhesion is turned off (Figure 4a–c).

2.4. Designing Solutions

With key mechanisms identified and a predictive model created, the model can now be used to explore solutions during the touchscreen design process.

It has been reported that increasing the wettability difference between two surfaces housing a capillary bridge decreases the amount of liquid transferred to the less wetting surface.[15] Since the contact angle of sebum on human skin is fixed, the only way to increase the wettability difference is by increasing the contact angle of sebum on the glass surface, that is, making it more oleophobic. Simulations were run for different contact angles ranging from 70° to 100°. The modeling results predict a reduction in the volume of the residual sebum droplet on the screens with higher contact angles (**Figure 5**). Smaller-sized residual droplets would cause very little increase in the total volume of sebum left behind on the screen. This would greatly reduce the appearance of preferential contamination on electroadhesive touchscreens.

In addition, since the volume of residual contaminants on the screen increases with increasing voltage (Section S5, Supporting Information), any technique that reduces the voltage requirement would reduce the volume of contaminants on the haptic regions compared to the sensing regions, and thus reduce the appearance of preferential contamination on the surface. Reducing the required voltage by optimizing the nanotexture shape of screen surfaces[5] or reducing the electroadhesion threshold with an increase in surface temperature[6] are examples of how this can be done.

3. Conclusion

The primary objective of this study was to understand the root cause of preferential contamination on the haptic regions of electroadhesive touchscreens and use this learning to build a predictive model that can be used to address this issue in the design of future screens. Several hypotheses were formulated and experimentally investigated to assess their potential contribution to increased deposition of fingerprint residue on the haptic regions of the screen. Sebum was determined to be the main constituent of the preferentially deposited fingerprint residue, and it can exist in two possible configurations at the finger-device interface: 1) a pendant droplet attached to the valleys of the fingerprints, and 2) a capillary bridge formed between the valleys of the fingerprint and the screen surface. The underlying mechanism causing preferential contamination can be attributed to contributions from two phenomena and can be explained as follows:

1) The electric field in the haptic regions causes electrohydrodynamic deformation of the pendant droplets attached to the valleys of the finger skin, leading to the formation of new capillary bridges. These newly formed bridges break when subjected to the shear force of the finger sliding over the screen, leaving behind an additional volume of sebum droplets on the haptic regions.
2) The electric field in the haptic regions stabilizes the capillary bridges existing between the finger ridges and the screen. This increased stability allows them to travel a larger distance laterally before rupture, thus increasing their likelihood of coalescing with other residual drops left behind on the screen from previous swipes. Over multiple swipes, the residual droplets get larger in size due to this stability-aided coalescence, resulting in larger-sized droplets over the haptic regions.

Thus, the cumulative effect of a larger total volume of sebum, as well as a greater fraction of sebum droplets of larger radii over the haptic regions compared to the sensing regions causes the visible preferential contamination on electroadhesive touchscreens.

We built and validated a multiphysics numerical model that can be used by designers to explore solutions and address this issue. As an example, we explored oleophobic glass surfaces with high contact angles as a possible solution. Other techniques that reduce the voltage required to produce the desired level of tactile effect (optimization of the nanotexture shape of glass surfaces or thermally assisted enhancement of electroadhesive tactile perception) have also been discussed. We realize that designing robust screens with such high contact angles for low surface tension fluids like sebum is challenging, and it would require multidisciplinary collaborative research to attain it, as well as develop other potential solutions.

4. Experimental Section

EHD Deformation: A droplet of artificial sebum was dispensed on a custom-built plate using a needle (Hamilton 91022) connected to a syringe (Hamilton 81120). The volume of the droplet (2.5 μL) was controlled with the help of a syringe pump (Chemyx Fusion 200). The plate was placed above an electroadhesive touchscreen with a small gap in between such that the sebum drop was in a pendant configuration, as in the finger-device interface. An electric potential was applied across the gap via a function generator (Siglent Technologies) in conjunction with a voltage amplifier (Trek 2210). To ensure that the electric force was not too high compared to the surface tension force (and thus ensuring the deformation/stabilization effect is not overestimated), the voltages applied were such that the electric Bond number was lesser than that at the finger-device interface in electroadhesive touchscreens (Section S4, Supporting Information). The deformation of the droplet was imaged with the help of a long working distance objective lens (Infinity K2 DistaMax) backlit by a light source passing through a telecentric lens (Edmund Optics TECHSPEC).

Electroadhesion Experiments: The electroadhesive screens used for the experiments were obtained from a commercial electroadhesive touchscreen (Tanvas MimoVue). A 120 V peak-to-peak voltage was supplied to the conductive layer of the screen and turned on and off at 15 Hz to render a generic tactile perception. This low-frequency pulse signal was modulated with a high-frequency carrier signal (at 20 kHz) to detect where the finger was located (using the sensing electrodes) at a fast rate and improve the consistency of the electroadhesive effect.[16] The contaminated finger was grounded by wearing an electrostatic discharge band wrist strap and then used to swipe the screen. This study was approved by the Institutional Review Board of Texas A&M University (IRB ID: IRB2019-0230D) and the participant took part with informed consent.

AFM Scans of Contaminated Screens: Surface characterization of contaminated electroadhesive screens was done using a commercial AFM (Jupiter XR, Asylum Research) system. To prevent the sebum droplets from contaminating the probe, a soft cantilever (AC240) was used. Imaging was done in AC tapping mode with a low amplitude to reduce the interaction forces between the tip and the sebum droplets. The droplets appeared as small peaks on the AFM scans and were clearly distinguishable from the underlying surface texture of the glass screens, which were much larger in size and look like valleys, as can be seen in Figure 4a. The sizes of the droplets were determined by extracting the areas enclosed by the sebum-air interface and calculating the equivalent radius of a circular region having the same area. The contact angle of the droplet was calculated from the topography of a line scan across the cross-section of a droplet. Using the radius and the contact angle, the volume of the droplet was then calculated by treating it as a spherical cap.

Supporting Information

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

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Conflict of Interest

J.E.C. and M.C. hold equity in Tanvas, Inc. Tanvas manufactures the haptic touchscreen used in this study. The remaining authors declare no conflict of interest.

Data Availability Statement

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

Keywords

electroadhesion, electrohydrodynamics, human-machine interfaces, surface haptics

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