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Vibration or Adhesion? Interfacial Shear Stress Transitions Govern Contact Behavior in Sliding Fingers under Electrostatic Actuation

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I. INTRODUCTION

Electrostatic actuation generates a force between objects, or fingers, that experience a difference in electric potential (voltage). Johnsen and Rahbek first described this phenomenon as *electroadhesion* under a fixed DC voltage [1]. They observed that this attractive force could increase friction between human skin and charged surfaces. Mallinckrodt *et al*. [2] later applied an alternating voltage to insulated metal electrodes and found that the resulting electrostatic force caused the finger to be periodically attracted to and released from the surface – an effect now known as *electrovibration*. Electroadhesion and electrovibration have often been used interchangeably in the literature and found applications in soft robotics, grippers, and tactile displays [3], [4].

Despite the interchangeable use of terms *adhesion* and *vibration* in the context of electrostatic actuation, these mechanisms produce fundamentally distinct physical effects that influence finger contact mechanics. Adhesion has been shown to increase friction by pulling the skin toward the surface [1], [2], whereas vibration induces oscillatory motion that can reduce friction [5], [6]. Interestingly, in electrostatic actuation, both effects originate from variations in the electric field but act in opposite ways—increasing friction in electroadhesion (adhesion effect) and decreasing friction in electrovibration (vibration effect). The interplay of these effects is largely unknown.

Electroadhesion creates an increase in the frictional force, which is often attributed to the increase in the real contact area, following the adhesion model proposed by Bowden and Tabor [7]. According to this model, the kinetic frictional force is defined as $F_t = \tau A_r$, where A_r is the real contact area composed of all the junctions made by contacting asperities and τ is the interfacial shear stress, which is the amount of stress applied to the contact area during sliding. So far, previous studies explain the increase in tangential force under electroadhesion by attributing it solely to the increase in real contact area [8], assuming that the interfacial shear stress remains constant.

In contrast, several studies have shown that tangential force decreases in the presence of mechanical vibration [5], [6]. Bochereau *et al*. demonstrated that, during fingertip–surface interactions, the real contact area is relatively insensitive to the dynamic loading rate. However, the interfacial shear stress –and consequently the tangential force– decreases as the loading rate increases [6]. Their results show that both interfacial shear stress and real contact area influence friction forces. The variations should therefore be jointly considered when studying electrostatic actuation.

In this work in progress, we demonstrate the existence of distinct vibration and adhesion regimes in electrostatic actuation. Electroadhesion increases both contact area and tangential force, whereas electrovibration reduces tangential force. This opposing interplay results in a decoupling between contact area and tangential force, leading to frequency-dependent variations in interfacial shear stress.

II. METHODS

We measured the finger contact area and interaction forces of four participants (three men, one woman; average age 27.6) while they slid their right-hand index finger across an electrostatically actuated capacitive touchscreen by applying an alternating voltage signal to its conductive layer. The touchscreen 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) [6]. Finger motion was controlled by a motorized linear stage at a fixed angle of 60°. The study was approved by the Ethics Council of TU Delft (application no 5108).

During each trial, the participant's finger was moved at a constant speed of 20 mm/s with a normal force of 1 N. Data was recorded only when the force was within ±10% of the target value, and the fingerprint image was visible. Voltage was alternately disabled and enabled at 100 V during the same sliding motion, applying 10 different sine wave frequencies ranging from 25 Hz to 2500 Hz, spaced logarithmically. Each session tested one frequency and included three repetitions. The real contact area was calculated from the fingerprint images using the method described in [9]. We report the values averaged across all trials and participants. We also modeled the reduction in tangential force under vibration using a quasi-static framework [5], which attributes the decrease to stick-slip behavior. This model is grounded in Amontons' law of friction and incorporates contact stiffness in both the normal and tangential directions, capturing frictional effects under oscillatory conditions.

III. RESULTS AND DISCUSSION

We observed that the real contact area of the fingertip oscillates at twice the frequency of the input voltage, in line

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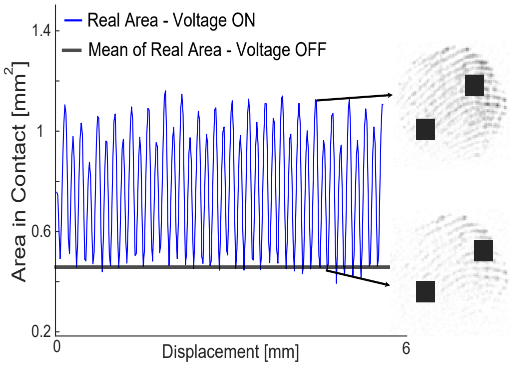

Fig. 1. Contact area versus finger displacement at a finger speed of 20 mm/s with example of contact area images when V = 100 V and V= 0 V.

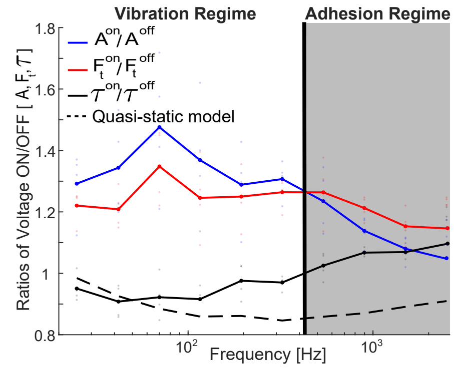

Fig. 2. Ratios of the area in contact, tangential force, and interfacial shear stress with voltage turned on and off with quasi-static model.

with electrostatic force behavior [4]. The contact area peaks at 100 V and is lowest at 0 V, matching the average area when electrostatic actuation is off, as shown in Figure 1.

We observed distinct trends in contact area, the ratio of the tangential force and the interfacial shear stress between voltage *on* and *off* conditions, as shown in Figure 2. The contact area ratio (A^{on}/A^{off}) is greater than the tangential force ratio (F_t^{on}/F_t^{off}) up to 420 Hz, where the interfacial shear stress ratio (τ^{on}/τ^{off}) remains below 1—defining the vibration regime. Beyond this frequency, the interfacial shear stress ratio equals or exceeds 1, indicating the adhesion regime. We conducted a statistical analysis to evaluate the difference across frequencies. Normality of the data was confirmed using the Lilliefors test. A one-way repeated measures ANOVA revealed a significant effect of frequency on τ^{on}/τ^{off} ($p < 0.001$). Post-hoc paired t-tests indicated significant differences in interfacial shear stress ratios between frequencies corresponding to the vibration and adhesion regimes ($p < 0.05$), highlighting a clear behavioral shift between these two regimes.

The reduction in interfacial shear stress at low frequencies ($<$ 420 Hz) can be attributed to the vibration effect of electrostatic actuation. A similar effect has been reported under dynamic loading on the fingertip [6]. Figure 2 shows that τ^{on}/τ^{off} was calculated using the friction predicted by this quasi-static model along with the ratio of contact area. The model agrees well with the experimental data in the low frequencies (below 120 Hz), where the error remains below 5%. As the frequency increases, the error gradually increases, reaching up to 11% in the vibration regime. The increase in error with frequency is likely due to the viscoelastic properties of the fingertip, which are not captured by the quasi-static model. At low frequencies, the fingertip exhibits primarily elastic behavior, while damping becomes more prominent above 100 Hz [10], introducing a delay in the harmonic response.

Our findings indicate that adhesion increases both friction and contact area, while vibration reduces interfacial shear stress and weakens the effect of adhesion on tangential force up to 420 Hz. Beyond this frequency, the fingertip cannot follow rapid motion changes effectively due to its natural frequency limit [10], [11]. As a result, the influence of electrovibration diminishes and adhesion becomes more dominant, which also explains the increased error of the quasi-static model at higher frequencies (Figure 2).

In conclusion, we observed and modeled the existence of distinct vibration and adhesion regimes in electrostatic actuation. Electroadhesion increases both contact area and tangential force, while electrovibration reduces tangential force, leading to a variation in interfacial shear stress. Our results show that the ratio of interfacial shear stress remains below 1 up to 420 Hz (vibration regime) and equals or exceeds 1 beyond this frequency (adhesion regime). This transition at higher frequencies is attributed to the diminished effect of electrovibration, as the fingertip is no longer able to follow rapid oscillations due to its natural frequency.

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