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Roughness perception of virtual textures displayed by electrovibration on touch screens

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Abstract— **In this study, we have investigated the human roughness perception of periodical textures on an electrostatic display by conducting psychophysical experiments with 10 subjects. To generate virtual textures, we used low frequency unipolar pulse waves in different waveform (sinusoidal, square, saw-tooth, triangle), and spacing. We modulated these waves with a 3kHz high frequency sinusoidal carrier signal to minimize perceptional differences due to the electrical filtering of human finger and eliminate low-frequency distortions. The subjects were asked to rate 40 different macro textures on a Likert scale of 1-7. We also collected the normal and tangential forces acting on the fingers of subjects during the experiment. The results of our user study showed that subjects perceived the square wave as the roughest while they perceived the other waveforms equally rough. The perceived roughness followed an inverted U-shaped curve as a function of groove width, but the peak point shifted to the left compared to the results of the earlier studies. Moreover, we found that the roughness perception of subjects is best correlated with the rate of change of the contact forces rather than themselves.**

I. INTRODUCTION

Touch screens have been used in over a wide range of portable devices nowadays, but our interactions with these devices mainly involve visual and auditory sensory channels, which are already overloaded. While a commercial touch screen today can easily detect finger position and its gestures, it does not provide the user with haptic feedback. However, haptic feedback can be used in touch screens as an additional sensory channel to convey information and also reduce the perceptual and cognitive load of the user. For instance, haptic effects can be used to send a personal message to loved ones in the form of a beating heart, to select the fabric of a cloth that we purchase online, to teach mathematics to primary school students (e.g. dragging one number on the secreen to the other to obtain the desired sum while feeling haptic resistance for incorrect matching), to differentiate the feel of riding a bicycle on smooth, bumpy, and sandy roads during game playing, and to design a new user interface (e.g. estimating the amount of data in a folder intuitively by the haptic resistance while dragging it on the screen).

One of the techniques used to generate haptic effects on a touch screen is electrovibration [1]. In this technique, the friction between the fingertip of the user and the touch screen is modulated via electrostatic forces. When an alternating voltage is applied to the conductive layer of a surface capacitive touch screen, an attractive electrostatic force is generated in normal direction between the finger and the surface. By controlling the amplitude, frequency, and waveform of the input voltage, the frictional force between the moving finger and the touch screen can be modulated [2], [3]. This technology has a great potential especially in mobile applications including communication, games, education, data visualization, and interface development for blinds.

Although it is straightforward to generate a tactile stimulus on a touch screen using electrovibration, its effect on our haptic perception is poorly understood yet. One of the areas that require further research in this regard is the realistic rendering of textures. In this study, we investigate the roughness perception of periodic virtual textures displayed by electrovibration. Our roughness perception of real textures has been already investigated extensively in the literature [4]–[14]. Based on the multi dimensional scaling (MDS) study conducted by Hollins et. al. [15], there are two main perceptual dimensions in texture perception: roughness/smoothness and hardness/softness. This finding was further confirmed by Hollins et al. [16] and Yoshioka et al. [17] in later studies. Since it is not possible to alter softness on touch screens via electrostatic attraction yet, we have focused on roughness perception.

In the literature, several types of stimuli have been used to investigate roughness perception of real textures; raised dots with controlled height and density [9], [12], dithered cylindrical raised elements [4], [5], [11], and metal plates with linear gratings [6], [10], [13]. These studies showed that size of the tactile elements (i.e gratings, dots, cones) and the spacing between them are critical parameters in roughness perception. Moreover, Hollins et al. [5] and Klatzky and Lederman [18] found that the underlying mechanism behind roughness perception is different for micro-textures (textures having inter-element spacing $<\approx$ 0.2 mm) and macro-textures (textures having inter-element spacing $>\approx$ 0.2 mm).

At macro-textural scale, Lederman and collegues [4], [6], [10], [13] observed that groove width has a greater effect on perceived roughness than ridge width. This observation has been supported by other studies later [14] suggesting that the perceived roughness increases monotonically with the groove width, but decreases modestly with the ridge width. On the other hand, further increasing the spacing between the tactile elements (more than 3.5 mm) causes the subjects perceive the surface as smooth rather than rough. Hence, roughness perception follows an inverted U-shaped function

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of groove width, reaching a maximum value at approximately 3.5 mm of bump separation. Based on these observations, Lederman and Taylor developed a mechanical model that estimated the perceived roughness as a power function of the total area of the skin that was instantaneously deformed through contact with the surface texture [4], [6]. Later, Connor et al. [12] developed a neural model which stated that roughness perception of macro textures is achieved by spatial cues through pressure change and finger deformation. These arguments were later supported by showing that speed has little effect on perceived roughness [9]. In contrast to these studies, Cascio and Sathian [14] showed that roughness perception is affected by temporal frequency, which is defined as the ratio of finger speed to wavelength of texture. They conducted experiments with different finger speeds on real textures. Their results showed that roughness perception of the subjects increased as a function of temporal frequency for textures with varying ridge widths. Moreover, Smith et. al. [11] reported that roughness perception is positively correlated with the rate of change in the lateral force. This result also implies that the temporal cues play a role in roughness perception of macro-textures.

At micro-textural scale, Hollins and colleagues [5] reported that the roughness perception is mainly achieved by vibratory cues. Moreover, they found direct evidence that roughness perception of micro-textures is mediated by Pacinian Corpuscles. They used a Hall effect transducer to record the vibrations generated on the skin when a set of micro-textured surfaces is passively presented to the index finger of subjects. They weighted the power of the measured vibrations by the spectral sensitivity of Pacinian mechanoreceptors to show that roughness estimates of the subjects were correlated with these weighted skin vibrations [19].

In this study, we have chosen our tactile stimuli at macro-textural scale. Since the tactile stimuli displayed to the subjects in our study is independent of spatial position, our study is best comparable to those on linear gratings. In those studies, the roughness perception has been typically investigated by square gratings of varying groove and ridge widths. Due to the time-dependent nature of our signals, we have opted to use ”wavelength” and ”duty cycle” as our

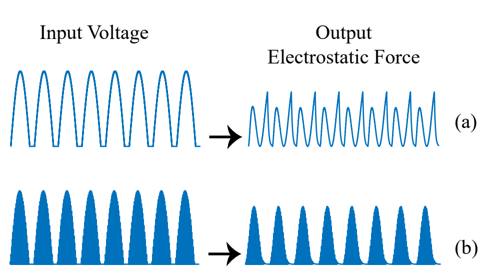

Fig. 1: The electrostatic forces generated by the model in [2]; a. without amplitude modulation, b. with amplitude modulation. Amplitude modulation prevents the distortions due to high pass filtering of human electrical properties.

design parameters, but adjusted their values to match the groove width values used in the literature while keeping the ridge width constant. The effect of wave amplitude on roughness perception has not been investigated in this study since it is already known that perceived roughness is positively correlated with the height of the surface features [20], [21].

This study contributes to the literature by answering the following research questions: 1) How does our haptic perception of roughness displayed by electrovibration change with waveform and groove width? 2) How does our roughness perception correlate with the contact forces acting on finger?

II. MATERIALS AND METHODS

A. Participants

We conducted an experimental study with 10 human subjects (3 women, 7 men) to investigate the roughness perception of haptic gratings. The ages of the subjects were varied between 22 and 30 (average = 26.4 ± 2.8). The subjects used the index finger of their dominant hand to explore the surface. 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 then signed the consent form before the experiments. The form was approved by Ethical Committee for Human Participants of Koç University.

B. Stimuli

We used the concept of amplitude modulation to generate our electrovibration stimuli. We modulated the amplitude of a low-frequency envelope signal, f_e, with a high frequency sinusoidal carrier signal, f_c, at 3kHz. Since 3kHz is far beyond the human vibration sensation range (up to 1kHz), this carrier signal did not cause any additional vibratory feelings. Moreover, the proposed amplitude modulation minimizes the perceptional differences due to the electrical filtering of human stratum corneum and eliminates low-frequency distortions as shown in Fig. 1 [2]. The finger scan speed, v, was maintained at approximately 50 mm/s during the experiments using a visual cursor displayed to the subjects. We selected this scan speed based on the values used in the literature [22].

In our implementation, we only consider the positive parts of the modulated signal (i.e. unipolar signal), $y(t)$, to display virtual textures on the touch screen. Due to the fact that the electrostatic force is a function of the square of the input voltage signal, a unipolar input (voltage) to the touch screen results in a unipolar output (electrostatic force) with the same wavelength, λ, and duty cycle of the input (Fig.1). An illustration of stimuli generation in our system is shown in Fig. 2. In addition to using a sine wave, we also utilized square, saw-tooth, and triangle waves as the modulated signal and altered their wavelength and duty cycle to generate different virtual textures.

We evaluated the roughness perception of 40 different virtual textures (Table I). The voltage amplitude for each stimulus was 100 V. We set the wavelengths and duty cycles

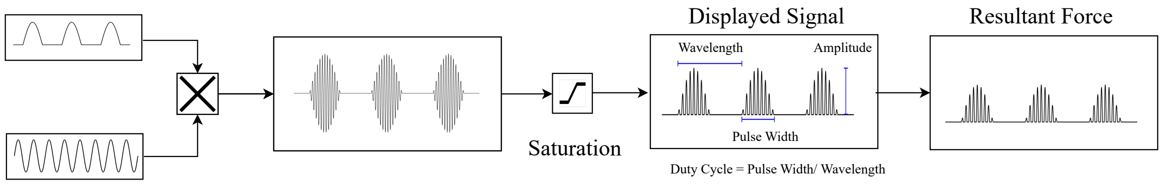

Fig. 2: Stimuli generation via electrovibration. A low frequency unipolar signal is modulated with a high frequency (3kHz) carrier signal. Only the positive parts of the signals are considered as the input to the touch screen. Due to the high frequency modulation, the resultant electrostatic force has the same wavelength and duty cycle as the input voltage signal.

of our virtual textures to match the typical groove width values used in the literature (Table I). The ridge width was kept constant as 0.5 mm. The resultant temporal frequency, f_e, was derived from $\frac{v}{\lambda}$.

TABLE I: Experimental parameters and their corresponding values. (GW: Groove Width, RW: Ridge Width)

Controlled Parameters			Corresponding Parameters		
Waveform	**GW (mm)**	**RW (mm)**	**Wavelength (mm)**	**Duty Cycle**	**Temporal Frequency (Hz)**
	0.125		0.625	0.8	80
	0.250		0.750	0.6666	66.67
	0.375		0.875	0.5714	57.14
Square	0.5		1	0.5	50
Sinusoidal	1	0.5	1.5	0.3333	33.33
Triangular	1.5		2	0.25	25
Saw-tooth	2		2.5	0.2	20
	3.5		4	0.125	12.5
	5.5		6	0.0833	8.33
	7.5		8	0.0625	6.25

Each texture was displayed 6 times to the subjects. Hence, the total number of haptic stimuli for each subject was 240 (40 texture $\times$ 6 repetitions). The stimuli were displayed in random order while changing the order for each subject in each session.

C. Experimental Setup

A surface capacitive touch screen (SCT3250, 3M Inc.) was used to display tactile stimuli. Desired signals were generated by a DAQ card (PCI-6025E, National Instruments Inc.) and boosted by an amplifier (E-413, PI Inc.) before transmitted to the touch screen. A compact monitor displaying a visual cursor moving with a speed of 50 mm/s was placed below the touch screen to adjust the scan speed of the subjects (Fig. 3). A force sensor (Nano17, ATI Inc.) was placed under the touch screen to acquire normal and tangential forces during the experiments. Both the DAQ card and the force sensor had a sampling rate of 10kHz. Also, an IR frame was placed above the touch screen to detect the actual scan speed of the subjects. This information was used to check if the actual scan speed of a subject had been significantly different from the desired value in each trial. If so, all the related data of that trial was discarded to obtain more consistent results.

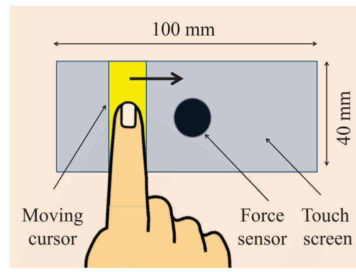

Fig. 3: The haptic exploration area on the touch screen.

D. Experimental Procedure

The subjects were instructed to sit on a chair in front of the setup and move their index finger back and forth twice in the horizontal direction to explore the haptic stimuli.

During the experiments, the subjects were allowed to replay the haptic stimuli only once by pressing the replay button. To reduce tiring of the subjects, an arm rest was placed under their wrist. The subjects were asked to wear noise cancellation headphones to prevent from any noise affecting their haptic perception. Before starting the experiment, the subjects were given instructions about the experiment and presented with a training session displaying all stimuli once in random order. It took about 30 minutes for each subject to complete one session including training. The experiments were performed in three separate sessions.

A Likert scale of 1-7 was used to rate the haptic perception of the subjects. After each trial, the subjects entered their rating of the stimulus using a pen-based stylus and a simple graphical user interface consisting of 7 radio buttons.

E. Data Analysis

The roughness estimates of each subject were normalized between 0 and 1 after each experimental session. Then, for each texture, the average of six estimates were calculated.

During each trial, both normal and tangential forces were recorded using the force sensor. A data segment of one second was chosen from the last stroke of each trial and the following metrics were calculated: rms of tangential force (RTF), rms of normal force (RNF), average friction coefficient (AFC), rms of rate of change in the tangential force (RTFR) and rms of rate of change in the normal force (RNFR). AFC was calculated by dividing the average tangential force to the average normal force. RTFR and RNFR were calculated as backward differentiation of recorded tangential and normal force, respectively. Each metric was normalized between 0 and 1 for each subject and session. Then, the average of six measurements was reported for each texture.

III. RESULTS

The normalized roughness estimates (means and standard errors) as a function of duty cycle, wavelength, and temporal frequency are shown in Fig. 4. Since the values for duty cycle, wavelength, and temporal frequency were selected to alter groove width (while keeping the ridge width constant), duty cycle and wavelength -or duty cycle and frequency- were coupled with each other. Yet, they were two different dimensions. The results were analyzed using 2-way ANOVA repeated measures. The results showed that both waveform and groove width had significant effects on the roughness perception of the subjects (Table II). Also, there was a statistically significant interaction between waveform and groove width. Bonferroni corrected paired t-tests showed that the subjects perceived the square wave as the roughest ($p<0.01$), while the other waveforms were perceived equally rough. Moreover, the difference in roughness perception was significant for the groove width varying between 1.5 and 7.5 mm ($p<0.01$), but not significant for the ones below 1.5 mm. Greenhouse-Geisser method was used to correct the fractional degrees of freedom in F-value.

TABLE II: ANOVA results for roughness perception.

Effects	F-value	p-value
Waveform	$F(2.01, 18.09) = 14.137$	$< 0.01^*$
Groove Width	$F(9, 81) = 3.289$	$< 0.01^*$
Waveform × Groove Width	$F(27, 243) = 1.811$	0.01^*

The measured values (RNF, RTF, AFC, RNFR, RTFR) as a function of groove width are shown in Fig. 6. We also analyzed these results using 2-way ANOVA repeated measures. The results showed that the main effects (waveform and groove width) and their interaction had no significant effect on RTF, RNF and AFC, but on RTFR and RNFR. Bonferroni corrected paired t-tests showed that RTFR and RNFR were significantly different for all waveform pairs ($p<0.01$) except triangular and saw-tooth waves. Moreover, the difference in RTFR and RNFR were significant for the groove width values between 1 mm and 7.5 mm ($p< 0.01$), but not significant for the ones below 1 mm.

TABLE III: ANOVA results for force metrics.

Metric	Effects		
	Waveform	Groove Width	Waveform x Groove Width
RNF	p = 0.310	p = 0.100	p = 0.102
RTF	p = 0.078	p = 0.100	p = 0.200
AFC	p = 0.340	p = 0.700	p = 0.279
RNFR	$p<0.01^*$	$p<0.01^*$	$p<0.01^*$
RTFR	$p<0.01^*$	$p<0.01^*$	$p<0.01^*$

IV. DISCUSSION

Our results showed that the subjects perceived the square wave as the roughest while the other waveforms (sinusoidal, triangle and saw-tooth) were perceived equally rough (Fig. 4). Hence, it can be deduced that our perception of roughness depends on the waveform of the tactile stimulus displayed by electrovibration. The earlier studies also support our findings. In our previous study [2], we measured the tactile detection thresholds of sinusoidal and square wave signals displayed by electrovibration. We found that square wave signals are more detectable than sinusoidal waves at frequencies lower than 60 Hz. Cholewiak et al. [23] conducted human experiments in virtual environments using a haptic device to investigate the amplitude detection thresholds for virtual gratings in the form of sinusoidal and square waves. The results showed that the detection threshold for the square-wave gratings was lower than that of the sinusoidal gratings. Kocsis et al. [24] conducted discrimination experiments with both real and virtual sinusoidal and triangular textured surface gratings. All

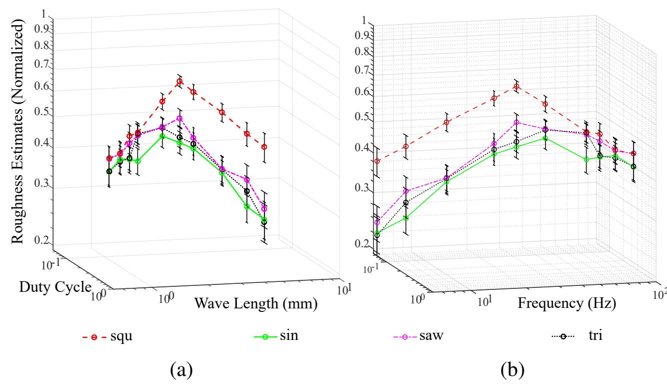

Fig. 4: Roughness estimates (means and standard errors) of 10 subjects as a function of duty cycle, wavelength, and temporal frequency.

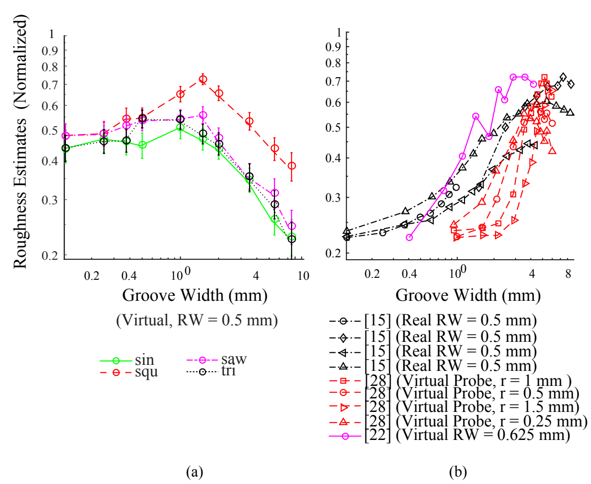

Fig. 5: a. Roughness estimates (means and standard errors) of 10 subjects as a function of groove width. b. Roughness estimates reported in literature.

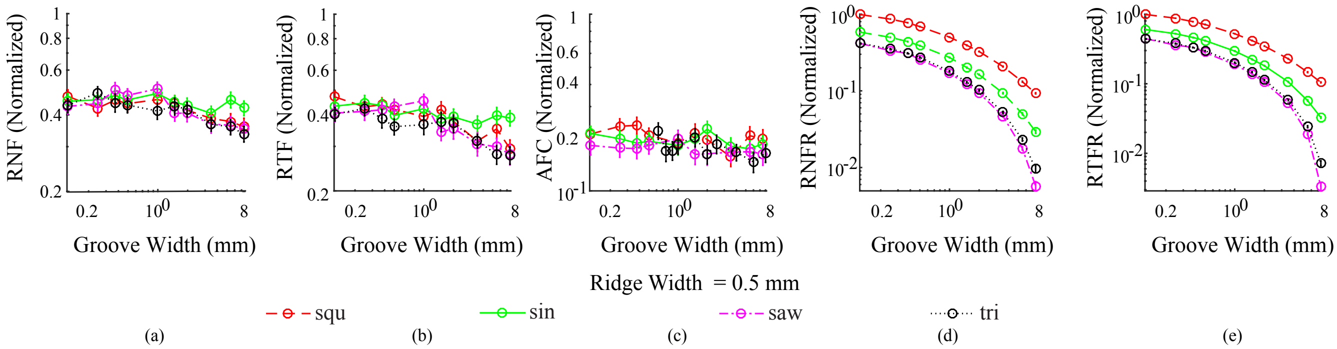

Fig. 6: Normalized force metrics (means and standard errors) a. RMS of normal force b. RMS of tangential force c. Average friction coefficient d. RMS of rate of change in normal force e. RMS of rate of change in tangential force.

gratings had a wave length of 2.5 mm while their height (wave amplitude) varied between 55-70 μm. The results showed that the discrimination thresholds did not differ significantly between sinusoidal and triangular gratings.

We found that the relation between roughness perception and groove width follows an inverted U-shaped curve as reported in earlier studies (Fig. 5). In those studies [13], [20], [25], the roughness perception reached its maximum value at groove width of approximately 3.5 mm, but it was 1.5 mm in our study. This discrepancy can be attributed to several factors. Hollins et al. [5] and Klatzky and Lederman [18] stated that the perception of real micro-textures is mainly achived by vibratory cues via Pacinian Corpuscle mechanoreceptors while that of the macro-textures is achieved by spatial cues through finger deformation and change in pressure. Although the textures were at macroscale in our study, the haptic stimuli were mainly perceived through the vibrotactile channel and the influences of pressure change and finger deformation on this perception were less significant (see Fig. 7). Another possible reason for the difference could be the effect of finger speed on the haptic perception of textures in our study. In the earlier studies performed with bare finger and real textures [10], the effect of speed on texture perception has found to be negligible, suggesting that the roughness perception is mainly governed by spatial cues. However, when the effect of spatial cues is reduced significantly and the vibration is the only feedback as in the case of exploring textures with a rigid probe, the speed of exploration appears to affect the haptic perception [4]. In fact, the location of the peak point shifts in roughness versus groove width curve with respect to the exploration speed. Cascio and Sathian [14] also showed that roughness perception is affected by temporal frequency, which depends on exploration speed.

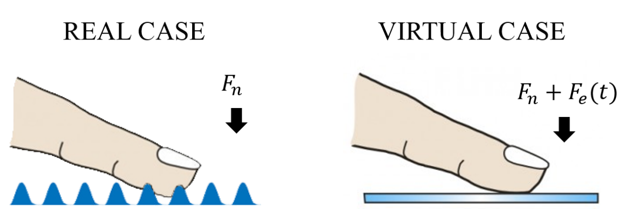

Fig. 7: Comparison of normal forces applied to fingertip while touching real textures and the virtual ones displayed by electrovibration on touch screens. Here, F_n is the applied normal force (quasi-constant during exploration) while F_e is the time-dependent electrostatic force.

Finally, our force measurements showed that RTFR and RNFR are the ones best correlated with the roughness perception of subjects. To better understand the reasoning behind this, we estimated the rms of electrostatic force (REF) and its derivative (REFR) using the model in [2] for the waveform and groove width values utilized in our experiment (Fig. 8). Here, REF and REFR were the highest for the square wave and lowest for triangular and saw-tooth waves. REF decreased with the increase in groove width in our case, since the corresponding duty cycle values decreased (see Table I). In addition to the reduction in the force magnitude, the decline in the temporal frequency as the grove width increases caused a similar trend in REFR. However, the difference caused by electrostatic force did not appear on the measured force magnitudes but on their derivatives. Since the normal forces applied by the subjects were not controlled in our experiment, the resultant force magnitudes (normal and tangential) showed fluctuations though they reduced as a function of increasing groove width (Figs. 6a and 6b), as observed in the simulations (Fig. 8a). Moreover, the

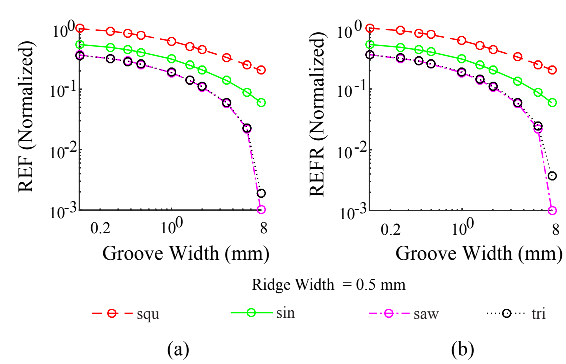

Fig. 8: a. RMS of the electrostatic force (REF) and its rate of change (REFR) calculated using the model in [2].

electrostatic force modulated the tangential force according to the Coulomb model, which resulted in an approximately constant friction coefficient as suggested in [3] and shown in Fig. 6c. In contrast to the real textures, the time-dependent change in the contact forces depends on only electrostatic forces which are almost ten times smaller than the applied finger force. This is why RTFR and RNFR were better correlated with the roughness perception of subjects, and their trends as a function of groove width were matched to that of the simulations (compare Figs. 6d, 6e with Fig. 8b).

V. CONCLUSION

In this study, we conducted psychophysical experiments with 10 subjects to investigate the human roughness perception on electrostatic displays. We rendered sinusoidal, square, saw-tooth, and triangular pulse waves in different groove widths while keeping the ridge width constant. We modulated these low frequency pulse waves with a 3kHz high frequency signal to prevent low frequency distortions on the electrostatic force. Our results showed that human roughness perception follows an inverted U-shaped trend with respect to groove width, as reported in the earlier studies. The subjects perceived square wave as the roughest while their haptic perception of the other waveforms was not significantly different from each other. Moreover, the roughness perception of the subjects was best correlated to the rate of change of the normal and tangential forces rather than their magnitudes.

To our knowledge, this is the first detailed study investigating human roughness perception of virtual textures on a touch screen. In addition to providing an insight to our understanding of human haptic perception, engineers and designers can benefit from our study while developing applications which involve rendering tactile effects on a touch screen. They can adjust wavelength, duty cycle and waveform of the voltage signals to generate tactile effects with desired roughness.

In this study, we adjusted the wavelength and duty cycle of our signals to match the groove width values in the literature. This gave us the opportunity to compare our results with those of the earlier studies. However, this choice did not allow us to investigate the individual effects of wavelength and duty cycle on our roughness perception, which we plan to do so in the near future. We will also expand our study by including micro-textures.

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