The Effect of Applied Normal Force on the Electrovibration

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Abstract— Electrovibration has become one of the promising approaches for adding tactile feedback on touchscreen. Previous studies revealed that the normal force applied on the touchscreen by the finger affects significantly the electrostatic force. It is obvious that the normal force affects the electrostatic force if it changes the contact area between the finger and the touchscreen. However, it is unclear whether the normal force affects the electrostatic force when the apparent contact area is constant. In this paper, we estimated the electrostatic force via measuring the tangential force of the finger sliding on a 3M touchscreen at different normal forces under the constant apparent contact area. We found that the electrostatic force increases significantly as the normal force increases from 0.5N to 4.5N. We explained the experimental results using the most recently proposed electrostatic force model, which considers the effect of air gap. We estimated the averaged air gap thickness using the electrostatic force model. The results showed that the relationship between the air gap thickness and the normal force follows a power function. Our experiment suggests that the normal force has a significant effect on the air gap thickness, thus require consideration in the design of tactile feedback.

Index Terms— electrovibration, electrostatic force, normal force, haptics

1 Introduction

Touchscreens are popular in the market of consumer products, such as smartphones, tablets, and laptop computers. Although those devices allow users to interact with digital content by clicking and sliding, a major problem with touchscreens is the lack of real tactile feedback such as texture, thermal and weight. If the content presented on the touchscreen could be displayed by both visual and haptic channels, it may greatly enhance interactive experience and alleviate burden on the visual channel.

One of the major approaches to develop tactile feedback on the touchscreen is friction modulation, which falls into two categories. The first is referred to as squeeze film effect [1, 2], which decreases friction between the finger and surface by generating mechanical vibration above the ultrasonic frequency. The second is referred to as electrovibration [3, 4], which increases the friction of the fingertip by the electrostatic force between touchscreen and fingers. Currently, electrovibration has received a more notable focus due to low power consumption and easy scaling, which is very suitable for commercial touchscreen devices.

While freely interacting with the electrovibration device, users usually apply different normal forces to the surface. Previous studies showed that users perceived different intensity of the electrovibration while different normal force was applied to the touchscreen surface during sliding [5]. Moreover, the applied normal force affects the perception threshold of the electrovibration [6]. These observations suggested that the applied normal force may affect the electrostatic force during interacting with the electrovibration device. The models for electrovibration indicated that the electrostatic force depends on the apparent contact area between the finger and the touchscreen [7, 8, 9]. Therefore, it is obvious that the normal force affects the electrostatic force if it changes the apparent contact area. However, it is unclear whether the normal force affects the electrostatic force when the apparent contact area is constant. The goal of this research is to find an answer to this question.

In this paper, we demonstrate by an experiment that the electrostatic force increases as the normal force increases, even though the apparent contact area is constant. The main contributions of our work are summarized as follows:

1) We proposed a method to keep the apparent contact area constant while finger slides on the touchscreen with different normal forces.
2) We demonstrated that the electrostatic force increased with the increased normal force while the apparent contact area was constant.
3) We explained the above result using the most recently proposed electrostatic force model which included air gap as an influencing factor. We estimated the relationship between the thickness of the air gap and the normal force, which was described by a power function.

The remainder of this paper is organized as follows: in section II we describe the related work. In section III, we

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estimated the electrostatic force via measuring the tangential force of the finger sliding on a 3M touch screen while keeping the finger apparent contact area constant. The experimental results are provided in section IV. In section V we discuss the results. Finally, the conclusion of our work is given in section VI.

2 Related work

Since electrovibration was discovered [4, 10, 11], various haptic devices have been developed. Strong and Troxel [12] firstly developed a tactile interface on the electrode array based on electrovibration. Various patterns could be displayed on this device by controlling each electrode individually. E-Sense [13] and TeslaTouch [14] were realized on the commercial transparent touch screen, which demonstrate that electrovibration could integrate easily with the widely used touchscreens. Hiroshi et al.[15] developed an electrostatic tactile display for creating local electrostatic force, which is induced by the beat phenomenon in a region where the excited X electrodes cross the excited Y electrodes. An augmented reality (AR) electrovibration device was presented in [16]. This device employed the principle of reverse electrovibration, in which a weak voltage signal is applied on the user body. Senseg [17] and Tanvas [18] applied electrovibration to touch screens such as smartphones and tablets. Recently, some flexible tactile devices based on electrovibration were developed [19, 20]. Beebe et al. [21] fabricated a polyimide-on-silicon electrostatic fingertip tactile display, which can generate the sticky perception at the fingertip using 200-600 V voltage pulses.

Input voltage plays an important role in generating electrovibration stimulus [22, 23, 24]. Different parameters of the voltage have been studied. Strong and Troxel [12] showed that the intensity of the electrovibration sensation primarily depends on the peak applied voltage rather than current density. Agarwal et al. [25] studied the relationship between the input voltage and the thickness of the insulator layer. They showed that the thickness has little effect on the threshold. Kaczmarek et al. [9] investigated the perceptual sensitivity of finger to polarity of the input voltage. They found that tactile sensation of electrovibration is more sensitive to negative or biphasic pulses than that for positive pulses. Wijekoon et al. [26] studied the intensity of the electrovibration. Their experimental results showed that there are significant correlations between intensity perception and voltage amplitude. Bau et al. [14] measured the absolute and discrimination thresholds of the voltage. The absolute threshold forms a U-shaped curve with respect to the frequency. Meyer et al. [14] estimated the electrostatic force by a tribometer. They indicated an expected square law dependence of frictional force on actuation voltage. Kim et al. [27] proposed a method based on current control to solve the non-uniform intensity problem due to varying environmental impedances. Kang et al. [28] investigated how to realize low voltage operation of an electrovibration display. They presented three types of input voltage signals and showed that the dc-offset method is the best way to decrease the activated voltage. Vardar et al.[29] studied the effect of voltage waveform on electrovibration perception. They showed that the participants are more sensitive to sensation generated by square wave voltage than sinusoidal one for frequencies lower than 60 Hz.

While the electrovibration was implemented in various prototype devices, the model of electrovibration undoubtedly has received attention from haptics researchers. Strong and Troxel [12] proposed the first mathematical model of the electrostatic force. Kaczmarek et al. proposed another model based two-dielectric parallel-plate capacitor principle [9]. Vezzoli et al. [30] made an improvement on the two-dielectric layers capacitor model, which focus on the temporal evolution of the stimulus and frequency dependence of the supply voltage signal. Most recently, the air gap between the finger and touchscreen was introduced into the models [7, 31]. A numerical analysis of light sliding showed that the air gap has a significant influence on the electrostatic force [7]. Shultz et. al [32] verified by experimental data the existence of the air gap, which increases significantly when finger transitioned from the stationary to the sliding.

Although different models of the electrostatic force were proposed, all of them share the same feature that the electrostatic force is proportional to the apparent contact area. As the normal force applied on the screen by the finger can change the apparent contact area, it is apparent that the normal force affects the electrostatic force, and thus electrovibration perception. Harald et al. [23] studied the influence of the applied normal force on voltage thresholds on an electrovibration device. Their result showed that the applied normal force influences the absolute detection threshold of the voltage at 240 Hz, 360 Hz, and 540 Hz. Moreover, our previous study found that the normal force during sliding affects significantly the electrovibration perception intensity [5].

To further understand the effect of applied normal force on the electrostatic force, in this paper, we intend to find out whether the electrostatic force changes with the normal force while the apparent contact area is constant.

3 Experiments

We used a thin insulating film with a hole in its center to control the apparent contact area between finger and touch screen. The finger can only contact the touchscreen through the hole. We designed and conducted three experiments, including two pre-experiments and one formal experiment. In the pre-experiment 1, we aim to verify that the electrostatic force applied on the fingertip can be neglected when the fingertip is covered by the insulating film. In the pre-experiment 2, we make sure that the apparent contact area is constant while the finger together with the insulating film slides on touchscreen. The aim of the two pre-experiments is to confirm the assumption of our experiment that electrostatic force is generated only in the apparent contact area where the finger is in direct contact with the 3M touchscreen and the apparent contact area is constant. In the formal experiment, we estimated the electrostatic force via measuring the tangential force

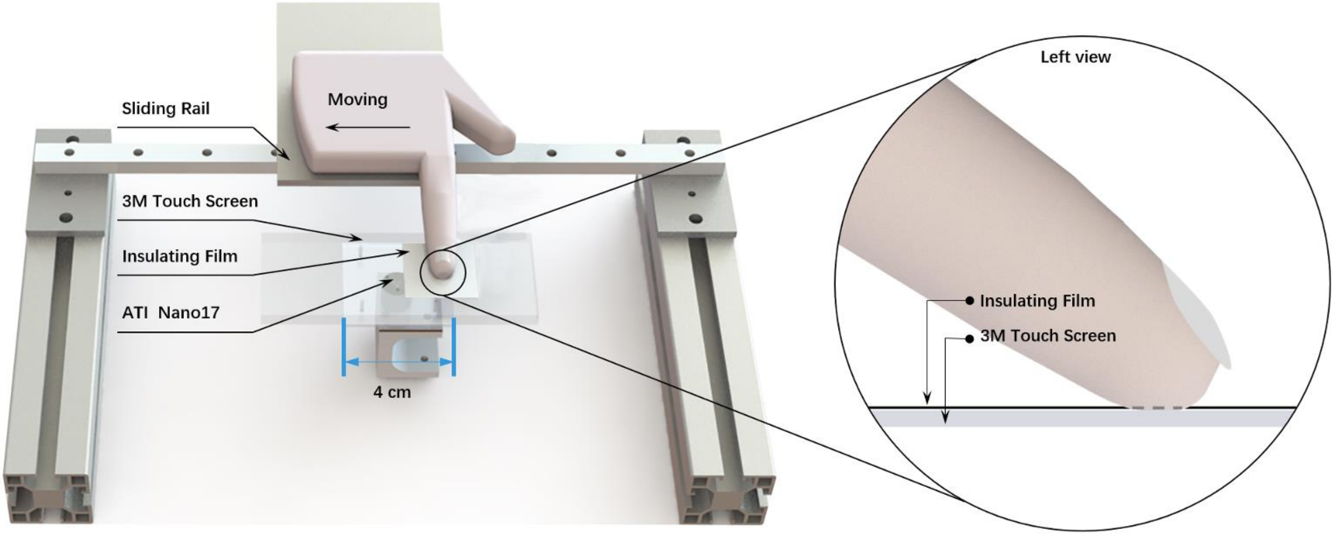

Fig. 1 Experimental apparatus.

of the finger sliding on a 3M touch screen with respect to different applied normal forces, which is used to examine and quantify the effect of applied normal force on the electrostatic force.

3.1 Experimental Apparatus

The apparatus is shown in Fig. 1. We used a 3M touchscreen as the tactile display, chosen due to its availability and performance stability. The screen consists of three layers: glass substrate, conductive layer (indium tin oxide) and insulator layer (SiO2, about 1 um thick). The insulator layer contacts with the fingertip. A high-sensitivity force sensor, ATI Nano17, was chosen to measure the force because of its high resolution (1/300 N) and its ability to measure three-dimensional forces. The force sensor was mounted below the 3M touchscreen. The force data was captured by a data acquisition board (Nation Instruments PCI-6220, Austin, Texas) at a sampling rate of 1 kHz. A carriage was mounted on the sliding rail (HIWIN MGNR15C, Taiwan), which allows participants to rest the wrist.

To ensure a constant apparent contact area, a thin insulating film was applied between the finger and the 3M touchscreen. The insulating film (Polyethylene) has a hole in its center which allows the finger to contact the 3M touchscreen. The insulating film is 0.07mm thick. To make sure the fingertip fully covers the hole during sliding, a small hole is required. However, the small hole leads to a small electrostatic force, which is difficult to measure. Hence, we set the diameter of this hole to 7mm.

To help participants keep the applied normal force stable, we provided a visual feedback system. As shown in Fig. 2, the top line of the blue bar moves up and down in real time with the applied normal force. Participants maintain the desired applied normal force according to the deviation between the required and real values of the normal force.

The input voltage was generated by a microcomputer (C8051F320) and amplified by a custom-built amplification circuit. The frequency error of the input voltage was no more than ±0.2% and the amplitude error of the input voltage was no more than ±4%. To make the input voltage more stable, participants were connected to the ground of the circuit by a grounding strap. The grounding strap is in direct contact with the skin through a copper foil (30 mm * 20 mm) which connected the ground of the circuit by a copper conductor, of which the resistance can be neglected.

3.2 Stimuli

Since the participants are more sensitive to stimuli induced by square wave voltage than sinusoidal one [29], the square wave was used in this study. The input voltage was fixed at 150 V, which is higher than the absolute detection threshold. We choose four voltage frequency levels (20, 70, 270, 1000Hz), which cover the sensitive range of the mechanoreceptors in skin. Harald et al. showed the highest applied normal force is around 5 N when users experience the electrovibration device [33]. Therefore, we observed the electrostatic force under 5 different normal forces (0.5, 1.5, 2.5, 3.5, 4.5 N). A total of 20 different measurements per subject were performed, as given in Table 1. The input voltage was turned on every 500 ms for 250 ms each time (Fig. 3).

Table 1 Experimental Parameters

Stimulus Parameter			Control Parameter
Waveform	peak-to-peak voltage (*V*)	Frequency (*Hz*)	Applied normal force (*N*)
Square	150	20 70 270 1000	0.5 1.5 2.5 3.5 4.5

3.3 Procedure

Before the pre-experiment 1 and the formal experiment, there was a session for training participants to maintain the stable normal force during sliding. During the training, the participants slide the fingertip on the device surface while watching the visual feedback on the computer.

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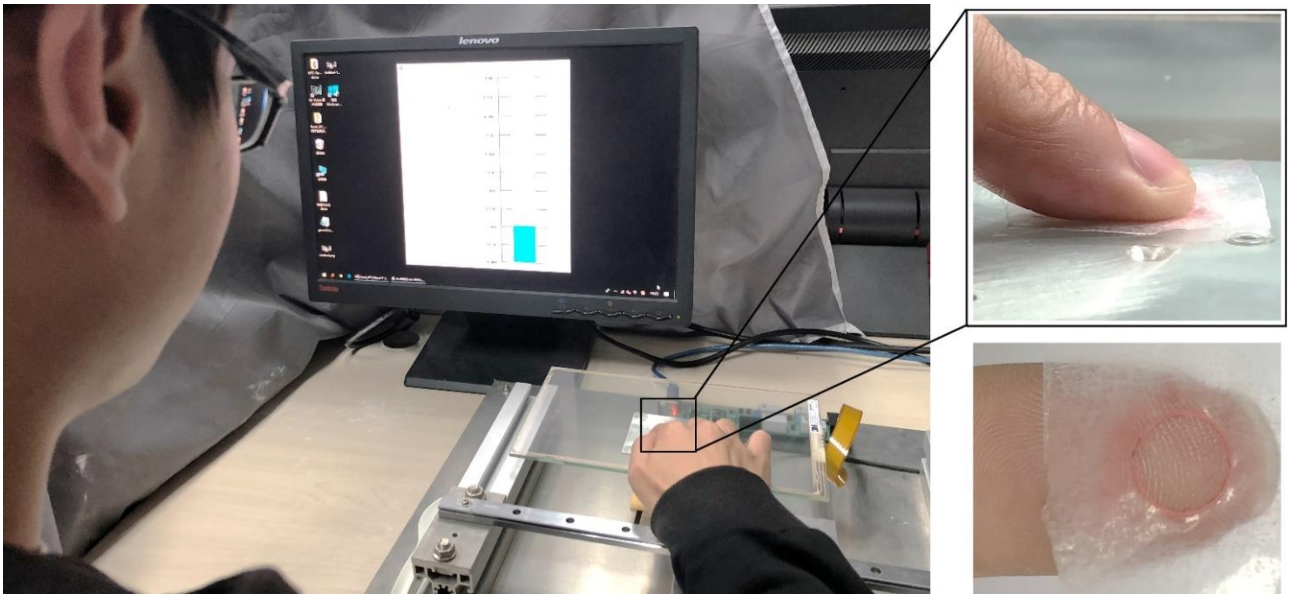


Fig. 2 Illustration of the formal experiment.

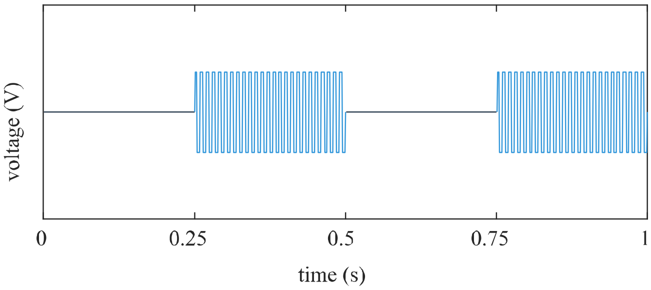


Fig. 3 Input voltage.

To reduce the task difficulty, a short sliding distance about 4 cm was selected (see in Fig. 2). The duration of the training session was about 15 minutes.

In pre-experiment 1, an insulating film with no hole was placed on the 3M touchscreen. A participant wore a ground strap on right wrist, which rested on the sliding carriage (Fig. 2). The index finger pressed on the insulating film with no hole and slid on the 3M touchscreen together with the insulating film. During each sliding, the participant was asked to maintain the required normal force. The tangential forces were measured based on which the electrostatic forces were estimated while turning on/off the input voltage. For each required normal force, the sliding was repeated three times

In pre-experiment 2, we used the ink printing method ([34, 35]) to measure the apparent contact area. A white paper was placed on top of the force sensor, which allowed participants to record apparent contact area by pressing down ink-stained index fingertip. The participants covered their fingertips with a thin film of ink by pressing onto an ink sponge. The stained fingertip then pressed onto the white paper through the hole of the insulating film with the required normal force. During the pressing, the applied normal force increased from 0 to the required value and was maintained within $\pm 0.1N$. To reduce errors from ink drying and image blurring, the participants were requested to conduct the test within approximately 3-5 seconds. To calculate the ink area, we transferred the ink area into an electronic image using a scanner.

In the formal experiment, participants sat comfortably in front of the apparatus and wore a ground strap on their right wrists, which rested on the sliding carriage. The insulating film with a 7 mm diameter hole in its center was placed on the 3M touchscreen. The participants pressed their index finger and slid on the 3M touchscreen while keeping the required normal force. The fingertips contacted the 3M touchscreen through the hole on the insulating film and slid together with the insulating film on the 3M touchscreen. Participants were asked to re-do the sliding if the applied normal force exceeded $\pm 0.1N$ of the required value. The normal force and tangential force were recorded during the sliding, which repeated three times. Each participant completed the formal experiment in 4 sessions (150 V, 20 Hz; 150 V, 70 Hz; 150 V, 270 Hz; 150 V, 1000 Hz). Each session lasted about 8 minutes. Participant was asked to take a 3-5 minutes break between two sessions. It took approximately 45 minutes for a participant to complete the measurements in the formal experiment.

Participants cleaned their hands prior to beginning the experiment. To decrease the hydration level of the fingertip, talcum powder was used to dry the fingertip in the pre-experiment 1 and the formal experiment.

Table 2 Participant information

Participant	Experiment		
	Pre-experiment 1	Pre-experiment 2	Formal experiment
P1	√	√	√
P2		√	√
P3		√	√
P4		√	√
P5		√	√
P6		√	√
P7		√	√
P8		√	√

A " √" indicates participation in the corresponding experiment

3.4 Participants

Eight participants from Beihang University were recruited (age 23-27 years old, average 25 years old). They were right-handed by self-report. All of them have no sensorimotor impairment with their right hands. They were compensated for their time. Table 1 shows which participants were tested in each of the experiments.

3.5 Data processing

A sample data collected in the pre-experiment 2 is shown in Fig. 4 which is approximated as a circle. The apparent contact area was estimated using the equation: $A = \pi \cdot r^2$, where r is the radius. An image-processing algorithm was developed in MATLAB to determine the value of the radius.

The sample data of the applied normal force and the frictional force collected in the pre-experiment 1 and the formal experiment is shown in Fig. 5. The gray area represented that the voltage is turned on. The change in friction caused by the electrostatic force was calculated by

$$\Delta f = f - f_a = f_{voltage\neq 0} - f_{voltage=0} \quad (1)$$

where Δf is the change in friction caused by the electrostatic force, $f_{voltage=0}$ is the averaged friction when the input voltage is turned off, $f_{voltage\neq 0}$ is the averaged friction when the input voltage is turned on. Note that the friction force due to the insulating film in contact with the touchscreen is included in the friction measurements. However, when calculating the Δf by Eq. (1), this component is canceled out.

The friction induced by the electrostatic force consisted of two components: a rectified DC component and a ripple component at twice the frequency of input voltage as shown in Fig. 5(b). The ripple force dominates at the input voltage of low frequency, while the rectified force dominates at the voltage of high frequency [32, 36]. At the voltage of 20 Hz and 70 Hz, the ripple frictional force was obtained by averaging the maximum values across all cycles during the measurement time of 250ms. Our previous study [4] showed that the amplitude of the ripple part is much smaller than the amplitude of rectified part as a 220 Hz square wave voltage was applied. Thus, at the voltage of 270 Hz and 1000 Hz, the measured friction represented the rectified force.

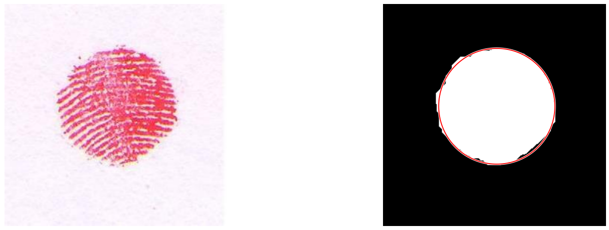
The electrostatic force can be estimated by [37]

$$F_e = \frac{\Delta f}{\mu} \quad (2)$$

where F_e is the electrostatic force, μ is the coefficient of friction. It is noted that μ might be different when the voltage is turned on and off. Due to the limitation of our measuring method, the difference in the friction coefficients is difficult to measure accurately. Thus, we assumed that the friction coefficient μ is not affected by the input voltage., which is calculated by

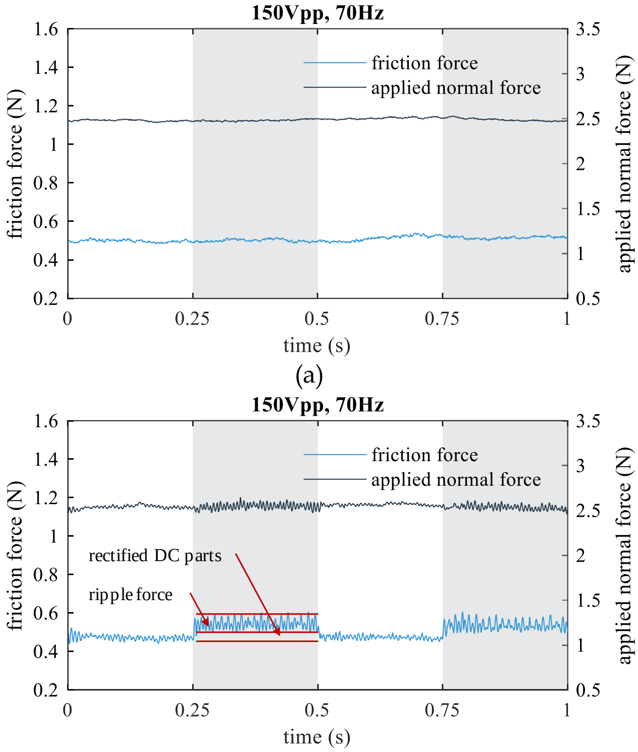
$$\mu = \frac{f_{voltage=0}}{F_n} \quad (3)$$

where F_n is the averaged normal force when the input voltage is turned off.



(a) (b)

Fig. 4 Sample of ink area. (a) an initial image. (b) the binary image of (a).



(b)

Fig. 5 (a) Sample of the raw force data at 70 Hz in pre-experiment 1. (b) Sample of the raw force data at 70 Hz in the formal experiment. The grey area denotes the input voltage is turned on.

4 Results

4.1 Pre-experiment 1

To determine whether an insulating film can prevent the electrostatic force between the finger and the 3M touchscreen, we measured the electrostatic friction when the input voltage was turned on/off. Fig. 5 (a) shows a sample of the friction force. Fig. 6 shows two data groups. One represents the friction force when the input voltage was turned off (black bars), the other represents the friction force when the input voltage was turned on (blue bars). The result in Fig. 6 shows that the frictions when the input voltage was turned on/off were closer. The average of the difference between the frictions in two conditions was 0.008 N. This result suggests that the electrostatic force applied on the finger can be neglected when the

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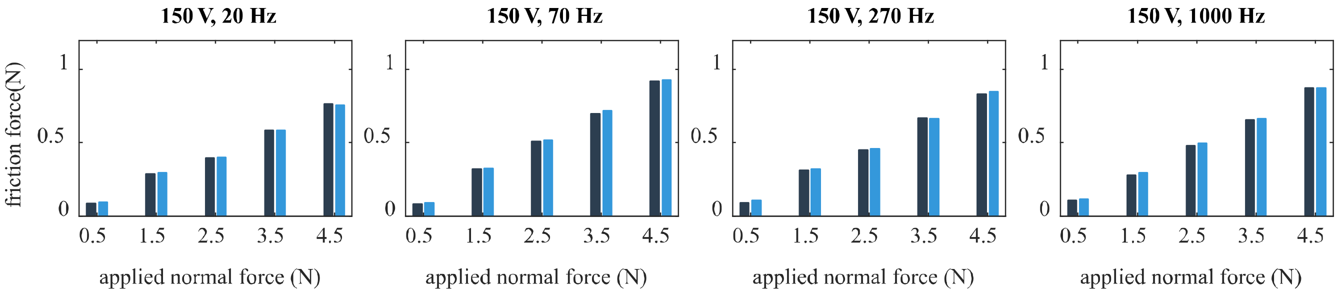

Fig. 6 The friction force versus applied normal force when the complete insulating film with no hole is applied to between fingertip and 3M touchscreen. Black bars denote the average of friction force when electrovibration is turned off. Blue bars denote the average of friction force when electrovibration is turned on.

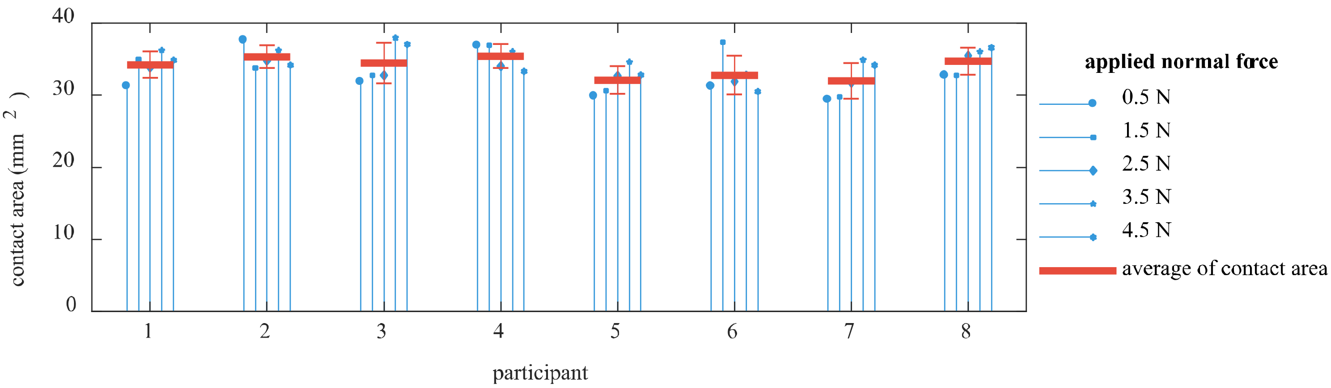

Fig. 7 Apparent contact area when the index finger touches the screen through the hole in insulating film.

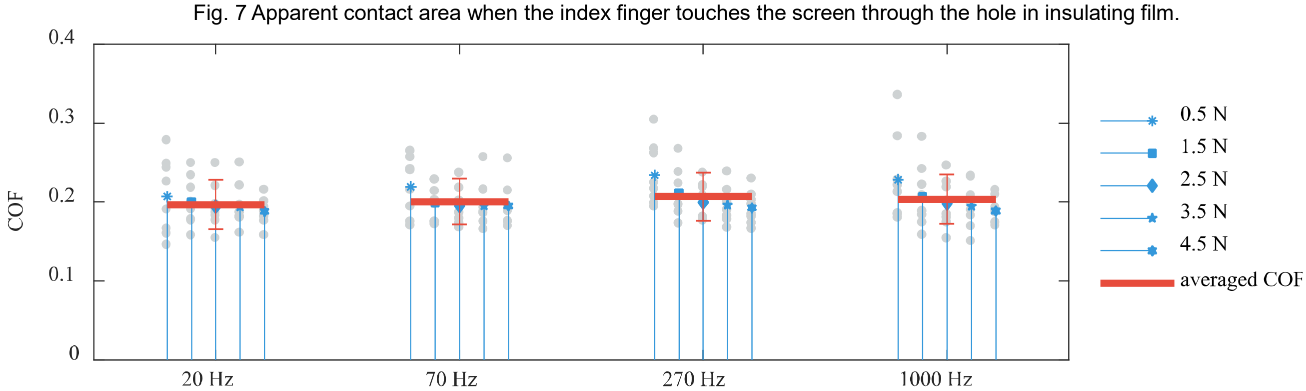

Fig. 8 The averaged COFs at different voltage frequencies. The grey dot denotes the COF of each of participants. The blue markers denote the averaged COFs among participants. The red lines denote the averaged COFs among applied normal forces.

insulating film was placed between the finger and the 3M touch screen.

4.2 Pre-experiment 2

Fig. 7 shows the apparent contact area of the index fingertip measured for each participant under the normal forces, 0.5 N, 1.5N, 2.5N, 3.5N, 4.5N. Each marker in Fig. 7 represents the apparent contact area corresponding to the applied normal force. The standard error of the apparent contact area at five normal forces is shown in Fig. 7. The total average of apparent contact area is 34.32 mm^2. One-way ANOVA analysis shows no significant difference in the apparent contact area when different normal forces are applied ($F(4,28)=2.62$, $p>0.05$). This result suggests that the method of using the insulating film to control a constant apparent contact area is effective.

4.3 Formal experiment

Fig. 8 shows the averaged COFs at four different voltage frequencies, which are 0.196, 0.200, 0.207 and 0.203. The standard deviation is 0.031, 0.029, 0.031 and 0.031. Fig. 9 shows the measured applied normal force with the standard deviation between 0.02 and 0.08 for all the values of normal force and the voltage frequency.

The estimated electrostatic force with respect to the applied normal force was shown in Fig. 10.. The average electrostatic force varies from 0.16 N to 0.44 N approximately as the applied normal force increases from 0.5 N to 4.5 N.

Two-way analysis of variance (ANOVA) with repeated measures shows that the main effect of applied normal force and frequency were statistically significant on the electrostatic force ($F(1.3, 9.2)=91.0$, $p<0.05$; $F(2.3, 16.0)=3.8$, $p<0.05$). Moreover, there was no significant interaction between applied normal force and frequency ($F(3.6, 25.0)=1.9$, $p<0.05$). Subsequent posthoc t-tests were run comparing the applied normal forces, adjusted using a Bonferroni correction. These tests showed

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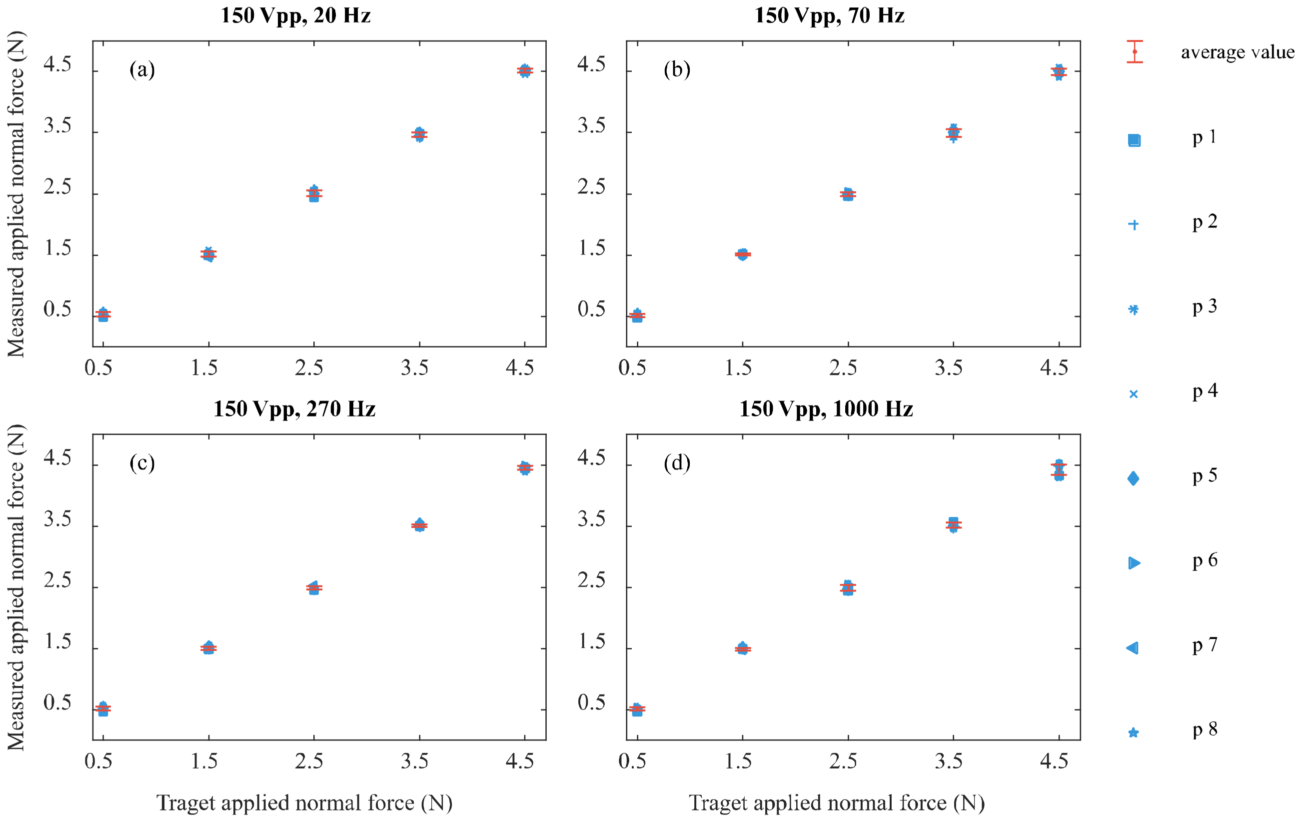

Fig. 9 The target applied normal force versus the measured applied normal force. The blue markers represent the data for each participant. The red dots represent the average value. The red vertical error bars represent the standard deviation.

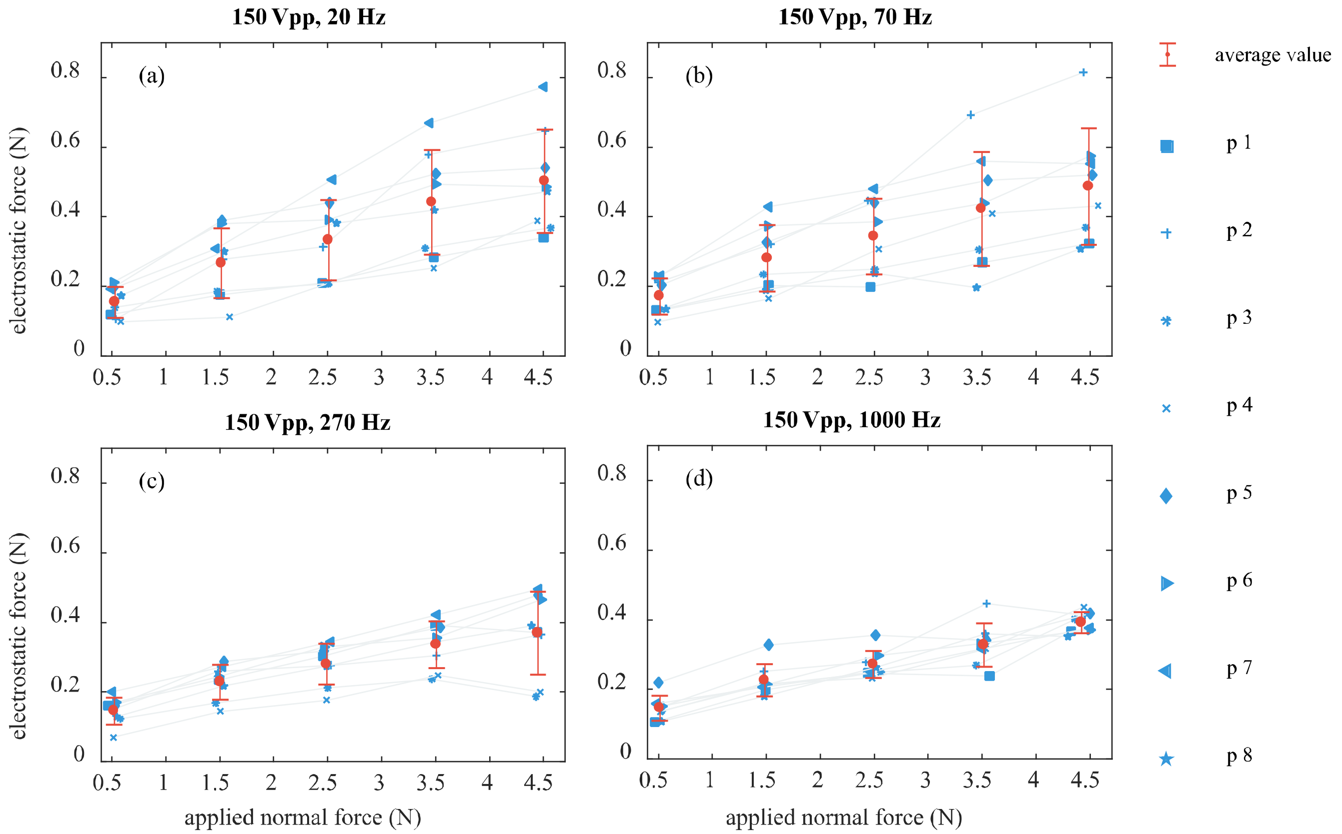

Fig. 10 The electrostatic force versus the applied normal force. The blue markers represent the data for each participant. The red dots represent the average value. The red vertical error bars represent the standard deviation.

that there was a statistically significant effect of the applied normal force on the electrostatic force (all p<0.05).

5 Discussion

It is known that the linear relationship between the apparent contact area and the electrostatic force has been revealed in the electrostatic force models proposed by different researchers [7, 9, 12, 31] .Thus, the normal force would change the electrostatic force if it changes the apparent contact area. Our experimental result shows that the increased normal force results in the increased electrostatic force, even though the apparent contact area is a constant. The reasons for this might be: 1) the true apparent contact area is different from the apparent contact area that we controlled in the experiment. While the apparent contact area is constant, the true contact area may change with the normal force which results in the change in the electrostatic force; 2) Other factors affecting the electrostatic force may exist which has not been identified in some electrostatic force models[9, 12]. Recently, two models for the electrostatic force were proposed which include air gap between the fingertip and the touchscreen surface as a factor [7, 31]. Here, we choose the model introduced in [8] to explain our results because our experimental condition is similar to the assumption of the model.

According to the model ([8]), the electrostatic force is determined by

$$F_e = \frac{A \cdot \varepsilon_0 \cdot \varepsilon_a}{2}\left(\frac{U}{T_a}\left|\frac{Z_a}{Z_i+Z_a+Z_{sc}}\right|\right)^2 \quad (3)$$

where A is the area of non-contact air gap sections between finger and the touch screen. ε_0 and ε_a represent respectively the vacuum permittivity, the relative permittivity of the air gap. U is the applied voltage. T_a is the thickness of the air gap. Z_i, Z_a and Z_{sc} denote the insulator layer, air gap and stratum corneum (SC) impedance respectively.

When an increasing normal force applies to the touchscreen, the fingertip could be closer to the surface. Therefore, the applied normal force affects both the thickness of air gap and the apparent contact area. Although the apparent contact area was constant in our experiment, the thickness of the air gap decreased with the increased normal force, which results in the increase of the electrostatic force as predicted by Eq. (3).

Using the data in Fig. 10 and Eq. (3), we can estimate the air gap thickness with respect to the normal force. According to the reference [32, 36], the gap impedance (Z_a) dominates the total impedance ($Z_i + Z_a + Z_{sc}$) as finger slid on the 3M touchscreen. Thus, we assume $Z_a/(Z_i + Z_a + Z_{sc})$ in Eq. (3) equals to 1. The parameters used in the estimation were listed in Table 3. Note that, the area in Eq. (3) is the non-contact air gap sections. However, since the area of real contact is much smaller than the overall apparent area of contact ([31]), we use the apparent contact area, 34.32 mm², to approximate the area of non-contact air gap sections.

Fig. 11 shows the estimated air gap thickness. Assume that the relationship between the air gap thickness and the applied normal force is,

$$T_a = a(F_n)^b \quad (4)$$

where T_a is the air gap thickness, and F_n is the applied normal force. We averaged the air gap thickness at four frequency and then estimated the relationship between the applied normal force and the air gap thickness. The parameters, a and b, corresponding to different frequencies are listed in Table 4.

We observed that the air gap thickness calculated is at the order of micron, which is consistent with the estimation in [31, 32] and the order of the measured skin roughness in [38]. However, it is much lower than the magnitude of the fingerprint height (59 ± 19.2 microns) [39]. How the air gap thickness relates to the magnitude of the fingerprint height is an open question.

Table 3 The parameters used in Eq. (3)

Parameter	Explanation	Value	Unit
A	apparent contact area	34.32	mm²
ε_0	permittivity of vacuum	8.854×10^{-12}	F/m
ε_a	relative permittivity of air	1	-
U	peak-to-peak voltage	150	V

Table 4 Parameters of the fitting for Eq. (4)

a	b	Adjusted R-square	Root mean squared error (RMSE)
1.69	-0.31	0.989	0.045

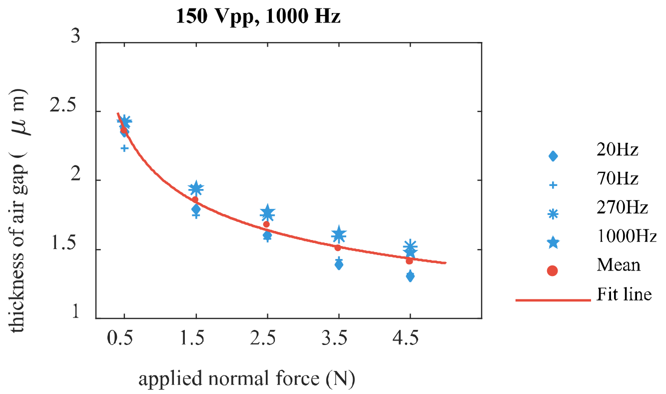

Fig. 11 Thickness of the air gap versus the applied normal force. The blue markers represent the thickness of the air gap while applying 20 Hz, 70 Hz, 270Hz and 1000 Hz voltage. The red markers represent the averaged thickness of the air gap. The red line is the fitting curve of the thickness of air gap versus the applied normal force.

6 Conclusions

In this study, we examined whether the electrostatic force changes with the normal force while the apparent contact area is constant. Our finding is that the electrostatic force increases with the increased normal force, even though the apparent contact area is constant. As the normal force changes from 0.5N to 4.5N, the average electrostatic force increases from 0.16N to 0.44N, while the apparent contact area is fixed to 34.32 mm^2. While estimating the electrostatic force, we assumed that the COFs are constant in the two condition (voltage on and off) due to the limitation of our measuring method. Understanding the difference between the two COFs relies on more accurate measurement of electrostatic force which is an interesting future work.

Our result reveals that, in addition to changing the apparent contact area, the normal force may affect other factor, which results in the change in the electrostatic force. This observation supports the recently proposed electrostatic force model which includes air gap thickness as an affecting parameter. By combining the result from our experiment and the force model, the relationship between the air gap thickness and the applied normal force is obtained as a power function. Note that this relationship was obtained with the constant apparent contact area. When the apparent contact area is different from the value we controlled in the experiment, whether the fitting curve in Fig. 11 is same requires further exploration.

The nonlinear relation between the air gap thickness and the applied normal force showed that the air gap thickness could be also changed by the normal force could, which help understand deeply the electrovibration model. Furthermore, this relationship implies that in order to estimate accurately the electrostatic force by the electrovibration model, understanding how the applied normal force influences the air gap is important. For the design of electrovibration device, the influence of the normal force on the electrostatic force suggests that it is possible to generate accurate frictional force and reliable tactile feedback by measuring the applied normal force in real time and adjusting the input voltage according to the measured normal force.

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