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Contact Behavior of Sliding Fingers on an Electrovibration Display Under Varying Exploration Forces and Speeds

Celal Umut Kenanoglu   Yasemin Vardar

I. Introduction

Touchscreens are an essential part of modern life, widely used in electronic devices. However, most touchscreen interactions still lack tactile feedback, which diminishes the user experience and limits potential applications. Surface haptics aims to address this limitation by enhancing user interaction with touch-sensitive devices through precise and realistic tactile feedback, thereby improving usability and engagement [1]. One promising method for generating tactile feedback is electrostatic actuation, which applies an alternating voltage to the conductive layer of a touchscreen [1], [2]. This creates a periodic attractive force between the surface and the user's fingertip. Systematic modulation of the voltage produces a variety of tactile sensations, forming the basis of the haptic rendering technology known as electrovibration.

Although electrovibration technology on touchscreens is well established and relatively easy to implement, its broader application is still limited by an incomplete understanding of the contact mechanics governing finger–touchscreen interactions under varying touch conditions. During typical touchscreen use, users apply different normal forces and sliding speeds, both of which influence the contact dynamics between the finger and the surface. Therefore, understanding how these varying exploratory conditions affect finger contact behavior—with and without electrovibration—is essential for advancing future applications of this technology.

Motivated by this need, several studies have investigated the effect of applied force and sliding speed on the generated electrostatic force [2]–[4]. For example, Guo et al. reported that electrostatic force increased with increasing applied normal force [3]. Moreover, Balasubramanian *et al*. demonstrated that higher sliding speeds increase the bandwidth of electrovibration-induced finger friction, while they did not observe a significant effect of applied normal force [4]. Vardar and Kuchenbecker also showed that the generated electrostatic force and electrical impedance at the finger-display interface change significantly depending on whether the finger is stationary or in motion [2].

Despite these findings, a comprehensive investigation into how the combined effects of varying speeds and normal forces influence the contact behavior of fingers under electrovibration—such as changes in finger contact area, electrostatic force, electrical impedance, and their interrelations— is still lacking.

Here, we addressed this research gap by measuring real contact area, electrical impedance, and electrostatic force while participants slid their fingers under varying touch conditions. By combining these mechanical and electrical measurements, our goal is to bridge the gap between the mechanical and electrical aspects of the finger–surface interaction and clarify their respective roles in electrostatic actuation. To the best of our knowledge, this is the first study to integrate mechanical and electrical measurements to reveal correlations that provide insight into electrostatic actuation behavior across different speeds and forces.

II. Methods

We measured the finger contact area, electrical impedance, and the interaction forces of the first author's finger when he slid his finger on an electrovibration display. The display—a capacitive touchscreen actuated by applying an alternative high voltage signal—was mounted on two six-axis force sensors to measure contact forces, sampled at 10 kHz. A high-speed camera positioned below the glass captured the fingertip contact area using the Frustrated Total Internal Reflection (FTIR) technique. Finger motion was controlled by a motorized linear stage, with the finger contacting the surface at a fixed angle of 60°. Electrical impedance was measured by placing a differential probe and shunt resistor between the amplifier and the touchscreen.

Preliminary tests were conducted in two separate experiments performed in the morning and evening. The study was approved by the Ethics Council of TU Delft (app. no 5108). During each trial, the finger was moved at three constant speeds (10, 20, and 30 mm/s), while the participant applied a target force of 0.5, 1, or 1.5 N, guided by LED feedback. Data were recorded only when the force was within ±10% of the target and the fingerprint image was visible. A 100 V, 75 Hz sine wave was alternately enabled and disabled during the same sliding motion. Each force level was tested once per trial, and the full procedure was repeated three times.

The real contact area was calculated from the fingerprint images using the method described in [5] for the subsequent analyses presented in this paper. In the results section (Figures 1b, c, e, and f), we report the mean values of raw data across all trials. Electrostatic force was calculated using the equation $(1-\mu_{\text{off}}/\mu_{\text{on}})F_n$, where μ is the friction coefficient and F_n is the normal force. Electrostatic pressure is defined as the ratio of electrostatic force to contact area. Impedance is the ratio of input voltage to the measured current.

The authors are with the Department of Cognitive Robotics, Delft University of Technology, Delft, The Netherlands. E-mails of authors are: {c.u.kenanoglu, y.vardar}@tudelft.nl

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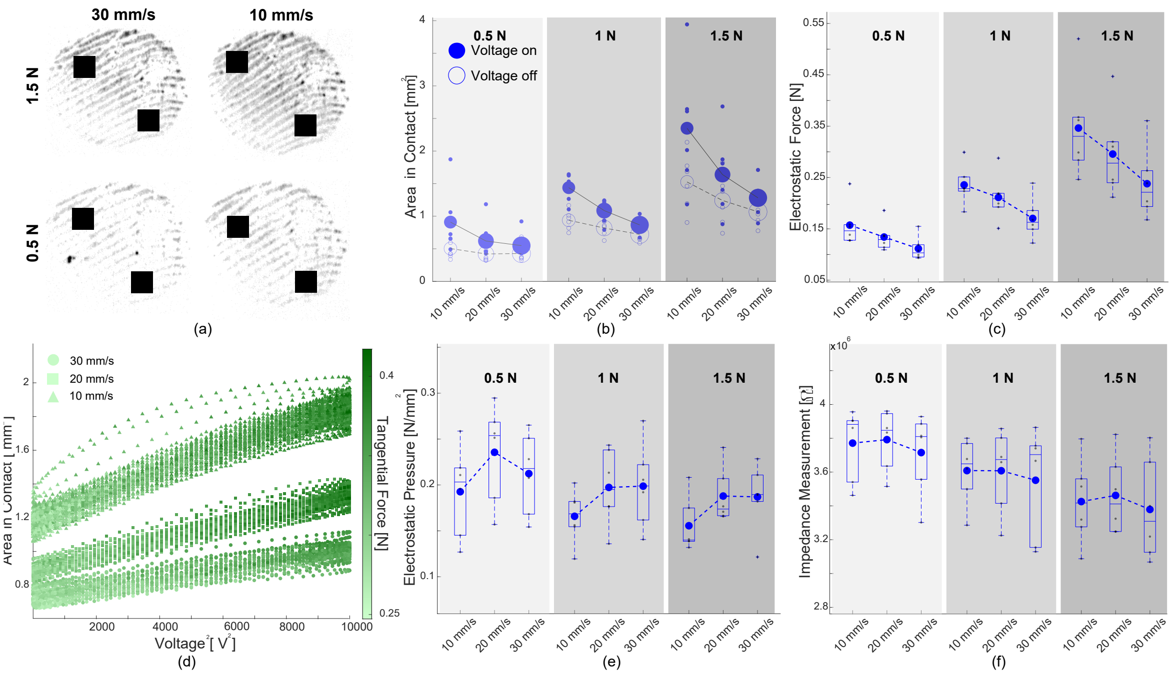

Fig. 1. (a) Example finger images, (b) contact area with the voltage turned on/off, (c) electrostatic force; (d) heatmap of contact area, tangential force, and voltage, (e) electrostatic pressure, and (f) total impedance of the finger–touchscreen interaction. Each blue circle represents the mean value across trials.

III. Results and Discussion

We experimentally showed the relationship between real contact area and electrostatic force under varying touch conditions. Contact area increases with higher normal force, lower sliding speed, and applied voltage, as shown in Figure 1a and b. Electrostatic force also increases with decreasing speed and increasing normal force, as illustrated in Figure 1c. This trend is consistent with previous findings under varying normal forces [3] and aligns with the parallel-plate capacitor model [6], which predicts that the electrostatic force is proportional to the contact area.

Real contact area and tangential force both increase with higher input voltage, as presented in Figure 1d. This indicates that applying voltage enhances both the skin–surface contact and the resulting frictional interaction. Additionally, lower finger speeds continue to yield higher contact area, confirming the trend observed in Figure 1b.

We also observed a relationship between electrostatic pressure and electrical impedance. Electrostatic pressure decreases as the applied force increases, as depicted in Figure 1e. For all speeds, the pressure is lowest at 10 mm/s, and highest for 20 mm/s except 1 N. Similar to electrostatic pressure, electrical impedance decreases as force increases (Figure 1f), consistent with previous findings [2]. The overall structure of Figure 1f is similar to Figure 1e. The measured electrical impedance captures the combined electrical behavior of the finger–surface system, which is influenced by both material properties and contact conditions.

Variations in impedance may be primarily influenced by changes in the air gap across different touch conditions. Lower normal forces are likely to result in a larger air gap, leading to higher impedance. Under these conditions, the stronger electric field may have a greater influence on contact area modulation, as the fingertip is more easily deformed by electrostatic attraction. This increased field-induced contact area, combined with the reduced mechanical preload, results in higher electrostatic pressure. It is surprising that the measurements of electrostatic force and total impedance do not show a clear correlation. However, more participant data is needed to better understand this relationship.

To the best of our knowledge, this is the first study to experimentally validate the relationship between contact area and electrostatic force. Our preliminary experimental results demonstrate a clear correlation between real contact area and electrostatic force, as well as a relationship between electrostatic pressure and electrical impedance under varying touch conditions. Future work will involve a larger participant pool to further validate and strengthen these findings.

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