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Detection and Discrimination Thresholds for Haptic Gratings on Electrostatic Tactile Displays

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Abstract—Designing algorithms for rendering haptic texture on electrostatic tactile displays requires a quantitative understanding of human perception. In this paper, we report detection and discrimination thresholds for haptic gratings rendered on such displays based on the waveform and amplitude of the applied voltage. The haptic gratings consist of functions that describe the variation in voltage amplitude as a function of the position of finger on the display. Four types of virtual haptic gratings are considered in two experiments. In Experiment I, we estimate the absolute detection thresholds of haptic gratings for four different voltage amplitude functions, consisting of spatial waveforms with sinusoidal, square, triangle, or sawtooth shape. In Experiment II, we report discrimination thresholds for haptic gratings at five reference values of the voltage amplitude (80, 120, 160, 200, and 240 Vpp) for each of the voltage amplitude functions used in Experiment I. The results indicate that the detection thresholds for the four virtual haptic gratings are between 30 and 36 Vpp, and that the JND increases with the increase of voltage amplitudes. In addition, the JNDs of the four virtual gratings differ significantly, with the lowest and highest values being given by the triangle and sawtooth waveform, respectively.

Index Terms—Electrostatic display, tactile feedback, voltage amplitude, haptic gratings, absolute detection thresholds, discrimination thresholds, JND

1 INTRODUCTION

THERE are many surface haptic devices that are able to successfully render virtual textures [1], [2], [3], [4]. Among them, the variation of forces can create powerful percepts during human haptic exploration [5], [6], [7], and many designs have focused on controlling surface interaction forces to render virtual haptic textures on haptic surface displays [8], [9], [10], [11]. This has motivated several studies of haptic texture rendering on electrostatic haptic display [12], [13], [14], which inputs variable voltage signals to control the electrostatic forces between finger and screen during bare finger interaction [15], [16].

Since the rendered haptic gratings are modulated by the applied voltage signals, a quantitative understanding of the perception of virtual textures in terms of applied voltage parameters is needed. Bau *et al*. [17] estimated the detection and discrimination thresholds (JNDs) of input voltage amplitude for different frequencies of voltage on an electrostatic tactile display (TeslaTouch). Their results revealed that the estimated thresholds of input voltage formed a U-shaped curve at the frequency scale indicating a minimum value of 8 Vpp and an average JND of the input voltage amplitude of 1.16 dB. Agarwal *et al*. [18] estimated perception thresholds of applied voltage at different top-layer polyimide thicknesses on a 4-inch hybrid natural/artificial electrostatic wafer and found that the thickness had little effect on the threshold. Kaczmarek *et al*. [19] observed differences in detection of electrovibration for positive and negative applied voltages on an electrostatic tactile display. Their findings demonstrated that perceptual sensitivity to positive pulses in electrovibration is less than that to negative or biphasic pulses, and that sensory thresholds of negative pulses were more stable than for waveforms incorporating positive pulses. Vardar *et al*. measured absolute detection thresholds of applied voltage using square wave and sinusoidal wave input signals at seven fundamental frequencies (15, 30, 60, 120, 240, 480 and 1920 Hz) on touchscreens (3M MicroTouch). They found a U-shaped tactile sensitivity across frequencies and that the sensory thresholds were lower for the square wave than the sinusoidal wave at fundamental frequencies less than 60 Hz, while they were similar at higher frequencies [20]. Kocsis *et al*. estimated the amplitude (i.e., height) discrimination thresholds for sinusoidal and triangular textured surface gratings of a fingertip on real gratings and of a stylus on real and virtual gratings [21]. Cholewiak *et al*. estimated the detection and discrimination thresholds for virtual haptic gratings using a force-feedback device that simulated sinusoidal and square-wave gratings with spatial periods from 0.2 to 38.4 mm [22]. Our previous work examined absolute detection and discrimination thresholds of amplitude and frequency of applied voltage on a flexible texture display (the FlexTouch device) [23]. We found that the measured absolute detection thresholds for input voltage formed a U-shaped curve as functions of the frequencies of the

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voltage, and that the JNDs depend linearly on the amplitude of reference voltage.

Several prior studies, including those noted below, have involved haptic texture rendering performed by modulating applied voltage [24], [25], [26]. One fundamental, and widely simulated, type of virtual haptic texture is the spatial grating [21], [22], [27] in which the applied voltage amplitudes varies periodically with the displacement of the finger in the direction perpendicular to the grating. Such a texture depends on the applied voltage amplitude, waveform, and wavelength. In order to render realistic textures, an appropriate modulation of input voltage to control the electrostatic force is important [28], [29], [30]. Although prior research has demonstrated that human perception for electrostatic forces is affected by input voltage parameters [17], [19], [31], these studies have not provided information about the influence of applied voltage on the detection and discrimination thresholds of rendered haptic textures on electrostatic surface displays. To the best of our knowledge, the present study is the first to explicitly investigate the effects of texture rendering patterns on the perception thresholds of applied voltage amplitudes. There are several open questions concerning the rendering of virtual haptic textures on an electrostatic tactile display: How does the virtual texture waveform influence human perception thresholds for voltage? Specifically, what is the absolute detection threshold for applied voltage for different virtual texture waveforms, and how do the different types of virtual textures affect voltage perception? Also, what is the discrimination threshold for applied voltage amplitudes for the different types of virtual texture?

In order to address these questions, we selected the haptic gratings as research objects in the current study. We investigated perception thresholds for virtual haptic gratings in relation to the parameters of applied voltage of electrostatic tactile display, as assessed through psychophysical experiments. This study pursued two objectives. First, the absolute detection thresholds of haptic gratings for the four different waveforms are measured. Second, the discrimination thresholds of virtual haptic gratings in the five applied voltage amplitude reference values are estimated.

The main contributions of our current work can be summarized as follows:

1) We investigated absolute detection thresholds of haptic gratings for the four types of voltage waveforms (sinusoidal, square, triangle, and sawtooth) of different magnitudes when sliding a finger across the surface of an electrostatic tactile display.
2) Discrimination thresholds of haptic gratings at five reference voltage values for the four different waveforms were estimated when a finger scanned across the surface of the electrostatic tactile display.

The remainder of the paper is organized as follows: In Section 2, we introduce the experiments and the general methods that are used, including the participants, electrostatic tactile display device, and information about the haptic gratings. The absolute detection thresholds of applied voltage amplitude for four different waveforms of haptic gratings are investigated in psychophysical experiments presented in Section 3. In Section 4, we estimate discrimination thresholds of applied voltage amplitude for four different waveforms of haptic gratings relative to five different reference values, using psychophysical experiments. The discussions of the results are performed in Section 5. Finally, the conclusions of the study are presented.

2 General Materials and Methods

This section covers the methods of two different experiments in the present study. Methods that are specific to each experiment are presented later in the respective sections.

2.1 Participants

Twelve right-handed participants (seven male and five female, aged between 21 and 28, mean 24) were selected to take part in the experiments. All of them were interviewed to ensure normal tactile abilities before the experiments. None had previous experience with the devices and they did not report any history of neurological illness or physical injury that might have affected their hand function. They were all undergraduate and graduate students at Beihang University. All participants gave written consent to participate in the study, and the experiments were performed consistent with the human participant testing regulations of the authors' institution. The information of the participants is shows in Table 1.

TABLE 1
Participant Information

Subject	Gender	Age	Experiment I	Experiment II
S1	M	24	√	
S2	F	23	√	√
S3	M	25	√	√
S4	M	24	√	
S5	M	25	√	
S6	M	22	√	√
S7	F	23	√	√
S8	F	28	√	
S9	F	28		√
S10	F	24		√
S11	M	21		√
S12	M	25		√

A " √ " indicates participation in the corresponding experiment.

2.2 Electrostatic Tactile Display Device

When a fingertip is in contact with the screen, a capacitance is formed between the finger and the electrode. Electrovibration modifies the forces felt by the finger in motion by a modulation of the applied voltage [32]. The modulation is due to an electrostatic attraction between a

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bare finger and the polarized surface (see Figure 1). The input voltage parameter (i.e., waveform, amplitude, and frequency) is controlled to modulate the electrostatic attraction force applied to fingertip while sliding a fingertip. Different tactile feelings can thus be produced on the fingertip.

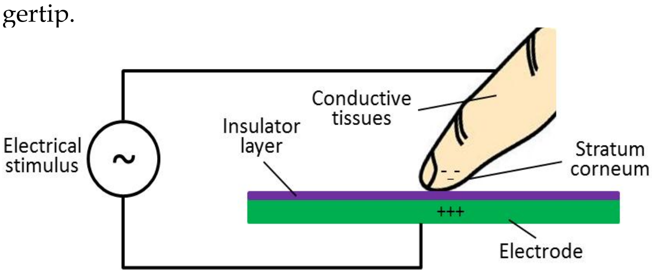

Figure1. Schematic illustration of electrode-skin interface.

For the two experiments, a custom-designed electrostatic tactile display shown in Figure 2 was utilized. The display is based on the physical principle that the Coulomb force exerted on a finger affects the attractive and frictional force felt by the finger sliding through a surface, as developed and validated in our prior research [25], [26].

Figure 2. The electrostatic tactile display device used in the current study [33], [34].

The functional diagram is presented in Figure 3. The haptic interface consists of the following three layers. The upper layer is an optical sensor (GSC0320, TMDTOUCH, China) with the accuracy of 0.01 mm for acquiring the finger position. The middle layer is a capacitive touch screen panel (3M MicroTouch), which generates the electrostatic tactile stimulation. The lower layer is a LCD screen (Surface Pro 3, Microsoft Inc., US) displaying visually rendered information. Our prior studies have indicated that the electrostatic tactile display device is able to render detailed shapes and textures of images on the surface by modulating applied voltage signals to generate different friction patterns [25], [26].

The resolution of the Microsoft Surface screen is 2160 x 1440 pixels and the size of Micro-touch screen is 12 inches. The tactile controller module generates the tactile stimuli signals and loads them to the Micro-touch screen, allowing the related tactile sensation to be provided to the fingertip. The tactile excitation signal generator is a programmable voltage source and generates voltages of four waveforms (sinusoidal, square, triangular and sawtooth wave) with amplitudes ranging from 0 to 350 Vpp (±2 Vpp) and frequencies ranging from 1 to 10 kHz (±1 Hz). The current limit is 10 mA to ensure the safety of users. The graphical user interface and software platform were based on custom software written in C++.

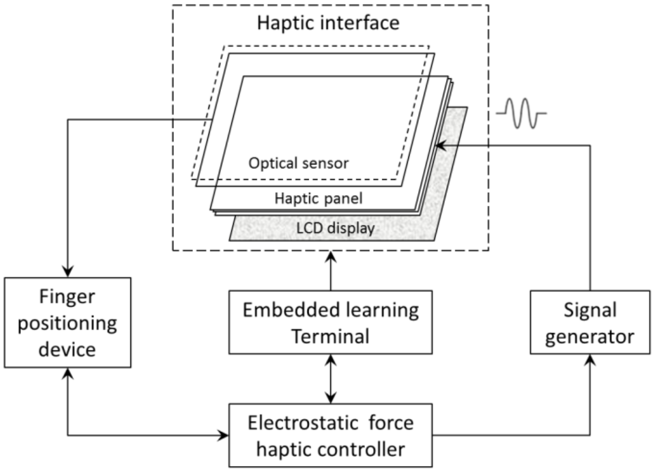

Figure 3. Functional diagram of a custom-designed electrostatic tactile device.

2.3 Haptic Gratings of Virtual Texture

Our goal was to use the electrostatic tactile display device to measure the perception thresholds of the amplitude of applied voltage with the virtual haptic gratings (within rendering capabilities of the device). The gratings were rendered by modulating the amplitudes of applied voltage with fingertip movement displacement, as shown in Figure 4. The applied voltage amplitudes were continuously varied to produce different tactile sensation on the finger, when sliding a finger on the surface of the electrostatic tactile display.

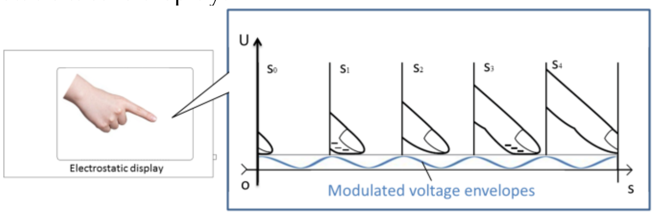

Figure 4. Haptic grating rendering by modulating the applied voltage with respect to the displacement of finger on the electrostatic tactile display.

The haptic gratings were generated by controlling the amplitude of voltage applied to the electrostatic display as follows:

$$\begin{cases} A = A_s f_s(s) \\ U = A f_t(t) \end{cases} \tag{1}$$

where A is the waveform generation function of the applied voltage amplitude, t denotes time, s is the displacement of finger with time t, U is the voltage applied to the electrostatic tactile display at finger movement displacement s, A_s is the observed amplitude of the applied voltage waveform, $f_s(s)$ denotes the function of the waveform with the finger movement displacement s, $f_t(t)$ denotes the carrier function of applied voltage.

For the sinusoidal wave,

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$$f_s(s) = \frac{1}{2} + \frac{1}{2}\sin\left(2\pi f_x s - \frac{\pi}{2}\right)$$

For the square wave,

$$f_s(s) = \begin{cases} 0, & \dfrac{n}{f_x} < s \le \dfrac{n}{f_x} + \dfrac{1}{2f_x} \\ 1, & \dfrac{n}{f_x} + \dfrac{1}{2f_x} < s \le \dfrac{n+1}{f_x} \end{cases}$$

For the triangle wave,

$$f_s(s) = \begin{cases} 2(s - \dfrac{n}{f_x}), & \dfrac{n}{f_x} < s \le \dfrac{n}{f_x} + \dfrac{1}{2f_x} \\ 2 - 2(s - \dfrac{n}{f_x}), & \dfrac{n}{f_x} + \dfrac{1}{2f_x} < s \le \dfrac{n+1}{f_x} \end{cases}$$

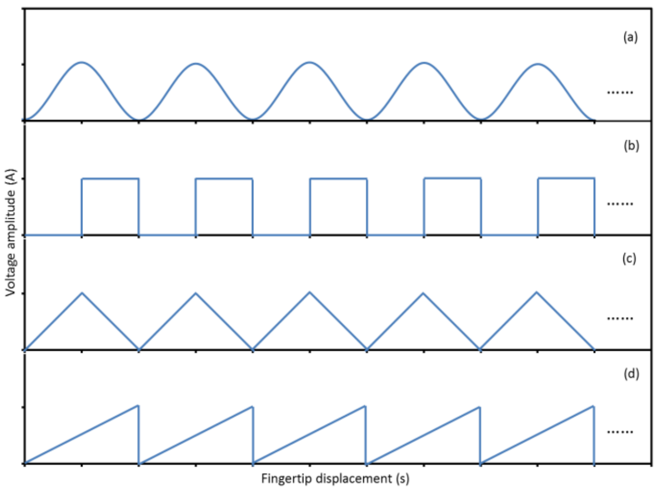
For the sawtooth wave,

$$f_s(s) = s - \frac{n}{f_x}, \qquad \frac{n}{f_x} < s \le \frac{n+1}{f_x}$$

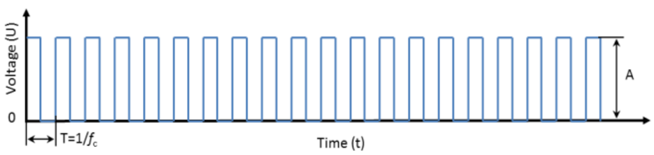
Furthermore,

$$f_t(t) = \begin{cases} 0, & \dfrac{n}{f_c} < t \le \dfrac{n}{f_c} + \dfrac{1}{2f_c} \\ 1, & \dfrac{n}{f_c} + \dfrac{1}{2f_c} < t \le \dfrac{n+1}{f_c} \end{cases}$$

where f_x is the displacement frequency of the haptic gratings, n is an arbitrary integer, and f_c is the frequency of the carrier voltage.



(A) Voltage amplitudes with fingertip displacement



(B) Square wave carrier voltage signals with time

Figure 5. Haptic grating waveforms defined by the amplitudes of applied voltage with respect to the displacement of finger. (a) sinusoidal wave, (b) square wave, (c) triangle wave, and (d) sawtooth wave.

The four types of waveforms of haptic gratings are shown in Figure 5(A). We modulated the amplitude of the high frequency carrier voltage in order to generate haptic gratings using the displacement (s) of the user's finger. The high frequency carrier voltage is the time-varying square wave signals, as shown in Figure 5(B). In the experiments, we investigated the amplitude of applied voltage for the four types of waveforms of haptic gratings. The applied wave carrier signals employed the square voltage at a fixed frequency of 240 Hz ($f_c = 240$) [20], [31]. We adopted 1 mm ($f_x = 1$) as the displacement period of the haptic gratings in our current study [22]. The control function of the waveform $f_s(s)$ included a sinusoidal wave, a square wave, a triangle wave, and a sawtooth wave, respectively, which were generated by controlling the applied voltage amplitude (A) according to the movement displacement of finger in our current study.

3 Experiment I: Absolute Detection Thresholds of Haptic Gratings

In this section, we present the method used to examine the absolute detection thresholds for the of magnitudes applied voltage of haptic gratings for the four different waveforms (sinusoidal, square, triangle, and sawtooth) on the electrostatic tactile display.

3.1 Experimental Procedure

A two-alternative forced-choice paradigm was used to estimate the absolute detection thresholds of the amplitudes of applied voltage with the four waveforms of virtual haptic gratings [35]. In the experiment, the touch screen of the electrostatic tactile display device was divided into two regions marked as A and B. One of the two regions had a tactile excitation signal, while the other had none. In each trial, the tactile excitation signal was randomly assigned to one of the two regions. The participant's task was to determine which region provided a tactile sensation.

We adopted a one-up/two-down adaptive staircase algorithm that is standard in psychophysics [36], as shown in Figure 6. The advantage of this algorithm is that it allows accurate estimation of detection thresholds with a relatively small number of trials [35]. At the beginning of each session, the applied voltage signal was set much higher than the anticipated detection threshold. The applied voltage amplitude was then reduced by 10 Vpp if the participant had made two consecutively correct responses. When the user made an incorrect response, the voltage amplitude was increased by 10 Vpp, making tactile excitation signal more prominent. A change from decreasing to increasing input voltage amplitudes, and vice versa, is referred to as a reversal. After the first three reversals the step size of the applied voltage amplitude change was reduced to 2 Vpp. The initially large 10 Vpp step size ensured faster convergence of amplitude towards the threshold level and the following smaller 2 Vpp step size guaranteed fine resolution of the threshold estimation. The session was terminated after 12 reversals at the 2 Vpp step size and the average value of the last 12 reversals was treated as an estimate of the voltage amplitude threshold level. To eliminate the effects of the experiment order, the order of haptic gratings for the four waveforms was randomly arranged in each session.

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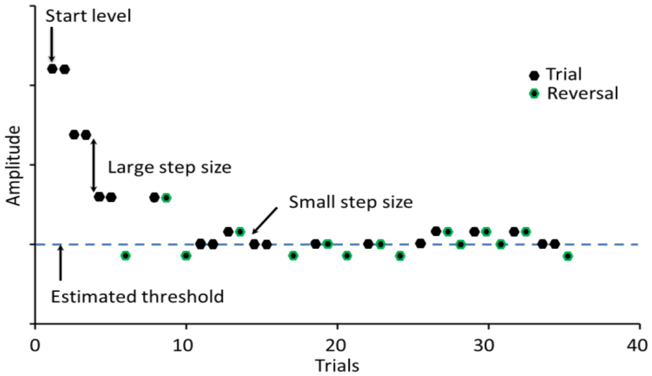

Figure 6. Example of a trial session that follows the adaptive procedure used in the experiments.

Figure 7 shows the experimental configuration used to test the absolute detection thresholds. Before starting the experiment, the participants were given instructions about the experiment and given time to familiarize themselves with the experimental hardware. During the experiment, participants were instructed to sit down in the chair so as to comfortably slide the right index finger across the surface of the electrostatic tactile display and make a distinction for stimuli tasks. Participants were required to determine which region provided a tactile sensation. The left wrist and the forearm of the participant were resting on a table, and the left hand put on the aluminum shell of the electrostatic tactile display device to form a closed-loop voltage. Each participant had six seconds to compare the signal in regions A and B, and responded by clicking the corresponding button (A or B) on the screen in each trial.

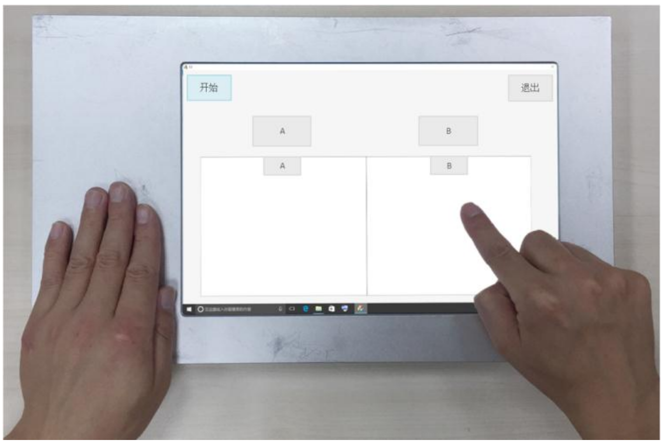

Figure 7. Experimental scenario of testing absolute detection thresholds of applied voltage amplitudes.

In order to reduce the effect of external environments on experiment results, the screens of the display were cleaned with isopropyl alcohol. Participants were instructed to wash their hands with soap and rinsed with water, and repeatedly slide his finger on the screen for more than one minute to eliminate the effects of moisture before experiment. An electric fan was used to continuously blow air over the touchscreen surface to minimize effects of moisture during experiment. Indoor temperature and humidity in the laboratory were kept at 23 ℃ to 28 ℃ and 35 % to 55 %, respectively.

3.2 Results

The mean value and standard deviation of the absolute detection threshold of applied voltage amplitude for four waveforms of haptic gratings for all participants are shown in Figure 8. A visual inspection of the measured data suggested that the thresholds differed across the four experimental conditions (sinusoidal wave, square wave, triangle wave, and sawtooth wave). The average absolute detection thresholds of applied voltage amplitude for haptic gratings of the sinusoidal wave (36.07 Vpp), square wave (30.56 Vpp), triangle wave (32.44 Vpp), and sawtooth wave (34.57 Vpp) suggested that there could be differences under the four experimental conditions. Among them, the average absolute detection threshold of applied voltage amplitude for the haptic gratings of the square wave was least and the average absolute detection threshold of applied voltage amplitude for the haptic gratings of the sawtooth wave was largest. However, a one-way repeated measures analysis of variance (RM-ANOVA) indicated that there were no significant differences in absolute detection thresholds of applied voltage amplitude for the four waveforms of gratings, with $F(3, 21)=0.448$, $p>0.05$.

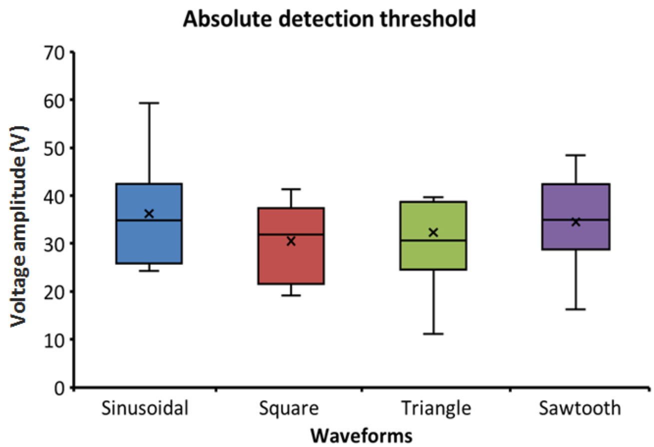

Figure 8. Mean values and standard deviations of absolute detection threshold of applied voltage amplitude for four waveforms of haptic gratings.

4 Experiment II: Discrimination Thresholds of Haptic Gratings

Experiment II investigated discrimination thresholds for applied voltage magnitude of haptic gratings for four different waveforms on the electrostatic tactile display.

4.1 Experimental Procedure

Five reference values of the voltage amplitudes of virtual haptic gratings for the four modulated waveforms were chosen to estimate the just-noticeable-differences (JNDs): 80, 120, 160, 200, and 240 Vpp. In order to eliminate order effects, the order of the amplitudes and waveforms was randomly arranged for each participant.

The applied voltage amplitude signal set consisted of

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the five reference values above the detection threshold. JND values were estimated using a three-alternative forced-choice paradigm [35]. In each trial, three tactile voltage signals were presented in different regions on the screen of the electrostatic tactile display device. Participants were required to identify the test signal, which was different from the other two same reference signals. The order of test and reference signals was randomized in each trial.

In the experiments, the observed amplitude of the applied voltage waveform was described as follows:

$$A = A_r + \Delta A \quad (2)$$

where, A_r is the applied voltage amplitude of reference signal, and ΔA is a variable increment of applied voltage amplitude.

At the start of the experimental session the test and reference excitation signals were selected to be easily discernable, i.e. ΔA was well above the anticipated JNDs. Two consecutively correct responses decreased and one incorrect response increased ΔA by 10 Vpp applied voltage for the first three reversals and by 2 Vpp for the rest of the session. The session was terminated after 12 reversals at the smaller step size. The average of ΔA from the last 12 reversals was then taken as JND estimates.

Figure 9. Experimental scenario of testing the differential thresholds of applied voltage amplitudes.

The experimental configuration used to test the discrimination thresholds is shown in Figure 9. In the experiment, the screen of the electrostatic tactile display was split into the three different regions marked with letters A, B, and C, respectively. Three tactile signals were respectively presented in different regions on the screen of the electrostatic tactile display device. Each participant had ten seconds to feel tactile sensations on three regions and select one of the three which was different from the other two by clicking buttons (A, B, or C) on the screen in each trial.

4.2 Results

The average values of JNDs of the amplitude of applied voltage for the four waveforms of haptic gratings are shown in Figure 10. The average JND values of applied voltage amplitude for haptic gratings increased as the reference values increased for the four different waveforms of voltage amplitude magnitude. In addition, one-way RM-ANOVA indicated that there were significant differences in the JNDs of haptic gratings among the five reference values of applied voltage amplitude for the sinusoidal ($F(4, 28)=6.196$, $p<0.05$), square ($F(4, 28)= 3.519$, $p<0.05$), triangle ($F(4, 28)=7.068$, $p<0.05$), and sawtooth wave ($F(4, 28)=3.539$, $p<0.05$), respectively.

In addition, from Figure 10, we found that the means of the JND values of voltage amplitude for triangle wave of haptic gratings were smallest in the four waveforms and the means of the JND values for sawtooth wave were largest. The lowest JNDs were 15.32, 28.92, 33.15, 50.16, 57.23 Vpp for the five reference values and the highest were 36.87, 44.76, 50.58, 59.60, 67.45 Vpp, respectively. Furthermore, in order to illustrate the differences in applied voltage amplitude for haptic gratings among the four waveforms, one-way RM-ANOVA was further performed among the five reference values of applied voltage amplitude, and the statistical results showed that there were significant differences in the JNDs of applied voltage amplitude for virtual haptic gratings among the four waveforms with $F(3, 12)=25.474$, $p<0.05$.

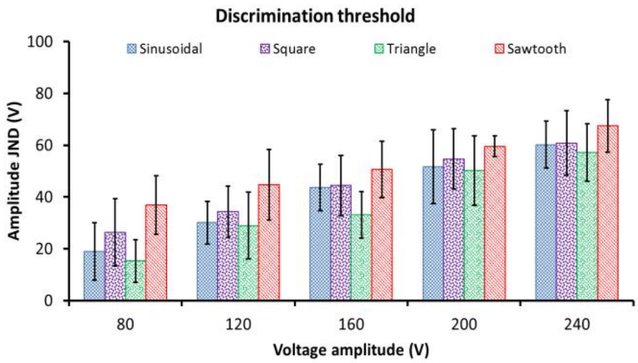

Figure 10. Mean and standard deviation of JNDs of the amplitudes of applied voltage for four different waveforms of haptic gratings.

5 Discussion

In Experiment I, the absolute detection thresholds of the amplitude of applied voltage for the four different waveforms of haptic gratings were investigated when users slide a finger across the surface of the electrostatic tactile display. According to the results of the experiments, the average absolute detection thresholds for the sinusoidal wave, square wave, triangle wave, and sawtooth wave were 36.07, 30.56, 32.44, and 34.57 Vpp, respectively. The average absolute detection threshold for the square wave was lowest and for sinusoidal wave was highest, but the differences among the different waveforms conditions were not statistically significant. The result would be similar with prior observations [21], [22], in which people are more sensitive to square haptic gratings, with period held constant, when perceiving them through a force-feedback device. The reason could be that the square wave grating maximizes the rate of change of texture with position, in the sense that the voltage, and friction force, vary abruptly within each cycle of the waveform as the finger moves. However, the average values of absolute detection

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thresholds of applied voltage amplitude for four waveforms of haptic gratings in the current study are all higher than that in [31]. In the literature, the reported results for the absolute voltage amplitude detection threshold for square wave signals on a 3M MicroTouch display is approximately 25 Vpp [31]. In this study, the minimal mean value of estimated absolute detection threshold of applied voltage amplitude occurred in the sinusoidal waveform of haptic gratings with 30.56 Vpp. The difference may be due to discrepancies in the displayed stimulus between the two studies. The full surface of touch screen presented the identical tactile stimulus signals in [31]. However, in our present study, the stimulus signals on the surface of the electrostatic tactile display are the virtual haptic gratings rendered by modulating the applied voltage amplitude. This difference hints that the texture rendering patterns might affect human absolute detection threshold of applied voltage amplitude. In order to enable users to experience tactile sensation, an applied voltage amplitude above the detection thresholds should be adopted when designing the haptic texture rendering algorithms on an electrostatic tactile display device.

In Experiment II, we estimated discrimination thresholds for the applied voltage amplitude for haptic gratings referenced to five voltage amplitude values for the four waveforms when users scanned a finger across the surface of the electrostatic tactile display. From the results of the experiments, the average JND values for voltage amplitudes of haptic gratings increased with the increase of reference values of voltage amplitude for all the four different waveforms. These results were consistent with our previous findings in [23]. However, the JND values of applied voltage amplitude for four waveforms of haptic gratings in the work presented here are all higher than that in the reference [23]. In [23], the reference voltage values were: 71, 95, 126, 168, 225 Vpp. The measured discrimination thresholds for voltage amplitude were approximately 12, 18, 21, 26, 32 Vpp, respectively. However, in the present study, we used different reference values of the voltage amplitudes for the same purpose: 80, 120, 160, 200, 240 Vpp. A square applied voltage was selected as the signal source in the experiment. The results show that the discrimination thresholds of voltage amplitude for a triangle waveform was smallest in the four waveforms and the estimated discrimination thresholds of voltage amplitude for the triangle waveform of haptic gratings were approximately 15.32, 28.92, 33.15, 50.16, 57.23 Vpp, respectively. The differences between the present work and our previous study in [23] could be due to at least two significant differences in the two studies. One is that the materials of electrostatic display used in the two studies are different. The material of electrostatic display (FlexTouch) in our previous study is a flexible indium tin oxide film, which consists of a base layer of Polyethylene naphthalate (PEN) and an ITO layer with a resin insulator [23], while, the electrostatic tactile display in this study is a rigid screen. The other is that the patterns of displayed tactile stimulus are different. In our prior study [23], the whole surface of electrostatic touch screen displayed the identical tactile stimulus. However, in the current work, four waveforms of haptic gratings were rendered on the surface of electrostatic tactile display by modulating the applied voltage amplitude. These results may indicate that larger discrimination thresholds may need to be accounted for, particularly when rendering tactile texture on a rigid electrostatic screen than on a flexible electrostatic film, but further research is needed to clarify the surface dependence of electrostatic texture perception.

For the present work, we determined absolute detection and discrimination thresholds of applied voltage amplitudes for haptic gratings via an electrostatic tactile display. However, this study still has some limitations. Due to the influence of certain factors, such as sliding velocity, normal force and moisture of finger, etc. [37], [38], the change of the friction coefficient between finger and touch screen is non-uniform. However, friction is a complex phenomenon, and would be difficult to account for within the scope of this paper. Thus, we were not able to investigate the perception thresholds of the friction caused by applied voltage. In next work, we plan to conduct a specific study to observe the effects of these factors on the perception thresholds for the friction. In addition, the differences between thresholds for detection of gratings that differed in waveform were not statistically significant. This was surprising, and further research into this aspect may be needed. Besides, we only investigated perception thresholds of applied voltage amplitudes for four waveforms of virtual haptic gratings for constant spatial periods, and did not consider the effect of varying the spatial period of the gratings. Thus, the results are unable to shed light on the perception thresholds for spatial periods of the haptic gratings. In the future, we plan to further investigate these issues, because they may be significant for the design of electrostatic tactile display devices, and indispensable to the design of haptic texture rendering algorithms.

6 Conclusions

Haptic gratings represent an important type of virtual textures on an electrostatic tactile display. In this paper, we conducted two experiments to investigate the detection and discrimination thresholds of the amplitude of applied voltage for four waveforms of haptic gratings (sinusoidal, square, triangle, and sawtooth).

In experiment I, the absolute detection thresholds of the applied voltage amplitudes for virtual haptic gratings were measured. We observed that subjects were more sensitive to the applied voltage amplitude of the haptic gratings for the square wave, however, this was not statistically significant. In experiment II, the discrimination thresholds of the applied voltage amplitudes with haptic gratings were estimated. We found that the JND increases with the voltage amplitudes. Moreover, the JNDs of the four virtual gratings differ significantly, with the lowest and highest values being given by the triangle and sawtooth waveform, respectively.

The measured perception thresholds in this study can

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provide a foundation for rendering virtual textures on electrostatic tactile displays. In order to render perceivable virtual textures using an electrostatic tactile display, the applied voltage amplitude must be higher than the values reported in Figure 8. Similarly, in order to render two distinctive textures, the difference between the applied voltage amplitude should be larger than the values reported in Figure 10. It is the goal of our next research to measure the absolute detection thresholds and JNDs for frictional forces of haptic gratings for different types of waveforms of frictional force magnitudes were estimated when sliding a finger across the surface of the electrostatic tactile display. An additional goal is to expand what we have learned in the present study by exploring more types of waveforms of haptic gratings (e.g., duty cycles or intervals within gratings), to extend these results to more general textures, and finally improve the fidelity of the texture rendering on electrostatic tactile displays.

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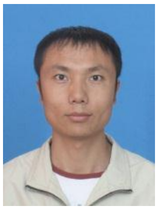

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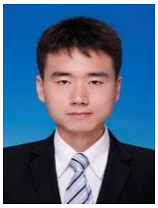

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