

# Fingertip Friction Modulation due to Electrostatic Attraction

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## ABSTRACT

The human fingertip is extremely sensitive to lateral (shear) forces that arise in surface exploration. We and others have developed haptic displays that work by modulating surface friction via electrostatic attraction. Despite the demonstrated ability of these displays to render haptic environments, an understanding of the fingertip-surface interface is lacking. We have developed a tribometer for measuring the lateral frictional forces on a fingertip under well-controlled conditions. We show an expected square law dependence of frictional force (and inferred electrostatic normal force) on actuation voltage, although we observe a large person to person variability. We model an expected dependence of the frictional force on the frequency of the actuation voltage, predicting a first order cut off below about 500Hz. However, our measurements are unambiguously at odds with the model's predictions.

**Keywords:** Tactile devices and display; Haptic rendering; Texture rendering.

**Index Terms:** H.5.2 [Information Systems]: User Interfaces—Haptic I/O

## 1 INTRODUCTION

The study of surface haptics focuses on tactile interactions between a fingertip and a physical surface. There exist many tactile displays that successfully render haptic environments explorable by a human fingertip on a surface. Because lateral (shear) force has been shown to create a powerful percept in human haptic exploration[15], many designs have focused on controlling surface friction to affect lateral force.

Most devices which control surface interaction forces do so through mechanical actuation. Nara et al[13] used surface acoustic waves to reduce the effective friction of a linear slider. Focusing on the bare finger, Watanabe and Fukui[20] built a device which created a sensation of “smoothness” when ultrasonic vibration was applied to the surface. This smoothness was attributed to a small film of air that develops between the surface and fingertip. The Tactile Pattern Display (TPaD) [11, 21] combines finger position sensing with ultrasonic vibration to create customizable textures on a glass surface. The ShiverPaD[5], ActivePaD[12], and LateralPaD[6] implement active lateral forcing on fingertips touching a glass surface.

Mechanical actuation, especially at ultrasonic frequencies, requires a significant amount of energy. While system resonances can be exploited to reduce energy loss, this limits the design flexibility of such devices. With the ever-increasing presence of touch

interfaces on mobile devices, purely electronic tactile displays show promise of practical application. Electronic tactile displays fall into two categories. *Electrocutaneous* displays stimulate tactile receptors in the fingertip by passing small amounts of electric current through the skin. *Electrostatic* displays use electrostatic attraction forces to increase the friction force on a finger sliding across the surface. Recent contributions from Bau et al. (TeslaTouch)[3] and Linjama et al. (E-Sense)[9] have shown the viability of electrostatic displays for low-power versatile applications.

## 2 BACKGROUND

Mallinckrodt et al.[10] first observed “electrically induced vibrations” in 1953 while touching a high voltage AC conductor coated with a thin layer of insulator. This effect was determined to be a mechanical interaction between the surface and fingertip induced by an intermittent electrostatic attractive force between the skin and conductor[7]. Electrostatic force was first used in haptics when Strong and Troxel[17] developed an electrode-array display, which used friction enhanced by electrostatic attraction to generate texture sensations on a surface. In their study, they observed that the intensity of the vibration sensation was primarily due to the peak applied voltage. Beebe et al.[4] developed a polyimide-on-silicon tactile display that used electrostatic force to create 100 Hz pulses of high friction to render textures or vibration on a surface. In a following study, Tang and Beebe[18] showcased the haptic ability of this display with tests by visually impaired subjects of detection threshold, line separation, and pattern recognition.

Researchers have since used human detection threshold to study the electrostatic effect further. Agarwal et al.[1] observed the relationship between dielectric thickness and voltage at the detection threshold, and Kaczmarek et al.[8] investigated the differences in detection for positive and negative voltages. While these efforts have studied human response to electrical stimulations, none have measured the mechanical effect of electrostatic attraction, and a detailed understanding of the finger-surface interface is still lacking.

Based on an ideal parallel plate model with no fringe fields, the electrostatic force across an insulator is given by:

$$F = \frac{\epsilon A V^2}{2 d^2} \quad (1)$$

where  $\epsilon$  is the permittivity of the insulator,  $A$  is the area of the conductors, and  $d$  is the insulator thickness. The voltage,  $V$ , is the voltage difference between the two conducting layers. Because the distance,  $d$  is typically very small (a few microns) to generate substantial force, this attraction force is difficult to measure. Any force transducer between the finger and surface changes the electrical configuration drastically. For this reason, an indirect tribological investigation of the interface mechanics is used in this study.

The tribology of the fingertip has been examined by several researchers. Tomlinson et al.[19] used a simple device with two load cells to determine a relationship between normal force and lateral friction force under voluntary motion on a variety of surfaces.

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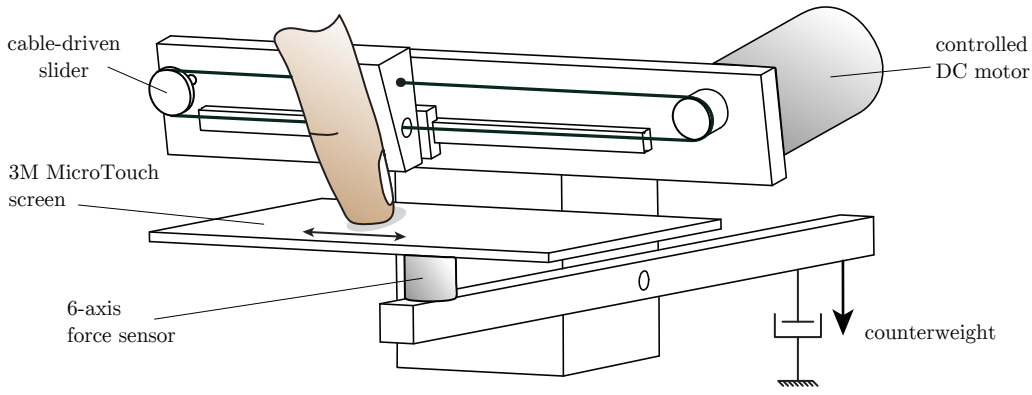


Figure 1: Tribometer drawing

André et al.[2] used a prism mounted on a multi-axis force sensor to image the fingertip during the transition from stick to slip contact. Pasumarty et al.[14] used a tribometer which controlled normal force and velocity to show that fingertips experience increasing friction forces after 20-30 seconds. This friction increase was attributed to moisture increase due to sweat gland occlusion. These efforts have established the large variance in fingertip friction, and emphasize the importance of controlling experimental conditions. In this paper, we present a device capable of measuring fingertip friction on a surface haptic display while carefully controlling normal force and velocity. We measure and quantify the friction modulating capabilities of electrostatic friction tactile displays, and infer the electrostatic normal force that causes an increase in friction.

### 3 METHODS

#### 3.1 Generating Electrostatic Force

The tactile display used in this research is a 3M MicroTouch screen, chosen because of its availability and construction. The screen consists of two thin layers deposited across the entire 6.7 inch diagonal glass substrate. The first layer on top of the glass is a thin layer of indium tin oxide (ITO), a transparent conductor roughly 40 nanometers thick. Atop the ITO sits a slightly textured layer of silica about one micron thick. The silica is the outermost layer and is in contact with the fingertip. Although this device was designed as a finger position sensor, these layers can also be used to generate electrostatic force on a fingertip. A schematic highlighting the relevant layers and electrical components is shown in figure 2.

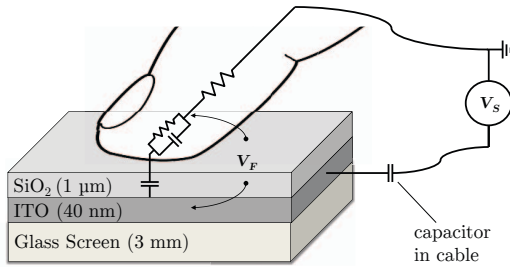


Figure 2: Finger-surface interface schematic

The outermost layer of skin, or stratum corneum, is approximately 200 microns thick at the fingertip and consists mostly of dead skin cells. This layer is modeled with a capacitor and resistor in parallel. The voltage,  $V_F$ , which generates electrostatic force on the finger is the potential drop from the ITO to the conducting

tissue beneath the stratum corneum. An AC excitation voltage,  $V_S$ , is applied to the screen's connector, which allows only capacitive coupling to the ITO layer. Therefore, the impedance of this coupling capacitor must be taken into account when assessing the  $V_F$ . A high-voltage piezo amplifier generates the supply voltage, and the base of the finger is grounded through the skin via a copper foil band. As a safety mechanism, a current limiter is used to cap the current at 6 mA.

To determine the electrostatic force on the finger, the parallel plate capacitor model is modified for the finger-surface interface. The capacitor has two insulators in series, the silica and the stratum corneum, as well as a free charge between the layers,  $Q_F$ , which leaks through the stratum corneum. Using virtual work principles to derive the electrostatic force on the finger gives:

$$F_e = \frac{\epsilon_0 A \left( V_F^2 - \frac{Q_F^2}{C_i^2} \right)}{2 \left( \frac{d_{sc}}{\epsilon_{sc}} + \frac{d_i}{\epsilon_i} \right)^2} \quad (2)$$

where  $\epsilon_{sc}$  and  $\epsilon_i$  are the relative permittivities of the stratum corneum and insulator,  $d_{sc}$  and  $d_i$  are the thicknesses,  $\epsilon_0$  is the permittivity of free space,  $C_i$  is the capacitance of the insulator, and  $A$  is the contact area.

Since  $V_F$  and  $Q_F$  are time dependent, the system dynamics plays an important role in the force generation. The free charge on the surface increases due to leakage current through the stratum corneum, at a rate determined by that layer's RC time constant. Because electrostatic force diminishes with the migration of charge to the surface of the silica, the force on the finger is frequency dependent. Modeling the system with resistors and capacitors as shown in figure 2 gives transfer functions for  $V_F$  and  $Q_F$ . Plugging the frequency responses into equation 2 results in a prediction of the force generated as a function of actuation frequency. This simple RC model predicts diminishing force generation below a first-order knee frequency due to stratum corneum resistivity. Using skin properties previously published[22], the resistivity and dielectric constant of the stratum corneum at 1 kHz are  $\rho_{sc} \approx 33 \text{ k}\Omega\text{m}$  and  $\epsilon_{sc} \approx 1000$  respectively. These values predict a knee frequency,  $f_c$  as follows:

$$f_c = \frac{1}{2\pi R_{sc} C_{sc}} = \frac{1}{2\pi \rho_{sc} \epsilon_0 \epsilon_{sc}} \approx 550 \text{ Hz} \quad (3)$$

The predicted knee frequency depends only upon the electrical properties of the stratum corneum. Since these properties are highly variant with respect to skin hydration, the knee frequency is rather uncertain.

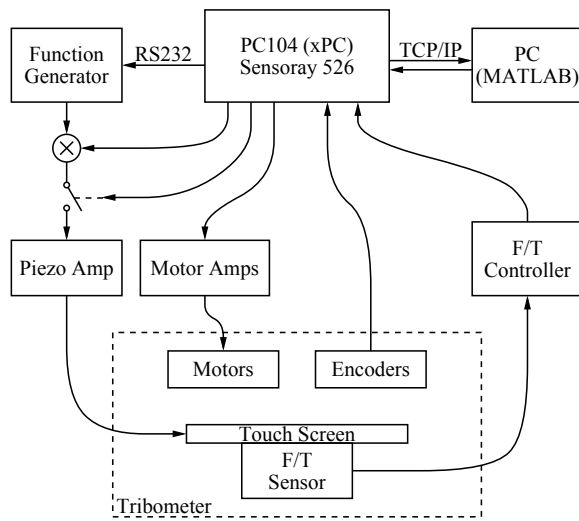


Figure 3: Experimental setup

### 3.2 Measuring Fingertip Friction

To quantify the force under different conditions, we built a tribometer to make precise measurements of finger friction, shown in figure 1. Preliminary measurements have shown an electrostatic friction force of around 100 mN. For this reason, a very high-sensitivity transducer is needed to accurately measure friction changes due to electrostatic attraction. Because the electrostatic effect causes rapid changes in friction, a high-bandwidth sensor is needed to properly capture these effects. The ATI Nano17 force/torque sensor chosen for this experiment offers 3mN resolution and has a resonant frequency of 7200 Hz. The sensor itself is mounted just below the tactile surface on a balance beam which presses into the finger with a normal force controllable by counterweights. To prevent vibratory motion, the balance beam is magnetically damped.

The finger is held by Velcro straps in a sliding carriage, which is driven translationally by a motor and capstan drive to reduce variation in finger velocity. To control the motor's velocity, a shaft encoder is used in a velocity feedback loop. The encoder has 2400 counts per revolution, resulting in a translational resolution of the slider of  $2\pi(6.35\text{mm})/2400$ , or about 20 microns. The control system is implemented on a PC104 stack running Matlab's xPC real-time operating system. An RS232-controlled function generator feeds into the high-voltage piezo amplifier. The xPC machine records all system data at 1kHz and transmits it via TCP/IP to a PC running Matlab.

A friction measurement begins by raising the screen up to the finger, and swiping the finger back and forth across the screen with a trapezoidal velocity pattern. Beginning on the left side of the screen, the finger is dragged back and forth several times. During an even swipe, the electrostatic effect is switched on when the finger is on the right-hand side of the glass; during an odd swipe, the left-hand side is the active portion. Data observed when the electrostatic effect is off is used to establish a baseline friction model.

Each subject washed his or her hands prior to beginning the experiment, and talcum powder was used to dry the fingertip and eliminate friction effects due to moisture. Every forty five seconds, the finger was removed from the surface for twenty seconds to prevent build up of moisture due to occlusion.

## 4 RESULTS

We tested the tribometer by measuring friction while a 10 Hz sine wave was applied to the screen's input. In figure 4, the raw data from one finger swipe is shown above the touch screen electrical

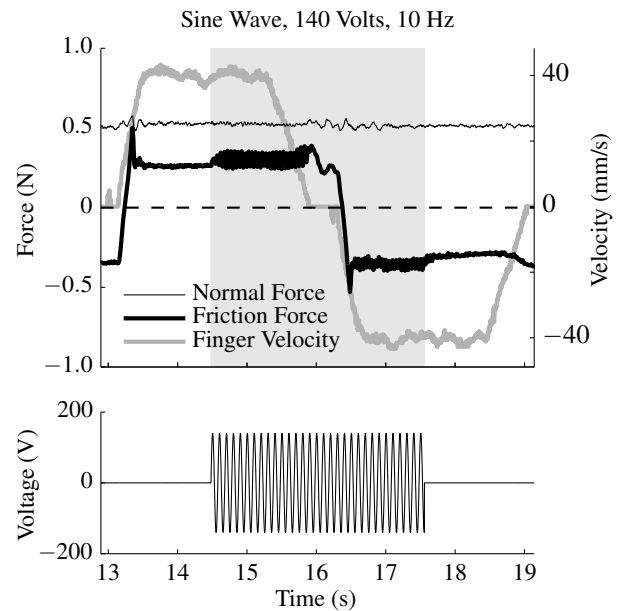


Figure 4: Overview of raw data with a 10 Hz sine wave electrostatic effect.

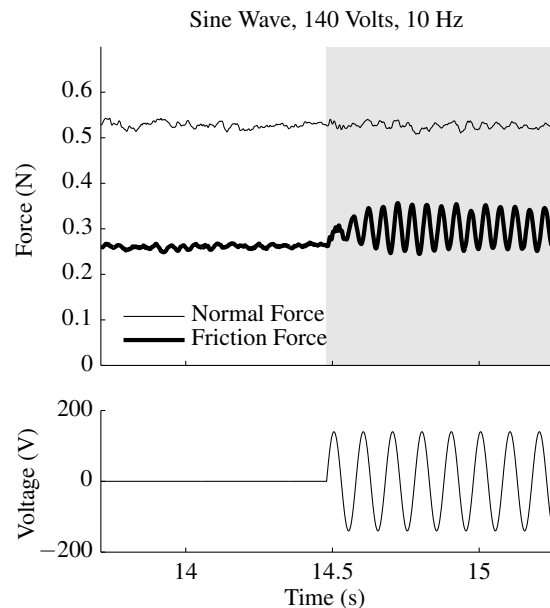


Figure 5: Close-up of raw data during electrostatic effect switch time. Supply voltage is 10 Hz, friction is oscillatory at 20 Hz.

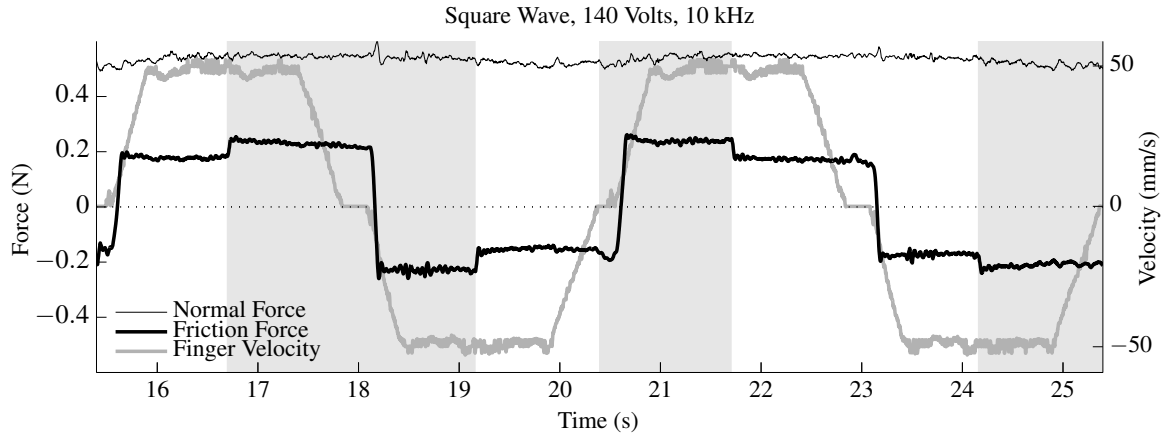


Figure 6: Overview of raw data taken for 10 kHz. An even swipe is shown followed by an odd swipe.

input in the bottom subplot. The gray area also indicates when the electrostatic effect is turned on. Close inspection of the normal and friction forces reveals a time varying force occurring at the surface, shown in figure 5. The peaks in the lateral friction force occur each time the input voltage reaches an extremum, regardless of sign. Because of this, the electrostatic effect is twice the frequency of the actuation signal, at 20 Hz in the case shown. These data verify that changes in frictional force are caused by the presence of an electric field, and that those changes are measurable by the tribometer.

If instead, a high-frequency square wave is used for actuation, the friction force is no longer oscillatory at 20 Hz, but is continuous. Figure 6 shows these raw data taken for a 140 volt 10 kHz square wave electrical input. When the supply voltage is turned on, during the gray portions of the plot, the friction force is greater than without any electric field. Because these steady forces are easier to compare across experiment trials, 10 kHz square waves are used to study the relationship between voltage and force.

The measured normal and friction forces were averaged across constant velocity segments, reducing the effect of measurement noise. Measuring friction at several different normal forces gives a local model for fingertip friction, seen by plotting on a friction versus normal force plot. As an example, figure 7 shows two data groups, one for data points during which the electrostatic force was present, and one for when it was not. The data taken when electrostatics is off provide a model for fingertip-surface friction, and the vertical difference between data points represents the increase in friction due to electrostatics.

The fingertip-surface friction shows a linear relationship between friction and normal force, which follows the Coulombic model of dry friction. Performing a linear regression on these data gives a friction coefficient,  $\mu$ . Assuming  $\mu$  itself does not change due to electric field, the increase in friction force can be attributed to an electrostatic attraction force, inferred by the equation:

$$F_e = \frac{\Delta F}{\mu} \quad (4)$$

where  $F_e$  is the electrostatic force,  $\mu$  is the slope determined by regression, and  $\Delta F$  is the average change in friction force. For each swipe of the finger, the change in lateral force,  $\Delta F$ , was calculated. Gathering all these values gives an average and a standard error, which are propagated through equation 4 resulting in an electrostatic force and confidence interval. Using the data shown in figure 7 the electrostatic force is 250 mN, with a standard error of 10 mN.

*Voltage Dependence:* The above analysis was completed for several input voltages, ranging from 60 volts to 140 volts. A log-log

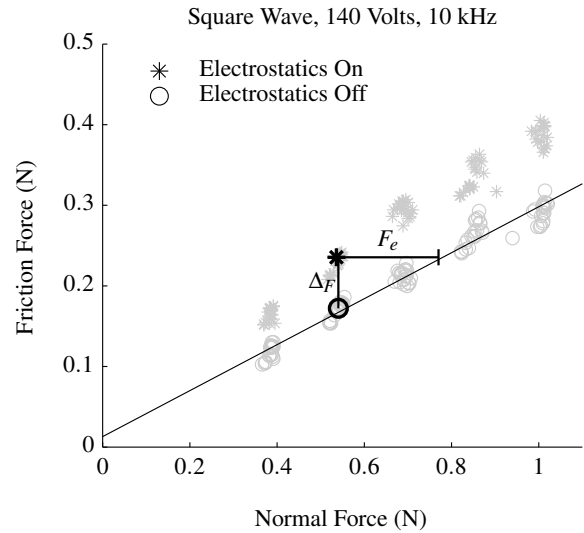


Figure 7: Sample lateral versus normal force plot of averaged data.  $F_e = 0.25$  N with standard error 0.01 N

plot of voltage versus electrostatic force is shown in Figure 8. Because of the series capacitance in the cable of the 3M touch screen, the voltage levels applied to the input cable do not correspond to the force generation voltage,  $V_F$ . While all subjects were able to detect the transient change when electrostatics was switched on and off, the measured lateral force generated varied significantly across subjects. All subjects showed increasing force with voltage relationship, the exponent of which was determined by fitting a line on a log scale. These exponents are shown in figure 8, and have mean 1.92.

*Frequency Dependence:* To observe the dependence of inferred electrostatic force on actuation voltage frequency, sine waves of 140 volt peak amplitude were used. Because of the high-frequency components of square wave signals, sine waves must be used when studying the frequency dependence of electrostatic force. Sine waves of 140 volt amplitude were used to maximize the signal to noise ratio in the force measurements. Repeating the experiments for frequencies ranging from 100 Hz to 10 kHz, the relationship between frequency and electrostatic force is shown in figure 9. As the frequency of the supply voltage signal increases, the force exhibited on the finger increases as well, but it does not match the shape

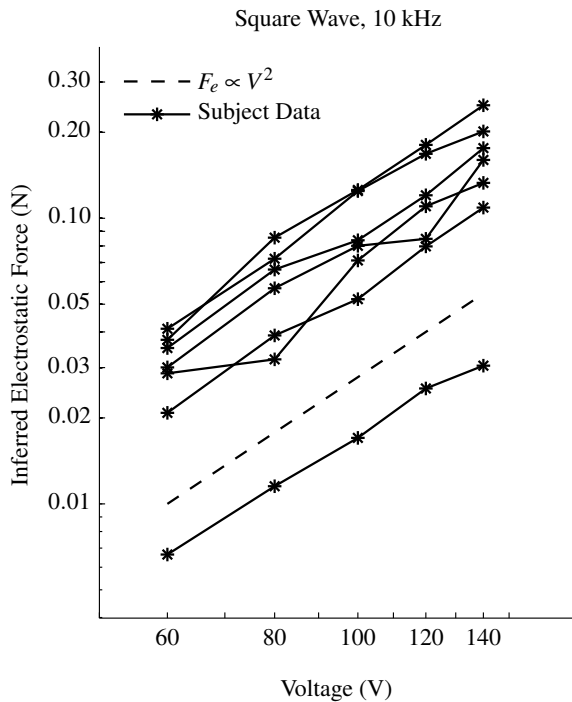


Figure 8: Log-log plot of inferred electrostatic normal force versus supply voltage at 10kHz square wave. Subject data points have average standard error of 5.4 mN. Mean exponent of the data 1.92, the dashed line shows an exponent of 2.

predicted by the simple dynamic RC model.

## 5 DISCUSSION

Past studies[1], have called into question the simplified parallel-plate capacitor model. However, these efforts operated under the assumption that human detection threshold was constant. Our research eliminates the human factor by directly measuring the interaction force at the surface-finger interface. Our data show a clear proportional relationship between electrostatic force and the square of supply voltage, which supports the capacitor model given in equation 2. However, the dynamic RC model from section 3.1 does not correctly model the charge leakage through the stratum corneum.

Detailed electrical modeling of the finger and screen system is needed to predict  $V_F$  and the force it generates. The RC model of the finger dynamics described earlier predicts a first-order knee frequency. While our data does show higher force measurements at higher frequencies, the shape of the curve shown in figure 9 is not characteristic of the prediction. The appearance is more in line with a fractional-order model, which is often associated with multi-scale effects[16].

The electrostatic effect shows promise in the field of haptics with the capability of producing lateral forces as high as 100 mN. This is similar to previously reported ultrasonically actuated surface haptic displays. The ShiverPaD generated 100 mN of lateral force using low frequency ( $\sim 800$  Hz) in-plane vibrations[5], and the LateralPaD generated 70 mN of lateral force with ultrasonic vibrations both in and out of plane[6]. These comparisons indicate that the electrostatic effect has potential applications not only in passive devices, but also in active devices intended to place a force on a stationary finger on the surface.

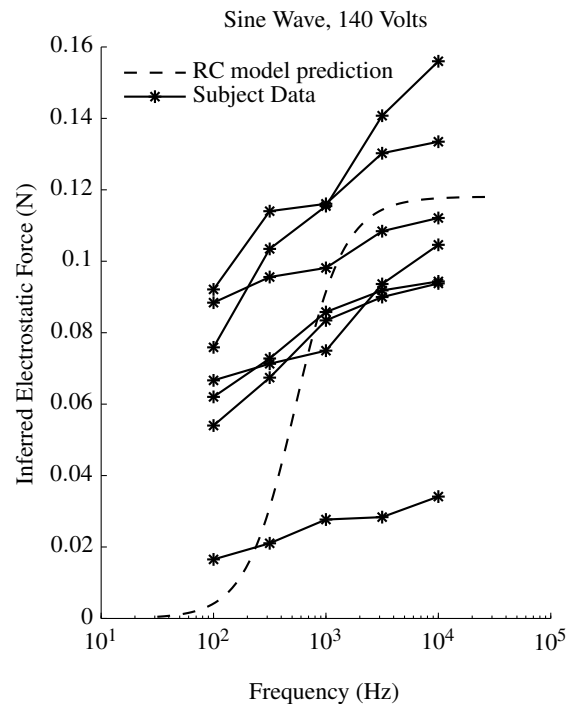


Figure 9: Inferred electrostatic normal force versus supply voltage average frequency. Prediction does not model the relationship properly. Subject data points have average standard error of 4.4 mN.

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