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# Surface Haptics via Electroadhesion: Expanding Electrovibration with Johnsen and Rahbek

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***Abstract*—This work aims to demonstrate and explain a nearly century old electrostatic haptic effect in human fingertips, which has since gone unreported. This effect, based on the original work of Johnsen and Rahbek [1], as well as research on electrostatic chucking devices [2], is capable of producing electrostatic forces on the finger an order of magnitude greater than those previously reported in literature. It is also capable of working with DC excitation, an aspect which stands out against previous reports which utilize purely AC excitation. This work also proposes a unified force model for this effect, drawn from electrostatic chuck research, and resolves this model with those in previous reports. We briefly discuss the background and specifics of the Johnsen-Rahbek effect, and include measurements made with our own electroadhesive surface and experimental apparatus. Finally, we discuss how this model fits in with previous observations, and its implications going forward.**

## I. Introduction

The work presented here is part of a larger research program called surface haptics. Surface haptics research asks the following question: how might one go about controlling the complex interactions between human fingertips and physical surfaces?

One popular answer to this question is based on varying the friction force (the lateral resistance to motion) of fingertips as they move on smooth surfaces. These variable friction displays are typically co-located with a visual display, and finger position is tracked by the system. The friction of the surface is then programmed to vary due to finger position, finger velocity, time, or any number of variables to produce complex tactile effects. One reason variable friction displays have come to receive considerable interest is because they can be seamlessly integrated into existing direct-touch user interfaces (e g. tablets and smartphones).

In one version of variable friction technology, ultrasonic vibrations act to reduce friction between the finger and the surface. In a second version, applied electric fields attract charge in the finger, pulling it to the surface and increasing friction. These types of displays have seen a wide variety of applications such as: increasing the physicality of touch interaction [3], influencing shape perception [4], rendering high fidelity textures [5], communicating emotion between partners [6], aiding the blind in navigation [7], and even turning everyday objects into expressive interactive surfaces [8]. With such a wide array of applications in mind, and with such seamless integration into existing interactions, these devices show great promise for the future of haptic interaction design.

While many early variable friction displays were based on the ultrasonic TPaD described by Winfield et al. in 2007 [9], comparatively little has been explored in the area of electrostatic displays since their modern introduction by Linjama et al. [10] and Bau et al. [11]. However, since electrostatic displays are inherently solid state and low power, two large practical advantages when compared to resonant ultrasonic devices, they have begun to garner greater attention. Despite this fact, the underlying principle of electrostatic attraction, or electrovibration as it is called in the literature, is not well understood, and principles for precisely controlling the effect have not been analyzed or established. The discussion below aims to answer some of these issues. Additionally, it aims to expand the concept of electrovibration by introducing the more general principle of electroadhesion.

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## II. Background

### *A. Electrovibration*

The current line of research concerning electrostatic variable friction displays dates back to 1953 when Mallinckrodt, by accident, noted that a certain brass electric light socket no longer felt smooth when the light was turned on [12]. As it turned out, the socket housing was connected to a live power wire, and current was flowing through the finger/surface interface. Using both bare and insulated aluminum plates, along with a 60Hz, 110V excitation, it was determined that an intermittent increase in friction was what created this peculiar resin-like feeling and faint 120Hz audible tone. It was theorized that either the outer keratin layer of skin or the varnish insulating layer acted as the dielectric of a capacitor. When voltage was applied, force developed between the capacitor plates, which were the metallic surface and inner conducive fluids in the skin. This AC effect was later given the name electrovibration and studied in more detail by Grimnes, who, again, used both bare and insulating surfaces [13]. Grimnes also noted that surface roughness seemed to have a certain effect, and the electrovibration intensity seemed to increase with the dryness of the skin. Measurements of the current flowing in the skin were in the microamp range, much below the traditional electro-cutaneous sensation limit of approximately 1 mA. Strong and Troxel were the first to use this electrovibration effect as a tactile display, forming an electrode pin array which could be independently excited with pulsed waveforms [14]. They also put forward the first

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mathematical model based on the previous capacitor plate explanation. Their model is given below:

$$F_e = \frac{A\varepsilon_0 V_t^2}{2\left(\frac{d_d}{\varepsilon_d}+\frac{d_s}{\varepsilon_s}\right)^2} \quad (1)$$

In this equation, the electrostatic normal force on the finger ($F_e$) is given in terms of the relevant area of contact ($A$), the permittivity of free space ($\varepsilon_0$), the total applied voltage between the electrode and ground ($V_t$), the thickness of the outer layer of skin ($d_s$) and dielectric insulating layer ($d_d$), and the relative permittivities of the skin ($\varepsilon_s$) and dielectric ($\varepsilon_d$) layers.

More recently, Beebe et al. developed a polyimide-on-silicon version of Strong and Troxel's tactile display [15], which was later used in tests with the visually impaired [16]. Little was mentioned, however, as to the underlying principle of the electrostatic effect. Psychophysical measurements have included voltage detection threshold in relation to dielectric layer thickness [17] and the polarity of the pulsed excitation waveforms [18]. The first systematic force measurements, however, were made by Meyer et al. [19], who recorded both normal and friction (lateral) forces as a subject's finger was driven across a commercially available surface capacitive touch screen (3M MicroTouch). This was the same type of device used in the TeslaTouch studies [4],[7],[11]. Using tribological methods, Meyer was able to infer the magnitude of additional normal force created when an AC excitation voltage was applied across the skin/surface interface. The general square law of the inferred normal force as a function of applied voltage was verified across several subjects, but the theoretical model used to describe the frequency dependence of the force seemed to be at odds with other recorded data. A conclusion of that work was that a more detailed electrical model of the finger/surface system was needed in order to accurately predict the electrostatically induced force. This more nuanced model, based on work done on electrostatic chucking devices, is presented later in this paper.

### B. Electroadhesion

The term electroadhesion is drawn from the 1923 work of Danish scientists Alfred Johnsen and Knud Rahbek [1]. Working with polished lithographic stone and metal surfaces, this term was used to describe the physical phenomenon of considerable adhesion which developed when the highly resistive stone was placed on top of a metal plate and a high voltage was applied between them. Interestingly, Johnsen and Rahbek also reported the use of electrostatic attractive forces on human fingertips some 30 years before the first report by Mallinckrodt. They even noted several key aspects of electrovibration, for instance, that force does not exist at DC with a completely insulating layer. They mentioned a previous design of the technology by an American inventor who employed a thin mica dielectric, but explained that, at DC, charge would quickly accumulate on the surface of the insulator and cancel any electroadhesive effect. They also mentioned that a faint tone twice the excitation frequency was heard as the finger

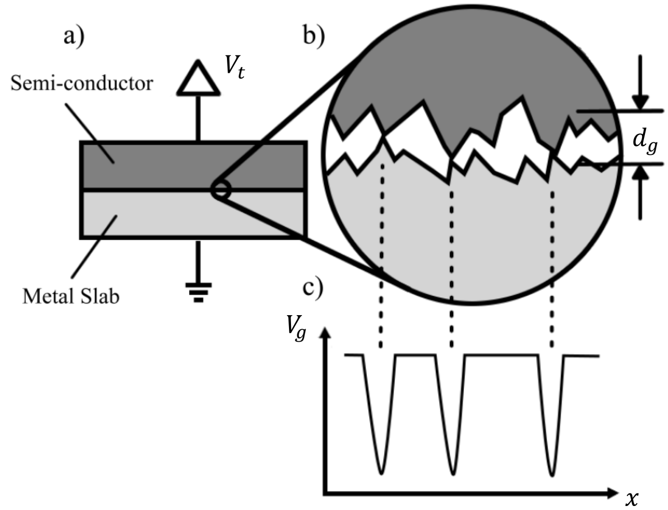


Figure 1. a) General setup of Johnsen-Rahbek devices b) Close up the contacting surfaces and the interface gap. Asperities keep the surfaces separated by approximately $d_g$ c) Voltage across the gap, $V_g$, plotted as a function of position. The voltage drops to zero at asperity contact points, but remains high elsewhere.

moved along the surface. The majority of their work, however, was focused on the DC version of the electroadhesive effect, as it was a highly intensified version of the AC effect. When the term Johnsen-Rahbek effect is used in literature, it solely refers to intensified electroadhesion with DC excitation.

An in-depth explanation of the Johnsen-Rahbek effect is beyond the scope of this paper, but a basic explanation is as follows. First, imagine a finely polished slab of semi-conductive material placed on top of a similarly smooth metallic plate (as seen in Fig 1a). Since the surface of the plate and the surface of the semi-conductor are highly polished, it would appear that the two materials are in intimate contact across their entire interface. However, due to the presence of microscopic asperities on the surface of each material (generally on the scale of microns), the area where the two surfaces come into real contact is a small fraction of the total apparent area of contact. There is, therefore, a non-uniform gap at the interface of the two surfaces (Fig 1b). This gap thickness is on the order of the average surface roughness of the two materials [20]. The gap is also composed primarily of air, as only a small set of highly resistive asperities from the slab of semi-conductor come into contact with the metal surface.

Next, imagine a constant voltage source is attached between the metallic plate and the non-contacting surface of the semi-conductor. Charge will make its way through the slab of semi-conductor and towards the gap at the interface, where it will then become constricted by the limited points of contact with the metal surface. It is this constricting geometry that can, in general, lead to high contact resistances between flat surfaces [21]. Since the only place for charge to travel is across the constriction points, these small points of contact will be the only place that the voltage drops to zero (Fig 1c). The majority of the interface, therefore, will have a very large voltage (though usually somewhat lower than the total applied voltage) across a gap that is only microns thick. Now, due to the fact that force on the plates of a parallel plate capacitor is inversely proportional to the square of the plate separation, the force across the air gap at the interface can be surprisingly large, with one researcher recording a measured adhesive pressure of nearly 10 N/cm$^2$ at a total applied voltage of 100V [22], and estimated gap voltage of 40V [23].

The explanation given above matches closely with the original one given by Johnsen and Rahbek in 1923, which has since been further investigated and validated. In 1950, Balakrishnan repeated the results of Johnsen and Rahbek, but instead used various magnesium and titanium oxides to get rid of the humidity dependence of the original devices [24]. Soon after, Stuckes further polished the metal surface to achieve nearly four times higher adhesive forces. She also put forward the idea of constricting resistance points at the interface, and an electrical circuit model to make sense of the data [22]. This approach was subsequently taken further by Atkinson, who incorporated Stuckes' initial explanations into a model that predicted anomalies in Stuckes' data at higher voltages [23]. Little additional progress was reported in the literature until Watanabe's creation and investigation of modern day electrostatic chucks with doped alumina [25]. Further work by Kanno [26], [27] and Qin and McTeer [2] combined the previous models into an electrical circuits based equivalent model, which is the basis of the model described later in this paper. We will briefly overview this model in the context of electrostatic chucks before applying it to human fingers.

### C. Johnsen-Rahbek Force Model

The force model for electrostatic chucks begins with the description of two electrically relevant layers. The first layer consists of the bulk of the semi-conductor material, which, in the literature, has been called the dielectric layer. This name is leftover from purely AC electrostatic chucks, where this layer is a pure dielectric with essentially infinite resistivity. In the context of Johnsen-Rahbek, however, the dielectric can be said to be leaky, that is, it has a finite resistivity that allows charges to pass through it. The second electrical layer consists of the dielectric/metal surface gap. As stated above, this layer consists mostly of a thin layer of air, with a small set of resistive asperities. The model then follows from two simple assertions. First, the only relevant force in the system is that which develops across the thin gap of air at the interface:

$$F_e = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{V_g}{d_g}\right)^2 \quad (2)$$

Equation (2) is simply the standard equation for force on an air filled parallel plate capacitor in terms of the gap separation ($d_g$), relative gap permittivity ($\varepsilon_g$), permittivity of free space ($\varepsilon_0$), area ($A$), and gap voltage ($V_g$). Note that the relevant area of the gap technically includes only the non-contact air gap sections, however, since the real area of contact is typically much smaller than the overall apparent area of contact, the latter is used in most contexts. To get a feel for this equation, consider a gap voltage of $V_g = 100\text{V}$, a gap thickness of $d_g = 1\mu\text{m}$, and a relative permittivity of $\varepsilon_g = 1$ (air), which would yield a predicted electrostatic pressure of 4.4 N/cm$^2$.

In reality, however, for a total applied voltage of 100V, the actual voltage across the gap will be somewhat lower. This is because of the model's second stipulation, which is that the gap voltage ($V_g$) is an attenuated version of the total applied voltage across the dielectric and gap system. If we model the system as two resistances in series, this is simply a resistive divider:

$$V_g = V_t \frac{R_g}{R_d + R_g} \quad (3)$$

$R_g$ is the previously mentioned gap contact resistance, and $R_d$ is the bulk resistance of the dielectric layer. Taken together, (3) and (2) lead to:

$$F_e = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{V_t}{d_g} * \frac{R_g}{R_d + R_g}\right)^2 \quad (4)$$

From this equation, we can see that, in order to achieve the maximum force possible for a given voltage, we must ensure $R_g \gg R_d$, that is, have a contact resistance that is much higher than the dielectric resistance. Additionally we must minimize $d_g$, that is, use contacting surfaces that are as smooth as possible. It is with this model in mind that we set out to find a suitable surface for finger-based electroadhesive devices.

## III. DC Electroadhesion with Human Fingertips

### A. Material and Model

We investigated many materials in an effort to find an appropriate surface for DC electroadhesion and human fingertips. As described in the original Johnsen and Rahbek paper, electroadhesion can be achieved with a bare metal plate and human fingers, as the outer layer of the skin can act as a somewhat resistive dielectric. Due to the highly variable nature of human skin, however, we soon discovered that it is highly advantageous for practical devices to have a surface coating on top of the bare metal plate. Furthermore, surface coatings need to offer high electrical resistivity, have minimal roughness, achieve excellent coating conformity, and ideally be easy to create or acquire. One material that fits these requirements, and has been found to offer good electroadhesive capabilities, is anodized aluminum. Indeed, similar doped alumina electrostatic chucks have been shown to have good DC electroadhesive properties [25], and anodized aluminum was used recently in electrovibration [8] for an AC electroadhesive effect. For our tests, we used 6061 anodized aluminum.

Another important factor in designing the electroadhesive system is the excitation source. We chose to use a current control amplifier, specifically a Trek model 610C high-voltage capable amplifier. This amplifier has a trans-conductance mode that allows the user to control an output current given an input voltage. The chief benefit of current controlled excitation is safety. Current was limited to no more than 100μA in our tests. Voltage was also limited to under 1kV. As noted in [8], these currents and voltages are

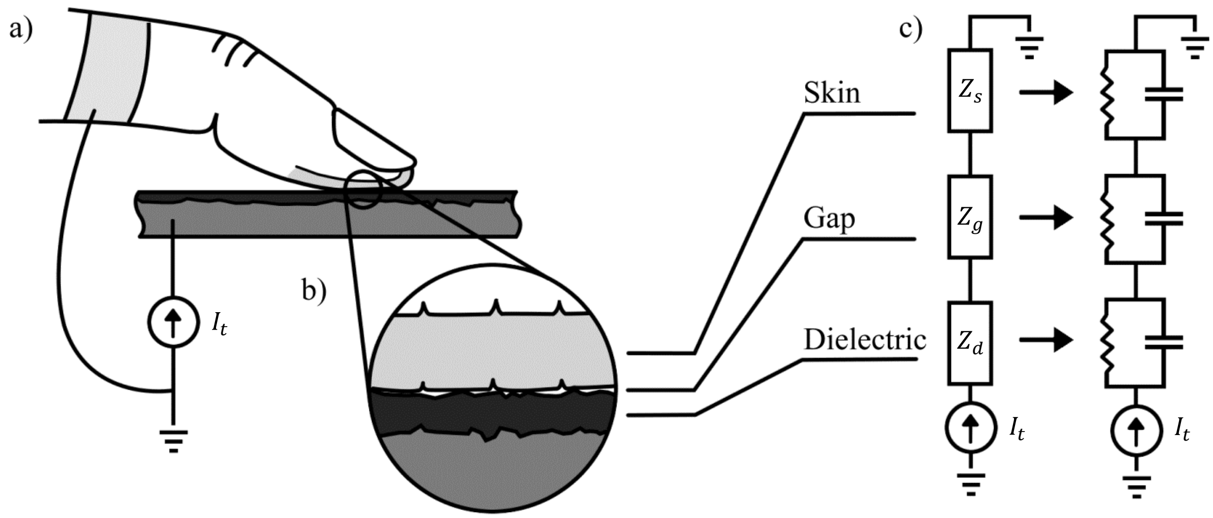


Figure 2: a) Overview of entire electrical system b) Detail of the skin/anodized aluminum interface, showing approximate geometry (not to scale) of the 3 electrical layers c) Generalized system impedance model, and equivalent RC impedance model. Model assumes force develops across $Z_g$.

much less than those experienced with static shocks occurring in day-to-day life, and they pose no known health concerns.

With a different system setup and excitation from traditional electrostatic chucks (Fig 2a), we must now also edit (4) to represent the skin/anodized aluminum system (Fig 2b). First, we can add in the additional skin layer to the resistor divider term:

$$F_e = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{V_t}{d_g} * \frac{R_g}{R_d+R_g+R_s}\right)^2 \quad (5)$$

Where $R_d$ now represents the bulk resistance of the anodization layer (previously the dielectric layer), $R_s$ represents the bulk resitance due to the outer layer of the skin, and $R_g$ represents the constriction resistance of the gap interface. Furthermore, if we note that:

$$V_t = I_t R_t = I_t(R_d + R_g + R_s) \quad (6)$$

We can combine (5) and (6) to yield the governing equation for our system at DC:

$$F_e = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{I_t R_g}{d_g}\right)^2 \quad (7)$$

Here we see that for a current controlled excitation, the force on the skin depends not on the entire system as shown by (5), but only on the constriction resistance of the skin/surface interface. A similar effect has been noted before with electrovibration devices, at it can lead to more consistent forces across multiple skin/surface interfaces [8]. Equation (7) helps explain why this is the case.

### *B. Parameter Measurements*

Though (5) or (7) are relatively simple, the parameter values are non-trivial to calculate. For $A$ we ensured a constant area by using a 150μm thick, electrically insulating plastic disc inserted between the finger and anodized aluminum. The disc was 12.5mm in diameter and had a 6.4mm diameter hole in the center of it which allowed the finger to electrically contact the anodized aluminum with an area of 32.17mm$^2$. Relative permittivity of the gap is assumed to be that of air, close to 1.

To estimate $R_g$, we used a method similar to [26]. We first measured the total system resistance $R_t$ by recording the applied current and resulting voltage during normal finger exploration. This was done via current and voltage monitor connections provided by the amplifier. We then measured the total system resistance with the contact resistance shorted out, (i.e. $R_d + R_s$) by placing conductive silver paste between the finger and the anodized aluminum. This conductive silver paste essentially causes $R_g$ to go to zero, as it fills the gap interface, ensuring intimate electrical contact. This measurement was made immediately after force data was taken. We then subtracted $R_d + R_s$ from $R_t$ to give an estimation of the contact resistance $R_g$. It is important to note that this estimate is prone to error, as it is well known that DC skin impedance can vary due to a wide variety of factors [28],[29], and because the skin/surface interface can change drastically with the addition of sweat or oils dirtying the surface. Nonetheless, by measuring resistances during and immediately after exploration, we estimated a contact resistance of approximately 7MΩ.

A measurement of the anodized aluminum surface roughness was made using a Zygo 3D optical surface profilometer. The average roughness was 0.34μm. A similar measurement of an alginate cast made of a finger pressing against a hard surface was made, but, as the distribution of surface heights was highly non-Gaussian, a single roughness parameter for the skin was difficult to compute. Numbers for this value in the literature are typically on the order of 20μm [30], yet data taken on our casts seem to indicate typical roughness below 5μm. This may be because the skin is flattened out under applied pressure. Further investigation as to the value of the $d_g$ parameter is needed. We can, however, conclude that, of the two contacting surfaces, the skin appears to be rougher than the anodized aluminum.

### *C. Force Measurement*

Using a tribometer similar to Meyer et al. [5], we measured normal force and lateral force as the lead author freely explored the surface. Normal force was measured using two strain gauge based load cells, while lateral force was measured using a high bandwidth, piezoelectric load cell. The lead author swiped left and right across the surface, using a metronome to maintain a speed of approximately 10cm/s. The excitation used to approximate DC was a 0.1Hz square wave, alternating between 0-100μA. Accordingly, the total voltage applied across the 8MΩ system impedance was approximately 800V. It was observed that over the course of several minutes of use the electroadhesive effect would become significantly stronger and then stabilize. This is possibly due to drying of the skin, which would, in turn, increase the gap resistance. Because of this, data was taken over the course of 500 seconds, and the first 250 seconds were excluded. An example plot of the data recorded can be seen in Fig 3. Each point on the graph represents the average of a single swipe left or right over the 250 seconds. Linear functions were fit to each set of data (current on and off).

From these data, we can estimate the additional normal force due to electroadhesion, in much the same manner as Meyer et al. [19]. We see an additional electrostatic normal force of approximately 7N. Using (7) and our parameter measurements, this corresponds to an effective gap thickness of 1.8μm. As mentioned above, this would seem to indicate that the skin is deformed under the applied pressure, similar to the behavior reported in electrostatic chucks [27].

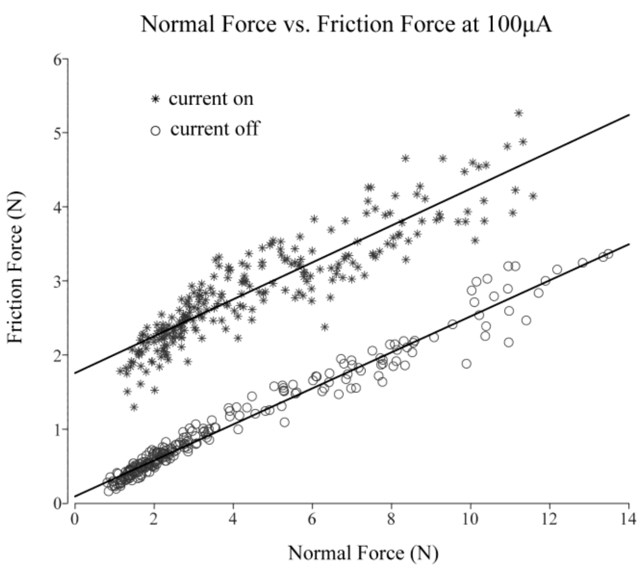


Figure 3. Each point is the time average of one swipe left or right. A friction force of 2.5N corresponds to a normal force of 3N with the current on, and 10N with the current off. The difference in normal force, 7N, is assumed to be the additional electroadhesive force.

## IV. Discussion

### A. Extension of Force Model

Up until this point in our discussion we have treated only the DC case, allowing us to model the solid layers as pure resistors. While this is a safe assumption for large timescales, it must be lifted if we are to extend the model to AC electroadhesion (i.e. electrovibration). To generalize, we model the impedance of each electrical layer as a resistor in parallel with a capacitor:

$$Z_x(\omega) = \frac{R_x}{1+j\omega R_x C_x},\ x = d, g, s \tag{8}$$

Where $x$ denotes the dielectric, gap, or skin impedance layer respectively (see Fig 2c). Replacing the resistor divider in (5) with an impedance divider, we obtain a generalized equation for force as a function of frequency:

$$|F_e(\omega)| = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{V_t}{d_g} * \left|\frac{Z_g(\omega)}{Z_d(\omega)+Z_g(\omega)+Z_s(\omega)}\right|\right)^2 \tag{9}$$

Equation (9) is, therefore, the proposed generalized force equation that extends a model of DC electroadhesion into the AC regime. This result may be compared to both Johnsen-Rahbek and electrovibration models by examining the impedance divider term at both low frequencies ($\omega \to 0$) and high frequencies ($\omega \to \infty$).

### B. Model at Frequency Extremes

Looking at (8), we note that for low frequencies, $Z_x$ reverts back to $R_x$, and the impedance divider term turns into a resistor divider as seen in (5). It is also interesting to note that (5) also explains why traditional electrovibration devices will not work with DC excitation. If we allow $R_d$ to go towards infinity (by using a perfectly insulating dielectric) we see that the model predicts the electroadhesive force will go to zero. This prediction aligns well with reports given in the background literature above, which state that charge will leak across the interface gap and collect on the surface of the insulator, negating adhesive effects.

If we instead look at (8) at high frequencies ($\omega \to \infty$), we see that the capacitor dominates over the resistor, and we have an impedance of $1/j\omega C_x$. The impedance ratio then becomes a capacitive divider and (9) turns into:

$$F_e = \frac{A\varepsilon_0\varepsilon_g}{2}\left(\frac{V_t}{d_g} * \frac{C_d C_s}{C_g C_d + C_g C_s + C_d C_s}\right)^2 \tag{10}$$

With a few simplifying assumptions, (10) can be put into a more familiar form. First, we can replace each capacitance term with the general capacitor equation $C_x = A\varepsilon_0\varepsilon_x/d_x$, and perform some algebra to produce:

$$F_e = \frac{A\varepsilon_0 {V_t}^2}{2\varepsilon_g\left(\frac{d_d}{\varepsilon_d}+\frac{d_s}{\varepsilon_s}+\frac{d_g}{\varepsilon_g}\right)^2} \tag{11}$$

If we assume $\varepsilon_g = 1$ (for air), we see that (11) takes the form of (1) proposed by Strong and Troxel with the addition of a $d_g$ term. We have therefore shown that, by modeling each electrical layer as a resistor and capacitor in parallel, we can extend force models from the Johnsen-Rahbek effect literature to incorporate dynamic electroadhesive effects. Note, however, that $\omega$ will typically neither be zero nor essentially infinite, therefore we must rely on equation (9).

## V. Conclusions

By unifying Johnsen-Rahbek and electrovibration force models, we can now see that both stem from the same underlying mechanism: Coulombic attraction across a very small air gap. The Johnsen-Rahbek effect typically means DC electroadhesion, while electrovibration refers to the purely AC version, but the fundamental difference between the two is academic. It is with this explanation that we hope to clarify the underlying principle of electrovibration, and offer some additional implications going forward.

First, we see that the model given above predicts a theoretical maximum electrostatic force for a given gap geometry and voltage, as expressed in equation (2). This equation is encouraging for the future of electroadhesive displays, as it implies that considerably high normal forces can be applied to bare skin for only milliwatts of electrical power.

Second, we can see that we will never be able to attain this maximum force, as there will always be an attenuation ratio of $|Z_g(\omega)|/|Z_t(\omega)|$ for voltage controlled setups. This effect can somewhat be mitigated by utilizing current control, but the maximum force will nonetheless fall off with $|Z_g(\omega)|$. Because these electrical impedance effects can come to dominate the overall force equation, it is vital that any further investigation into the nature of the electroadhesive force make an effort to characterize the system as a whole, including the relevant properties of the skin/surface interface. It is this detailed characterization that was most likely missing from the data presented in [19]. In that work, it was observed that the force seemed to follow a fractional-order model with frequency. This behavior could be due to the dispersive nature of human skin, which is well documented in the literature [32], and has since been applied to electrovibration [33]. Therefore, with a proper measurement of the relevant system impedances in (9), the correct magnitude of the force as it evolves with frequency could be calculated.

## ACKNOWLEDGMENT

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