Effect of Waveform on Tactile Perception by Electrovibration Displayed on Touch Screens

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Abstract—In this study, we investigated the effect of input voltage waveform on our haptic perception of electrovibration on touch screens. Through psychophysical experiments performed with eight subjects, we first measured the detection thresholds of electrovibration stimuli generated by sinusoidal and square voltages at various fundamental frequencies. We observed that the subjects were more sensitive to stimuli generated by square wave voltage than sinusoidal one for frequencies lower than 60 Hz. Using Matlab simulations, we showed that the sensation difference of waveforms in low fundamental frequencies occurred due to the frequency-dependent electrical properties of human skin and human tactile sensitivity. To validate our simulations, we conducted a second experiment with another group of eight subjects. We first actuated the touch screen at the threshold voltages estimated in the first experiment and then measured the contact force and acceleration acting on the index fingers of the subjects moving on the screen with a constant speed. We analyzed the collected data in the frequency domain using the human vibrotactile sensitivity curve. The results suggested that Pacinian channel was the primary psychophysical channel in the detection of the electrovibration stimuli caused by all the square-wave inputs tested in this study. We also observed that the measured force and acceleration data were affected by finger speed in a complex manner suggesting that it may also affect our haptic perception accordingly.

Index Terms—Electrovibration, waveform, detection, tactile perception, psychophysical experiments, force, acceleration, touch screen

1 Introduction

Capacitive touch screens are indispensable part of smart phones, tablets, kiosks, and laptop computers nowadays. They are used to detect our finger position and enable us to interact with text, images, and data displayed by the above devices. To further improve these interactions, there is a growing interest in research community for displaying active tactile feedback to users through the capacitive screens. One approach followed for this purpose is to control the friction force between fingerpad of user and the screen via electrostatic actuation [1], [2], [3]. If an alternating voltage is applied to the conductive layer of a touch screen, an attraction force is generated between the finger and its surface. This force modulates the friction between the surface and the skin of the finger moving on it. Hence, one can generate different haptic effects on a touch screen by controlling the amplitude, frequency and waveform of this input voltage [1], [4], [5].

The electrical attraction between human skin and a charged surface was first reported by Johnsen and Rahbek in 1923 [6]. Around thirty years later, Mallinckrodt discovered that applying alternating voltages to an insulated aluminum plate can increase friction during touch and create a strange resin-like feeling [7]. He explained this phenomenon based on the well-known principle of parallel-plate capacitor. Later, Grimnes named this phenomenon as "electrovibration" and reported that surface roughness and dryness of finger skin could affect the perceived haptic effects [8]. Afterwards, Strong and Troxel [9] developed an electrotactile display consisting of an array of electrodes insulated with a thin layer of dielectric. Using friction induced by electrostatic attraction force, they generated texture sensations on the touch surface. Their experimental results showed that the intensity of touch sensation was primarily due to the applied voltage rather than the current density. Beebe et al. [10], developed a polyimide-on-silicon electrostatic fingertip tactile display using lithographic microfabrication. They were able to generate tactile sensations on this thin and durable display using 200-600 V voltage pulses and reported the perception at the fingertip as "sticky." Later, Tang and Beebe [11] performed experiments of detection threshold, line separation and pattern recognition with visually impaired subjects. Although they encountered problems such as dielectric breakdown and sensor degradation, the subjects were able to differentiate simple tactile patterns by haptic exploration. Agarwal et al. [12] investigated the effect of dielectric thickness on haptic perception during electrostatic stimulation. Their results showed that variations in dielectric thickness had little effect on the threshold voltage. Kaczmarek et al. [13] explored the perceptual sensitivity of the human finger to positive and negative input pulses. Their results showed that the subjects perceived negative or biphasic pulses better than positive ones. In all of the above studies, electrovibration was obtained using opaque patterns of electrodes

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on small scale surfaces. However, in the recent works of Bau et al. [1] and Linjama et al. [2], electrovibration was delivered via a transparent electrode on a large commercial touch surface, which demonstrates the viability of this technology on mobile applications. Bau et al. measured the sensory thresholds of electrovibration using sinusoidal inputs applied at different frequencies [1]. They showed that the change in threshold voltage as a function of frequency followed a U-shaped curve similar to the one observed in vibrotactile studies. Later, Wijekoon et al. [4], followed the work of [2], and investigated the perceived intensity of modulated friction generated by electrovibration. Their experimental results showed that the perceived intensity was logarithmically proportional to the amplitude of the applied voltage signal.

To understand how mechanical forces develop at fingertip-surface interface, Mayer et al. [14], developed a tribometer and measured the lateral force to estimate the electrostatic attraction force for the applied voltage. They showed the effect of actuation frequency on the lateral frictional force despite some subject-dependent variability. They reported that this person to person variability highly depends on varying environmental impedances caused by voltage controlled electrovibration. Later, Vezzoli et al. [15] improved the model of electrovibration by including frequency-dependent electrical properties of human skin as documented in [16]. Recently, Kim et al. [17], suggested a method based on current control to solve the nonuniform intensity problem and developed a hardware prototype working with this principle. The results of their user study showed that the proposed current control method can provide more uniform intensity of electrovibration than voltage controlled one.

Although electrovibration can potentially provide rich tactile sensations, the number of applications of this technology is limited yet due to our poor understanding of the electrical and mechanical properties of human finger and its interaction with a touch surface. For example, both the electrical and mechanical impedances of the human finger are frequency-dependent, and the coupling between them has not been well understood yet [1], [14], [15], [17]. Moreover, human to human variability of these properties and the influence of the environmental factors on these properties further complicate the problem.

In addition to the physical factors mentioned above, it is known that human tactile (mechanical) perception varies with stimulation amplitude and frequency [18]. Even though the effects of amplitude and frequency on the human tactile perception of electrovibration have already been investigated using pure sine waves [1], there is no earlier study on how our perception changes when another waveform is used. In this paper, we investigate how input voltage waveform alters human haptic perception of electrovibration. This work is mainly motivated by our initial observation that square-wave excitation causes stronger vibratory sensation than sine-wave excitation. According to the parallel-plate capacitor principle, the electrostatic force is proportional to the square of the input voltage signal, hence the electrostatic force generated by a square-wave is supposed to be constant [5], [19]. Since DC (constant) excitation voltages do not cause vibration sensation (though it causes adhesion sensation as reported in [6], [20]), the square wave excitation is expected to be filtered electrically by the stratum corneum. This filtering suppresses the low-frequency components in the excitation voltage and generates an electrostatic force with a distorted waveform. We hypothesise that the stronger vibratory sensation caused by a square wave is due to the high-frequency components in the resulting force signal. Since this waveform is rather complex (contains many frequency components), it can activate different psychophysical channels at different threshold levels [18], [21]. These four psychophysical channels (NPI, NPII, NPIII, P) are mediated by four corresponding mechanoreceptors and enable tactile perception. To predict tactile sensitivity, the Fourier components of the waveform should be analyzed by considering human sensitivity curve [18].

In this paper, using a simulation model developed in Matlab-Simulink, we first show that the forces displayed to human finger by electrovibration are very different for square and sinusoidal input voltages at low fundamental frequencies due to electrical filtering. Then, we show that the force waveform generated by square-wave excitation contains high-frequency components to which human tactile sensation is more sensitive. We support this claim by presenting the results of two experiments conducted with eight subjects. In the first experiment, we measure the detection threshold voltages for sinusoidal and square signals at various frequencies. In the second experiment, we actuate the touch screen at those threshold voltages and measure the contact force and acceleration acting on the index finger of subjects moving on the touch screen with a constant speed. We analyze the collected data in frequency domain by taking into account the human sensitivity curve and show that the square wave excites mainly Pacinian channel [22], [23]. Our results also suggest that scan speed has a significant effect on measured acceleration and force data and potentially on our haptic perception.

2 Waveform Analysis of Electrovibration

Based on the well-known principle of parallel-plate capacitance effect [19], the electrostatic force acting on a human fingertip placed on a touch screen can be estimated as

$$F_e = \frac{\epsilon_0 \epsilon_{sc} A}{2} \left(\frac{V_{sc}}{d_{sc}} \right)^2, \tag{1}$$

where ϵ_{sc} is the relative permittivity of the stratum corneum, ϵ_0 is the permittivity of vacuum, A is the area of the fingerpad, d_{sc} is the thickness of the stratum corneum. V_{sc} is the voltage across the stratum corneum, which can be expressed as a function of the voltage applied to the conductive layer of the touch screen, V, as

$$V_{sc} = V \frac{Z_{sc}}{Z_{body} + Z_{sc} + Z_{air} + Z_i}, \tag{2}$$

where, Z_{body}, Z_{sc}, Z_{air}, and Z_i represent the impedances of the human body, stratum corneum, air gap and touch surface respectively (see Fig. 1).

The electrostatic force formulas given in [14], [15] are slightly different than Equation (1). In those articles, the authors expressed the perceived electrostatic force as the force generated between the conductive layer of the touch screen

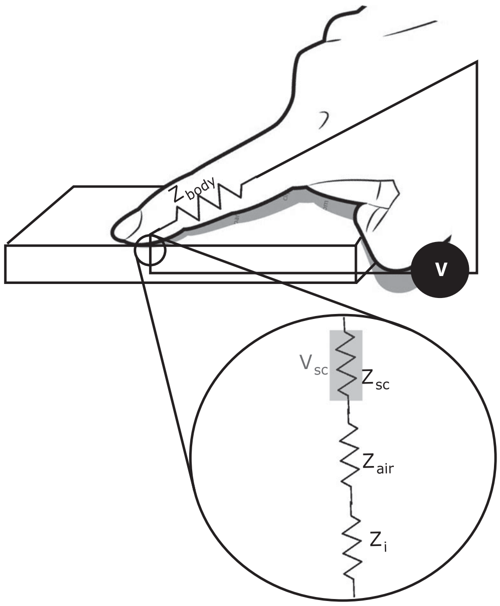


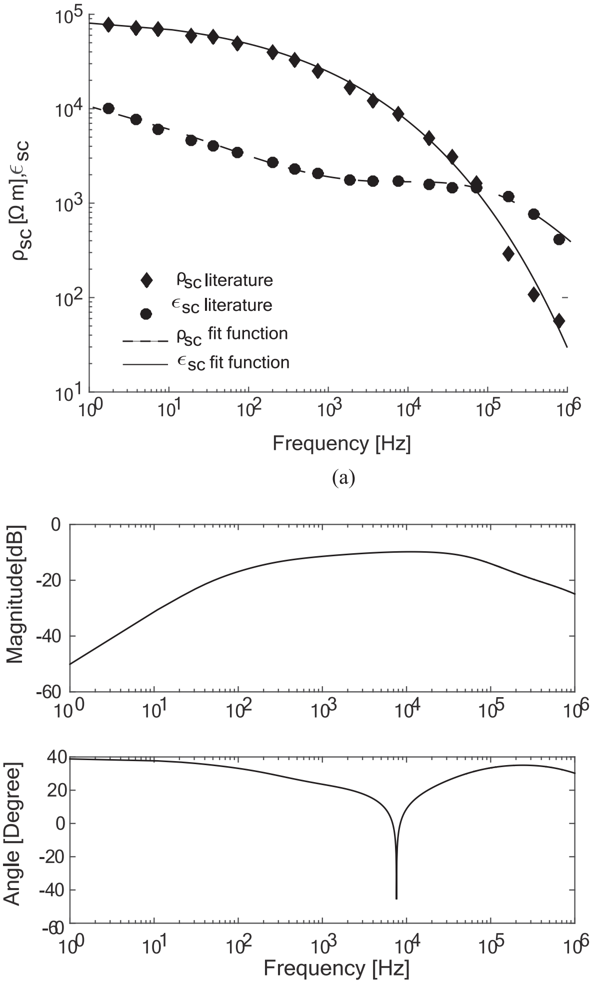
Fig. 1. An electrical model of human finger on a touch screen.

and human finger. More recently, Shultz et al. [20] derived this formula according to the voltage difference across the air gap (i.e., gap between human fingertip and the insulator layer of the touch screen). However, in our opinion, the perceived tactile effects due to the electrostatic forces occur at the inner boundary of the stratum corneum, as the mechanoreceptors are located close to the epidermal junction or in the dermis [24], [25], [26]. Hence, we used V_{sc} and not V in our calculations. The reader may refer to [19] for more information related to the derivation of the electrostatic force generated at the boundaries of two parallel or series dielectrics.

To investigate the effect of waveform in electrovibration, we developed an equivalent circuit model of human finger in Matlab-Simulink environment [5]. In this model, we neglected the capacitance of the human body and air gap and also the internal resistance of the touch screen. The capacitance of the touch screen was calculated based on the properties of a commercial touch screen (3M Inc.), which was also used in our experiments.[1] Previous studies showed that the human skin (especially sweat ducts and the stratum corneum) is not a perfect dielectric and has frequency-dependent resistive properties [13], [16], [27], [28]. Therefore, we modelled stratum corneum as a resistance and a capacitance in parallel. In [15], Vezzoli et al. used frequency-dependent values of resistivity, ρ_{sc}, and dielectric constant, ϵ_{sc}, of human stratum corneum reported by [16]. Their simulations showed that intensity of electrovibration was highly frequency-dependent. Similarly, we fitted polynomial functions to the experimental data reported by [16] and used those functions in our Matlab simulations (see Fig. 2a). Table 1 tabulates the parameters used in our model. For more information regarding this model, the reader may refer to [5].

Fig. 2b represents the Bode plot of the transfer function $\frac{V_{sc}(s)}{V(s)}$, estimated by using the values tabulated in Table 1. The

1. This touch screen is originally designed for capacitive-based touch sensing and composed of a transparent conductive sheet coated with an insulator layer on top of a glass plate. To generate haptic effects via electrovibration, the conductive sheet is excited by applying a voltage signal through the connectors designed for position sensing [1].



(a)

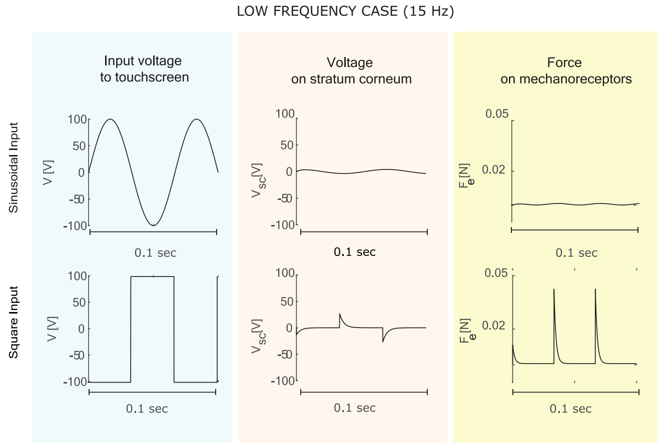
(b)

Fig. 2. (a) The experimental values of resistivity and dielectric constant of stratum corneum as reported in [16] and the polynomial functions fitted to them. (b) The transfer function between V_{sc} and V.

system displays the behavior of a bandpass filter with cut-off frequencies, f_{low}, and, f_{high}, at approximately 1 and 20 kHz respectively. Hence, it shows a first order high pass filter behaviour up to 1 kHz, which can cause distortions on the voltage that is transmitted to stratum corneum at low frequencies.

TABLE 1
The Description of the Parameters Used in the Circuit Model and the Corresponding Values Used in the Matlab Simulations

Parameter	Explanation	Value	Unit
A	Area of the human fingertip	1	cm^2
ϵ_0	Permittivity of vacuum	8.854×10^{-12}	F/m
R_{body}	Resistance of human body [17]	1	$k\Omega$
C_i	Capacitance of the 3M MicroTouch	$C_i = \frac{\epsilon_0 \epsilon_i A}{d_i}$	F
ϵ_i	Relative permittivity of the insulator	3.9	-
d_i	Thickness of the insulator	1	μm
R_{sc}	Resistance of stratum corneum	$R_{sc} = \frac{\rho_{sc} d_{sc}}{A}$	Ω
C_{sc}	Capacitance of stratum corneum	$C_{sc} = \frac{\epsilon_0 \epsilon_{sc} A}{d_{sc}}$	F
ρ_{sc}	Resistivity of stratum corneum	Fig. 2a	Ωm
ϵ_{sc}	Relative permittivity of the stratum corneum	Fig. 2a	-



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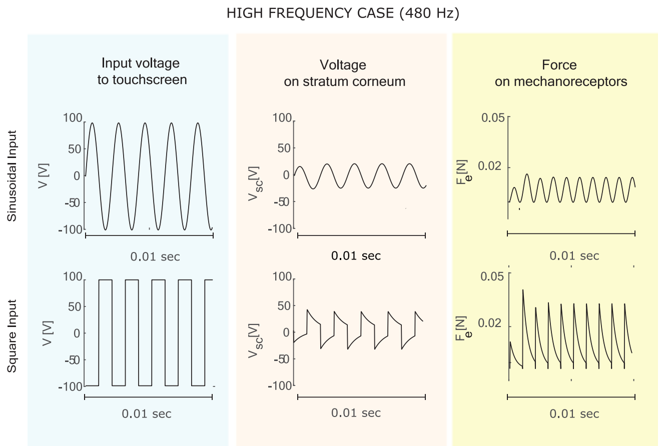


(b)

Fig. 3. Simulation results: (a) Low frequency case. (b) High frequency case.

To test the effects of this electrical filtering, we performed simulations with two different input waveforms (sinusoidal and square) at two fundamental frequencies (15 and 480 Hz). Fig. 3 shows the input voltage signal, the voltage across stratum corneum (filtered signals), and the resultant electrostatic force transmitted to mechanoreceptors for both waveforms at low and high frequencies (Fig. 3a and 3b). In low-frequency case (15 Hz), when the input is a sinusoidal signal, the output force signal is phase-shifted, and its amplitude drops significantly. Whereas, for a square wave signal, the output contains exponentially decaying relatively higher amplitude transients. In the high-frequency case (480 Hz), the decline in the output amplitude of the sinusoidal signal is much less, as expected from high pass filtering. Also, the output of the square signal resembles the input signal more because the signal alternates faster than the discharge rate of the capacitor formed by the human skin and touch screen insulator. The results depict that the stimuli on the mechanoreceptors have different waveform and amplitude than those of the input voltage signal.

If a complex waveform (containing many frequency components) arrives at mechanoreceptors, it can activate different psychophysical channels at different threshold levels [18], [21], [29]. These four psychophysical channels (NPI, NPII, NPIII, P) are mediated by four corresponding mechanoreceptor populations, which enable the tactile perception [18], [21], [22], [30], [31]. For this reason, the Fourier components of the stimulus should be weighted with the inverse of the human sensitivity curve to predict tactile sensitivity to complex stimuli [18]. The stimulus detection occurs at the channel where the maximum of this weighted function is located in the frequency domain. For example, a sinusoidal signal contains a single frequency component. To be able to detect this signal, its energy level must be higher than the human sensation threshold at that frequency. However, a square signal contains many frequency components. Detection occurs as soon as the energy level of one frequency component is higher than the human sensation threshold at that frequency. The tactile detection process for electrovibration is illustrated in Fig. 4. Here, a sinusoidal and a square voltage signals at the same fundamental frequency but different amplitude are applied to the touch screen. Due to electrical filtering of human finger, they generate electrostatic forces on the mechanoreceptors with the *same* amplitude. Therefore, the energy in 30 Hz component is the same for both force signals shown in Fig. 4c. However, the square wave input has higher frequency components, which are weighted more with respect to the human sensitivity curve (Fig. 4d). As a result, the weighted force signal contains a relatively high frequency component of 180 Hz (Fig. 4e). Therefore, in this illustration, the square wave is detected, but the sinusoidal wave is not.

3 Materials and Methods

3.1 Experiment 1: Psychophysical Experiments

To investigate how our detection threshold changes with input waveform, we conducted absolute detection experiments. These experiments enable us to determine the minimum voltage amplitude that the observer can barely detect [22], [31], [32], [33]. We aim to compare detection thresholds for sinusoidal and square wave voltage inputs at different frequencies to support our arguments made in Section 2.

3.1.1 Participants

We performed experiments with eight subjects (four female, four male) having an average age of 27.5 (SD: 1.19). All of the subjects were right-handed except one. All of them were engineering PhD students. The subjects used the index finger of their dominant hand during the experiments. They washed their hands with soap and rinsed with water before the experiment. Also, their fingers and the touch screen were cleaned by alcohol before each measurement. The subjects read and signed the consent form before the experiments. The form was approved by Ethical Committee for Human Participants of Koç University.

3.1.2 Stimuli

We estimated absolute detection thresholds for seven input frequencies (15, 30, 60, 120, 240, 480 and, 1,920 Hz) and two waveforms (sinusoidal and square).

3.1.3 Experimental Setup

The experimental setup used for the psychophysical experiment is shown in Fig. 5a. A touch screen (SCT3250, 3M Inc.)

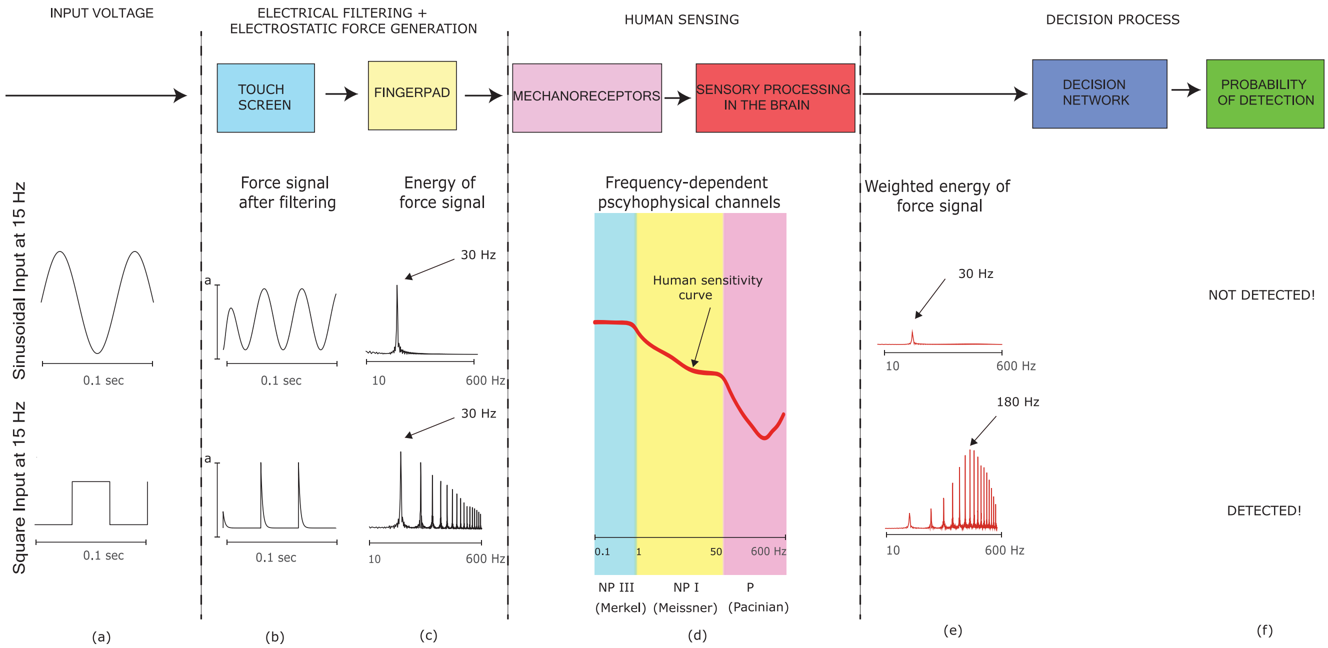


Fig. 4. An illustration of how tactile detection occurs. (a) Input sinusoidal and square voltage signals at 15 Hz applied to touch screen at different amplitudes. (b) These input signals are filtered electrically by human finger (see Fig. 3 for filtering process) before generating electrostatic forces with the *same* amplitude on the mechanoreceptors. (c) The energy of the force signal originated from the sinusoidal wave contains only one frequency component (30 Hz due to squaring in Equation (1)) while the one from the square wave contains many frequency components. (d) The frequency-dependent human sensitivity curve; the most sensitive frequency regions of three psychophysical channels are color-coded. The fourth channel (NPII) does not appear in this illustration. (e) When the Fourier components of the force signals are weighted by the inverse of the human sensitivity curve, the resulting signals from the sinusoidal and square waves have their maximum peaks at 30 and 180 Hz, respectively. Moreover, the energy of the frequency component for the square wave case is larger than that of the sinusoidal one at those frequencies. (f) Therefore, the square signal is detected, but the sinusoidal signal is not.

was placed on top of an LCD screen. An IR frame was placed above the touch screen to detect the finger location. The touch screen was excited with a voltage signal generated by a DAQ card (PCI-6025E, National Instruments Inc.) and augmented by an amplifier (E-413, PI Inc.). Subjects entered their responses through a computer monitor. An arm rest supported the subjects' arms during the experiments. For isolation of the background noises, subjects were asked to wear headphones displaying white noise during experiments.

3.1.4 Procedure

We used the two-alternative-forced-choice method to determine the detection thresholds. This method enables criterion-free experimental results [22]. We displayed two regions (A and B) on the LCD screen (Fig. 5a). Tactile stimulus was displayed in only one of the regions, and its location was randomized. The finger position of the subjects was detected via the IR frame. The subjects were asked to explore both areas consecutively and choose the one displaying a tactile stimulus.

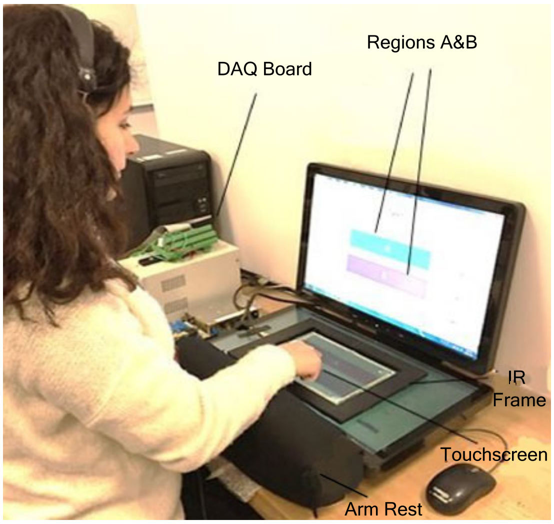
We changed the amplitude of the tactile stimulus via one-up/two-down adaptive staircase method. This procedure decreases the duration of the experimentation by reducing the number of trials [22], [30], [31], [34], [35]. We started each session with the stimulus amplitude of 100 V. This initial voltage amplitude provided sufficiently high-intensity stimulus for all the subjects. The voltage amplitude of the new stimulus was adjusted adaptively based on the past responses of each subject. If the subject gave two consecutive correct answers, the voltage amplitude was decreased by 10 V. If the subject had one incorrect response, the stimulus intensity was increased by 10 V. The change of the response from correct to incorrect or the vice versa was counted as one reversal. After four reversals, the step size was decreased by 2 V to obtain a more precise threshold value, as suggested in [1]. We stopped the experiment after 18 reversals and estimated the absolute detection threshold as the average of the last 15 reversals (Fig. 5b). The subjects completed the experiments in 14 sessions, executed in 7 separate days (two sessions per day). The duration of each session was about 15-20 minutes.

3.2 Experiment 2: Force & Acceleration Measurements

We measured the contact forces and accelerations acting on subjects' finger moving on the surface of the touch screen, which was actuated at the threshold voltages estimated in Experiment 1. Our main goal was to determine the frequency components of these recorded signals in order to validate our theoretical model and simulation results. We calculated the signal energies and weighted them with human sensitivity curve to estimate which components enabled the tactile detection. We also investigated the effect of scan speed on measured signals.

3.2.1 Participants

We conducted experiments with eight (four female and four male) subjects having the average age of 27.8 (SD: 2.1). The subjects read and signed the consent form before the



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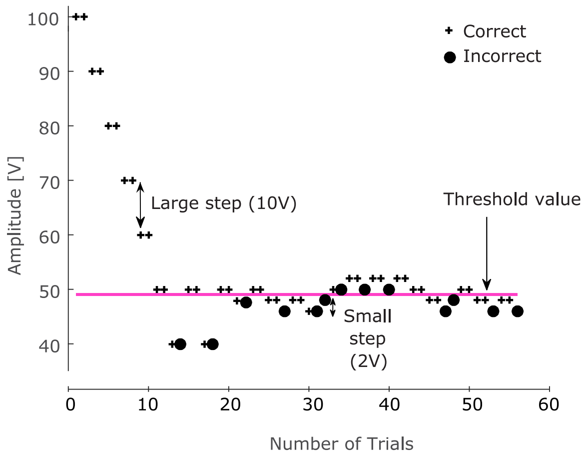

(b)

Fig. 5. (a) Experimental setup used in our psychophysical experiments. (b) An example data set collected by one up-two down adaptive staircase method.

experiments. The form was approved by Ethical Committee for Human Participants of Koç University. The subjects washed their hands with commercial soap and rinsed with water before each measurement. Then, they dried their hands in the room temperature and ambient pressure. Also, the touch screen was cleaned by alcohol before each measurement.

3.2.2 Stimuli

We measured accelerations and forces under 48 different conditions; there were 2 waveforms (sinusoidal, square), 6 frequencies (15, 30, 60, 120, 240, 480 Hz), and 4 finger scan speeds (10, 20, 50, 100 mm/s), which are tabulated in Table 2. In each measurement, one parameter was changed while fixing the others. We selected the finger scan speeds based on the values used in the earlier studies [36], [37], [38], [39]. The amplitude of the input signals was chosen 8 dB SL (sensation level: 8 dB higher than the threshold) more than the averaged threshold values measured in Experiment 1 (see Section 3.1).

TABLE 2
Experimental Parameters

Type	Parameter	Value	Unit
Test	**Frequency** **Waveform** **Scan Speed**	15, 30, 60, 120, 240, 480 Sinusoidal, Square 10, 20, 50, 100	Hz - mm/s
Control 1 (EMI Effect)	**Frequency** **Waveform**	15, 30, 60, 120, 240, 480 Sinusoidal, Square	Hz -
Control 2 (No excitation)	**Scan Speed**	10, 20, 50, 100	mm/s

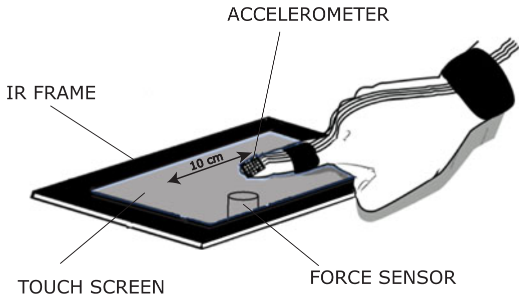

Fig. 6. Illustration for the attachment of force sensor and accelerometer.

Initially, we performed two separate control measurements to test the reliability of the collected data.[2] First, the forces and accelerations were measured when the finger was stationary in 12 conditions to observe the electromagnetic interference (EMI) effect on the sensors (Table 2). Second, the forces and accelerations were measured without any electrostatic excitation in 4 conditions (Table 2). Therefore, 64 different (48 test, 16 control) measurements were performed in total for each subject.

3.2.3 Experimental Setup

The experimental setup was similar to the one used in our psychophysical experiments (Fig. 5a). For this experiment, the touch screen (SCT3250, 3M Inc.) was placed on top of a force sensor (Nano17, ATI Inc.). The sensor was attached to the screen and an aluminium base using double-sided adhesive tapes (3M Inc.). The aluminum base was also attached to a stationary table by the same adhesive tape. The touch screen was excited with a voltage signal generated by a signal generator (33220A, Agilent Technologies Inc.). The voltage signal from the generator was amplified by an amplifier (E-413, PI Inc.) before transmitted the touch screen. An IR frame was placed on top of the touch screen to measure the finger scan speed during experiments. An accelerometer (ADXL 335, Analog Devices Inc.) was glued on the fingernail of the subjects. The accelerometer and force data were acquired by two separate DAQ cards (USB-6251 and PCI-6025E, NI Inc.). The cables of the accelerometer were taped on the finger and arm of the subjects as shown in Fig. 6. Both accelerometer and force data were acquired using

2. In the first set of control measurements, we checked the signal to noise ratio (SNR). If the SNR value of a measurement was lower than 5 dB, that measurement was repeated. In the second set of control measurements, we checked the signal energies due to finger motion without any electrostatic excitation. These energies were compared to those obtained from the test measurements to investigate the effect of electrostatic excitation (see Section 4.2).

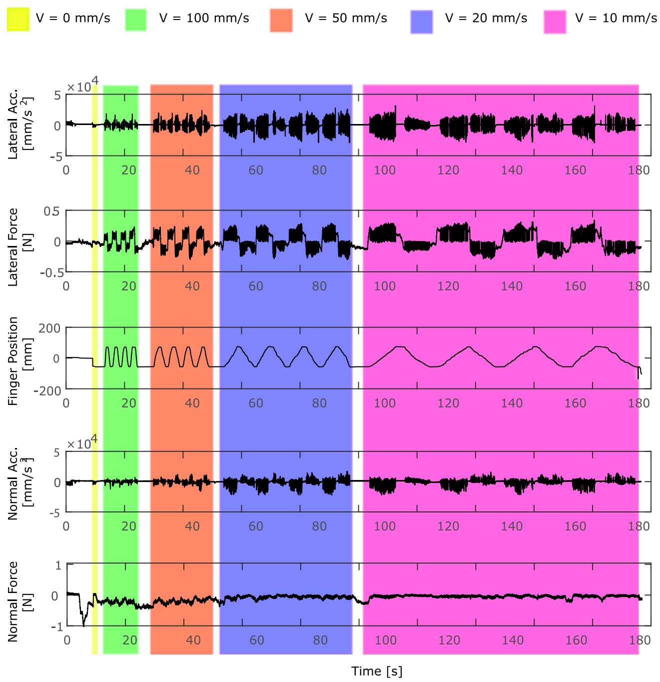

Fig. 7. Data collected during one experimental session. The input voltage was a square wave at 60 Hz.

LabView (NI, Inc.). An arm rest was used to support the subjects' arm during the experiments. The subjects were asked to wear a ground strap on their stationary wrist. The subjects were also asked to synchronize their scan speeds with the speed of a visual cursor displayed on the computer screen.

3.2.4 Procedure

The subjects were instructed to sit on a chair in front of the experimental setup and move their index fingers back and forth in the horizontal direction on the touch screen. They were asked to move their finger only in a 10×3 cm rectangular region on the touch screen. They were asked to synchronize their fingers with the motion of a moving cursor on the computer screen. Also, they received visual feedback about the magnitude of the normal force that they applied to the touch screen. For this purpose, two led lights were displayed on the computer screen and used to keep the normal force between 0.1 and 0.6 N. We selected this range based on the normal forces reported in the literature as relevant to tactile exploration [39], [40]. If the user applied less than 0.1 N to the touch screen, the led labelled as "press more" turned to green. However, if the user applied more than 0.6 N, the led labelled as "press less" turned to red. The subjects were instructed to complete four strokes (two forward, two backward) under each experimental condition.

Before starting the experiment, the subjects were given instructions about the experiment, and asked to complete a training session. This training session enabled subjects to adjust their finger scan speed and normal force before the actual experimentation. The experiments were performed in two blocks. The first and second blocks had six and seven sessions respectively. The experimental blocks were formed based on the input voltage waveform whereas the sessions were based on the input voltage frequency. The second block also contained one session without any input voltage. It took approximately 1.5 hours to complete all the measurements for a subject, including the time for attaching the accelerometer to the subjects' finger and the training session.

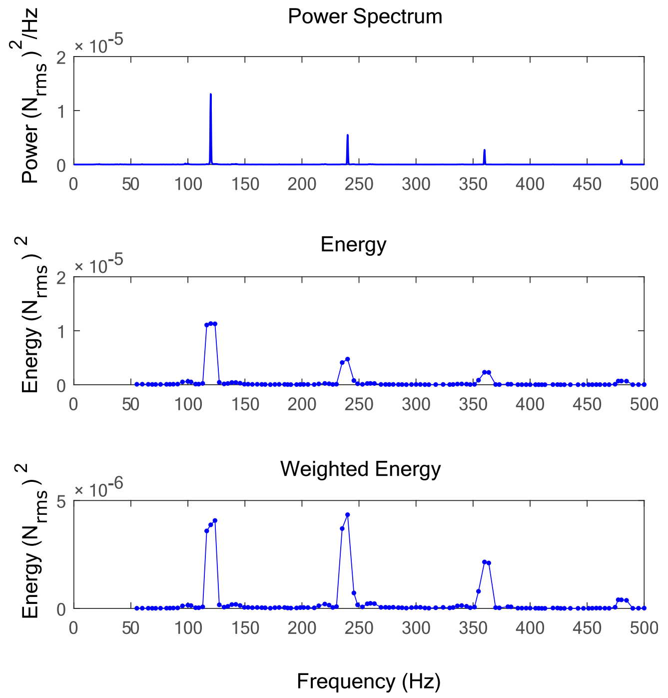

Fig. 8. Exemplar plots of average power spectrum, energy (in unit time), and weighted energy as a function of frequency. The plots were generated using the force data recorded at the finger scan speed of 20 mm/s (the input voltage was a square wave at 60 Hz).

3.2.5 Data Analysis

The force and acceleration data were analyzed in Matlab. An example data collected during one session is shown in Fig. 7. The figure shows force and acceleration data recorded at different scan speeds. We calculated the displacement values by integrating the acceleration data twice as suggested in [41].

The collected force, acceleration and displacement data were segmented according to the finger scan speed (see coloured regions in Fig. 7). Then, DC offset was removed from each segment by subtracting the mean values. To remove the low-frequency noise due to finger motion, data in each stroke was filtered by a high-pass filter having a cut-off frequency of 10 Hz. Afterwards, the RMS of each stroke was calculated and an average RMS was obtained for each finger speed using the data of 4 strokes.

For detection analysis, power spectrum of each stroke was calculated for the signals in the normal direction. Then, an average power spectrum was obtained for each finger speed using the power spectrum of 4 strokes. The peak frequencies were determined using this spectrum. The energy (in unit time) of each peak frequency was calculated by integrating its power spectrum data for the peak interval. Finally, the calculated raw energies were multiplied by the inverse of the normalized human sensitivity function to obtain the weighted ones (Fig. 8). We used the human sensitivity functions reported in [42], [43] for the force, acceleration and displacement data, respectively. Moreover, we calculated the corresponding electrostatic forces generated by the same waveforms and amplitudes via Matlab

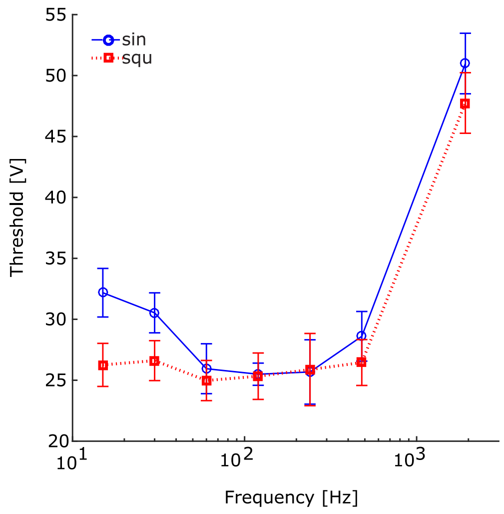

Fig. 9. The average detection thresholds of the subjects for seven fundamental frequencies (15, 30, 60, 120, 240, 480, 1,920 Hz) and two different waveforms (sinusoidal and square).

simulations. We also calculated the weighted energies of those simulated forces using the same data analysis approach discussed above.

In addition, the average friction coefficient was calculated by dividing the unfiltered lateral force of each stroke to those of normal force. Then, an average friction coefficient of each condition was obtained using the data of 4 strokes.

4 Results

4.1 Results of Experiment 1

Fig. 9 depicts the measured threshold voltages for seven fundamental frequencies (15, 30, 60, 120, 240, 480, 1920 Hz) and two different waveforms (sinusoidal and square).

We analyzed the results using two-way analysis of variance (ANOVA) with repeated measures. Both main effects (frequency and waveform) were statistically significant on the threshold levels ($p < 0.01$). Moreover, there was a statistically significant interaction between frequency and waveform ($p < 0.01$).

Additionally, the effect of the waveform on our tactile perception at each frequency was analyzed by Bonferroni corrected paired t-tests. The results showed that there was a statistically significant effect of the waveform on our haptic perception for fundamental frequencies less than 60 Hz. The difference between square and sinusoidal waves was significant at frequencies greater than and equal to 60 Hz. The corrected p-values for each frequency (15, 30, 60, 120, 240, 480, 1,920 Hz) are 0.008, 0.016, 1, 1, 1, 0.168, and 0.128, respectively.

4.2 Results of Experiment 2

The RMS values calculated for each condition from acceleration and force data (lateral and normal), and friction coefficients are plotted against fundamental frequencies of the input signals (Fig. 10). The data from different scan speeds were averaged for the clarity of plots. The results were analysed using three-way analysis of variance (ANOVA) with repeated measures. The results showed that finger scan speed had a significant effect on force, acceleration, and friction coefficient ($p < 0.05$).

To test the reliability of the measurement results, the average energies calculated for no electrostatic excitation were compared to those of electrostatic excitation using independent t-tests. Electrovibration generated a statistically significant difference in all calculated energies for both waveforms (sinusoidal and square) and for each response type (acceleration, force, and displacement) ($p < 0.05$).

The average weighted energies calculated for each actuated condition from displacement, acceleration and force data (normal) are plotted against fundamental frequencies of the input signal (Fig. 11a, 11b, and 11c). They are also plotted as a function of the frequency component having the highest energy (Fig. 11e, 11f, and 11g). The frequency interval in which the Pacinian channel is the most sensitive is marked as pink. Moreover, the average weighted energies estimated from Matlab simulations are also compared to those of the experimental results (Fig. 11d and 11h).

We analyzed the weighted energy results for all the measured variables using three-way analysis of variance (ANOVA) with repeated measures. The effects of waveform, frequency, and scan speed on the weighted energy were significant ($p < 0.05$). Their interactions except the one between speed and frequency were also statistically

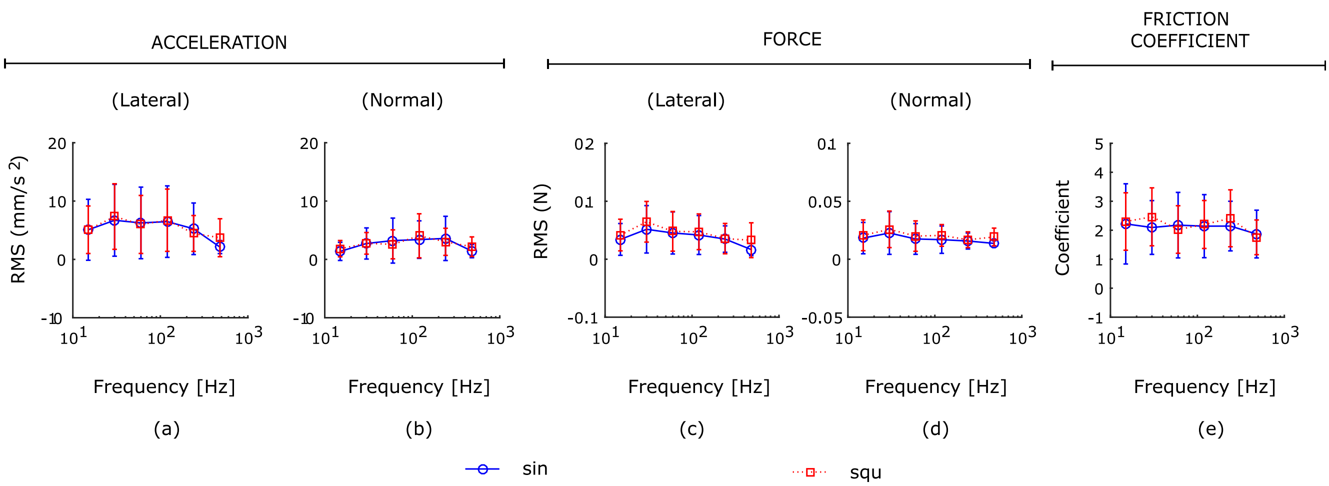

Fig. 10. (a), (b) The means and standard deviations of acceleration, (c), (d) force, and (e) friction coefficient. The data from different scan speeds were averaged for the clarity of plots.

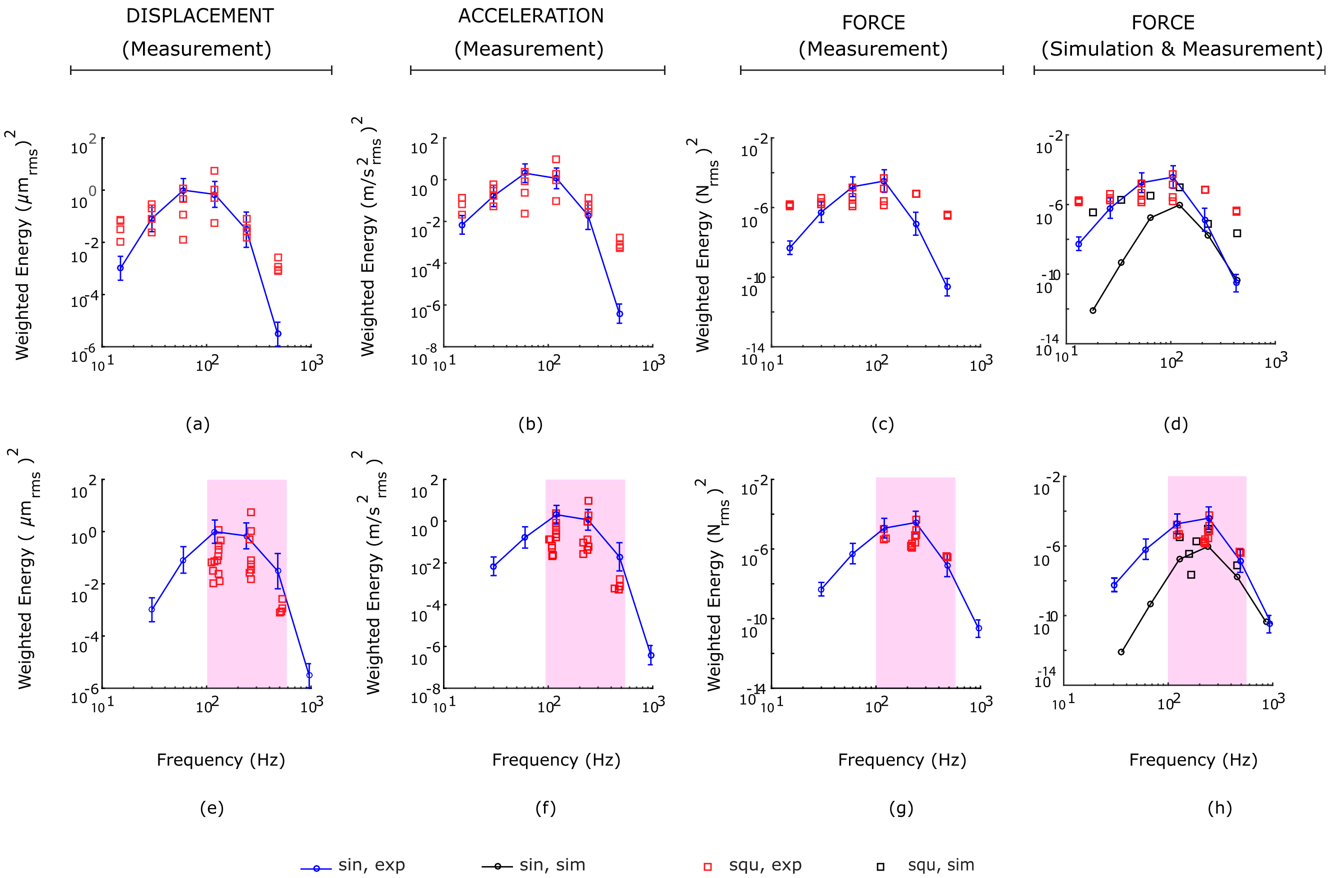

Fig. 11. (a), (b), (c) The weighted energies of the displacement, acceleration, and force signals at threshold are plotted against the input fundamental frequency and (e), (f), (g) the frequency component with the highest energy. The output data for the input sinusoidal signals recorded at different scan speeds were averaged for the clarity of plots. The output data for the input square signals were not averaged because they contain energy components at many frequencies. The weighted energies of the simulated force signals at threshold are plotted against the fundamental frequency (d) and the frequency component with the highest energy (h) and compared with those of the measurements. The pink regions indicate the frequency interval where the Pacinian channel is the most sensitive.

significant ($p < 0.05$). Moreover, Bonferroni corrected paired t-tests showed that the weighted energies were statistically different for sinusoidal and square waves at fundamental frequencies 15, 30 and 480 Hz ($p < 0.05$), and similar for the other frequencies.

For square signals, we calculated the proportion of the frequency components that were within the sensitivity range of the Pacinian channel (100-500 Hz) to the total number of components for each response type (acceleration, force, and displacement) for measured and simulated variables. The results showed that the frequency components having the highest energies were accumulated between 100-500 Hz for the square signals.

5 Discussion

Our results showed that human perception of electrovibration on touch screens is frequency-dependent as in vibrotactile studies. The detection thresholds obtained from our psychophysical experiments (Fig. 9) followed the well known U-shaped human sensitivity curve. The threshold values were low between 60 and 240 Hz, and higher for the rest. The corresponding detection energies of force (measured and simulated), acceleration (measured) and displacement (measured) signals calculated at these thresholds naturally displayed an inverted U-shape trend as a function of frequency (Fig. 11a, 11b, 11c, and 11d). These results are consistent with the existing vibrotactile literature [18], [21], [22], [31], [43]. In earlier studies, the detection thresholds of the index or middle finger were measured as a function of frequency by using various contactors. Typically, sinusoidal displacements with slow onset and offset times was used as stimuli, which generate mechanical excitation with a single frequency component. In our case, alternating electrostatic forces are generated at the contact interface based on the square of the voltage applied to the touch screen (Equation (1)). This nonlinear transformation introduces frequency components not present in the original signal. For example, when a pure sinusoidal voltage is applied to the touch screen, the force waveform has twice the frequency of the input wave. Hence, the detection results presented in Fig. 9 for square and sinusoidal stimuli should be interpreted by multiplying the values on the frequency axis with a factor of two. When the calculated energies are plotted against the frequency component having the highest energy (Fig. 11e, 11f, 11g, and 11h), the peak values are between 100 and 500 Hz, which is similar to those reported in the earlier vibrotactile literature [18], [22], [43]. In [1], Bau et al. measured absolute detection thresholds of electrovibration stimuli for sinusoidal inputs. Their results also followed a U-shaped trend, but their detection threshold values for sinusoidal inputs were slightly lower than our results. This difference might be caused by the experimental factors such as the angle of contact, movement direction, environmental factors such as finger moisture and contact temperature, the number of subjects, and subject-to-subject variability such as the variability in fingerprints and finger electromechanical properties [39], [40], [44], [45], [46], [47].

We found that participants were more sensitive to square excitation than sinusoidal one for frequencies lower than 60 Hz. The results suggested that Pacinian channel was the primary psychophysical channel in the detection of the electrovibration stimuli caused by all the square-wave inputs tested in this study. If a complex waveform, i.e., one which has many frequency components, is applied to the touch screen, the frequency components in the range of 50-250 Hz would be mostly active in stimuli detection due to the high sensitivity of Pacinian channel at twice of these frequencies. For example, due to electrical filtering of finger, low-frequency components of a square wave excitation are suppressed. Therefore, the voltage across the dielectric layer contains exponentially decaying high-frequency transients. The electrostatic force generated based on these transients is rather complex, including twice the frequencies and distortion products of the input signal components. Due to the frequency-dependent human tactile sensitivity, the frequency components in the force waveform will not be equally effective in detection (see Fig. 4). For example, when the weighted energies are plotted as a function of fundamental frequencies (Fig. 11a, 11b, 11c, and 11d), it is difficult to interpret the results in terms of tactile detection. On the other hand, when the weighted energies are plotted as a function of frequency components with the highest energies in the force, acceleration, and displacement signals in our study (Fig. 11e, 11f, 11g, and 11h), the peak values fell into the range of 100-500 Hz (see the pink regions in Fig. 11e, 11f, 11g, and 11h), which suggest that mainly the Pacinian channel was effective in detection for square wave inputs [18], [21].

In Matlab simulations, we used the values of the human skin parameters (ρ_{sc} and ϵ_{sc}) measured at the *fundamental* frequencies. Although this is a valid assumption for the sinusoidal wave, it is a simplification for the square wave, since square wave contains many frequency components. This limitation might have contributed to the differences in experimental and the simulation results. In general the force amplitudes and energies estimated through simulations were lower than those measured through experiments for both square and sinusoidal waves (Fig. 11d and 11h). Experimental factors such as moisture, temperature, and subject-to-subject variability of fingertip mechanical and electrical properties might have contributed to the differences [39], [40], [44], [45], [46], [47]. For example, measuring electrical impedances directly from the subjects might lead to a better match of the experimental and simulation results. Also, future models of mechanical interpretation of electrovibration may help to explain the mismatch. For example, a more accurate estimation of the force energies at the mechanoreceptor level could potentially be obtained by linking the electrostatic forces generated at the fingerpad to the mechanical forces measured at the contact interface during finger movement.

The changes in RMS of measured mechanical forces, accelerations and friction coefficients as a function of waveform were not significant most probably because the input signals were normalized referenced to the threshold levels. However, when we inspect Fig. 10, the RMS values as a function of frequency are almost constant. This has to be due to the nature of RMS measurement which is not suitable for modelling the detection. On the other hand, it simplifies the illustration of time varying sensor output data.

Measured force, acceleration and friction coefficients were affected by finger scan speed in a complex manner suggesting that it might also affect our haptic perception accordingly. The results showed that the magnitude of contact forces and accelerations were appeared to be positively correlated with the scan speed though the friction showed a negative correlation. Similar results were also obtained in the earlier studies. Using an artificial finger which had similar electrical and mechanical properties of a real human finger, Mullenbach et al. investigated that lateral forces generated by electrovibration increased as a function of scan speed [48]. Moreover, in our experiments the acceleration and force energies increased as the scan speed was increased. The earlier studies in tribology literature support this result [44], [49], [50], [51], [52]. The effect of scan speed on the measured forces and accelerations and their energies suggest that the viscoelastic characteristics of human finger also plays a role in tactile sensing of electrovibration. The possible effect of skin mechanics on psychophysical detection thresholds were also suggested by Yildiz and Güçlü in [31]. In that study, they measured vibrotactile detection thresholds of Pacinian channel at 250 Hz and mechanical impedances of fingertips of seven subjects. They reported that there was a significant positive correlation between loss moduli of the skin and detection thresholds.

As far as we know, this is the first study which investigates the effect of input voltage waveform on haptic perception of electrovibration in the frequency domain. The earlier research studies have already investigated the detectability and discriminability of mechanical waveforms in real and virtual environments and the results of these studies can be compared with ours. For example, Summers et al. [53], observed that vibrotactile sine waves and monophasic/tetra-phasic pulses at suprathreshold levels resulted in similar scores in a frequency identification task. They concluded that temporal cues are more important than spatial cues in that particular task. We think their results can be interpreted that the strongest frequency component in complex waveforms (after correction for human sensitivity) drives the stimulus detection. Cholewiak et al. [54] investigated the perception of virtual gratings containing multiple spectral components. They performed detection and discrimination experiments with virtual sinusoidal and square gratings displayed by a force-feedback device at various spatial frequencies. Their results showed that detection thresholds of square gratings were lower than the sinusoidal ones at lower spatial frequencies. Similar to our results, they explained that the square gratings are detected based on their harmonic components having the lowest detection threshold.

6 Conclusion

In this study, we investigated how input voltage waveform affects our haptic perception of electrovibration on touch screens. Through psychophysical experiments with eight subjects, we first measured the detection thresholds of electrovibration stimuli generated by sinusoidal and square voltages at various frequencies. We observed that the subjects were more sensitive to square wave stimuli than sinusoidal one for fundamental frequencies lower than 60 Hz. We hypothesized that the sensation difference of waveforms in low fundamental frequencies is due to frequency-dependent electrical properties of human skin and human tactile sensitivity. To validate our hypothesis and observe if there was any other physical factor which may affect our perception of electrovibration perception, we conducted a second experiment with another group of eight subjects. We collected force and acceleration data from fingertips of the subjects while they explored a touch screen displaying electrovibration stimuli at threshold voltages. We analyzed the collected data in frequency domain by taking the human tactile sensitivity curves given in [42], [43] into account. The results suggested that Pacinian was the primary psychophysical channel in the detection of the square wave input signals tested in this study. Moreover, our results showed that measured acceleration and force data are affected by finger scan speed.

To the best of our knowledge, this is the first detailed study investigating the effect of input voltage waveform on haptic perception of electrovibration. Our findings not only help us to understand the mechanism of human tactile sensing of electrovibration but also may help engineers and designers to develop applications displaying tactile effects to the users through a touch screen. For example, a user interface developer designing a virtual dial on a touch screen may prefer to use low frequency square pulses rather than sinusoidal ones to display tactile dents. On the other hand, less detectable sinusoidal signals could be used to display frictional feedback to the user while she/he turns the dial on the screen for better control. Furthermore, the perception difference between waveforms may also be used for pattern and edge recognition. When a blind user explores a virtual shape on a touch screen, the edges can be conveyed by low-frequency square waves while a sinusoidal wave can be used for smoother feeling inside. Moreover, since the detection of tactile stimuli is determined by frequency components below 1 kHz, it may not be necessary to transmit higher frequency components which would be lower than the detection thresholds. This ensures transmission of less data without sacrificing the perceptual needs for systems with limited bandwidth.

Furthermore, the results of this study can be a guide for developing an electromechanical model of human finger linking the electrostatic force displayed to human finger pad by electrovibration to the mechanical forces felt at the finger contact interface. As our results suggest, frictional forces modulated by the contact interface and scan speed have influence on mechanical vibrations measured at fingertip and hence potentially on our tactile perception. Finally, our results also suggest that tactile perception of electrovibration is similar to that of vibrotactile stimuli. We have recently started to investigate psychophysics of masking by electrovibration as done similarly in vibrotactile studies. This may help us to augment tactile effects displayed to the user through the touch screen.

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