Tactile Perception of Virtual Edges and Gratings Displayed by Friction Modulation via Ultrasonic Actuation

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Abstract—Tactile discrimination and roughness perception of real textures are extensively studied and underlying perceptual mechanisms are relatively well-established. However, tactile perception of virtual textures rendered by friction modulation techniques on touch surfaces has not been investigated in detail yet. In this study, we investigated our ability to discriminate two consecutive step changes in friction (called edges), followed by discrimination and roughness perception of multiple edges (called periodic gratings). The results showed that discrimination of two consecutive edges was significantly influenced by edge sequence: a step fall in friction (FF) followed by a step rise in friction (RF) was discriminated more easily than the reverse order. On the other hand, periodic gratings displayed by consecutive sequences of FF followed by RF were perceived with the same acuity as compared to vice versa. Independent of the edge sequence, we found that a relative difference of 14% in spatial period was required to discriminate two periodic gratings. Moreover, the roughness perception of periodic gratings decreased with increasing spatial period for the range that we have investigated (spatial period > 2 mm), despite the lack of spatial cues on grating height. We also observed that rate of change in friction coefficient was better correlated with the roughness perception than the friction coefficient itself. These results will further help to understand and design virtual textures for touch surfaces.

Index Terms—Tactile perception, ultrasonic vibrations, surface haptics, textures, friction modulation

1 Introduction

Touch-enabled devices like smartphones and tablets are ubiquitous now-a-days, and are being used everyday for telecommunication, e-commerce, games and entertainment, professional and social networking, information gathering on the Internet, etc. However, all the devices commercially available today provide visual and auditory feedback to their users but almost no tactile feedback, though it is known that tactile feedback improves task performance and realism when interacting with digital data [1]. Moreover, tactile sensation is a significant factor for preference and admiration of certain consumer products due to their texture. Therefore, a great deal of research is being carried out in recent years to develop and study techniques that can render tactile information on touch-enabled devices. In this regard, ultrasonic actuation and electrovibration are two emerging techniques that work on the principle of friction modulation. Ultrasonic actuation reduces, while the electrovibration increases the friction between fingerpad and touch surface. In ultrasonic actuation, a surface is vibrated at an ultrasonic resonance frequency, which creates a lubrication effect between fingerpad and the surface due to bouncing of fingerpad on a cushion of squeezed air [2], [3]. In electrovibration, an electrostatic force of attraction is produced by applying a voltage signal to the conductive layer of a capacitive touch screen, which increases the friction between its surface and fingerpad [4], [5].

Friction modulation techniques can potentially display a variety of tactile stimuli on the interaction surface of touch-enabled devices. For example, periodic modulation of friction magnitude generates a feeling of textured surfaces [6]–[16]. Alternatively, data-driven techniques can be used for more realistic rendering of virtual textures [17]–[20]. Moreover, tactile rendering of 3D virtual shapes or bumps is possible by mapping the gradients of a surface to magnitude of friction forces [21], [22]. Finally, short duration friction pulses can render virtual edges or haptic-detents, which can improve the user performance in target acquisition tasks [1], [23]–[25], and enhance the design and use of virtual widgets such as knobs in digital user interfaces [26], [27].

To use friction modulation techniques effectively for texture rendering, it is important to understand our tactile perception of textures and the underlying mechanisms. For example, several studies have already shown that roughness is one of the most critical perceptual dimensions in differentiating real surfaces [28]–[31]. Furthermore, it has been observed that temporal cues (mediated by PC-afferents) play a dominant role in the discrimination and roughness perception of fine surface features (micro-textures), while spatial cues (mediated by SA1-afferents) are found to be dominant in the discrimination and roughness perception of coarser ones (macro-textures) [32], [33].

To investigate the discrimination and roughness perception of macro-textures, surfaces with periodic topographies such as raised-dots and linear gratings have been typically utilized in earlier studies. This is due to the fact that the real surfaces we touch and interact in our daily life have

M.K. Saleem and C. Basdogan are with the Department of Mechanical Engineering, Koc University, Istanbul, Turkey, 34450. Email: ksaleem13@ku.edu.tr, cbasdogan@ku.edu.tr
C. Yilmaz is with the Department of Mechanical Engineering, Bogazici University, Istanbul, Turkey, 34342. Email:cetin.yilmaz@boun.edu.tr

complex topographies and frictional properties, which make them difficult to study systematically in tactile perception studies. Since, this study is focused on linear gratings, the related literature on tactile perception of real and virtual gratings is discussed in detail below.

1.1 Discrimination and Roughness Perception of Real Gratings

Discrimination and roughness perception of real gratings at macro scale is primarily governed by spatial cues. Several studies have shown that the roughness perception of linear gratings increases with groove width and decreases with ridge width [34]–[40]. On the other hand, Drewing [41] investigated the roughness perception of linear gratings having a low ridge height for spatial periods varying from 0.5 to 10 mm and observed an inverted U-shape trend in roughness perception. The difference in results between [41] and the previous studies [34]–[40] is related to the degree of spatial deformation of fingerpad under normal loading [34]. Increasing the groove width allows the fingerpad to penetrate between the ridges, thus increasing the skin deformation, and consequently the perceived roughness. However, when the ridge height is low, fingerpad contacts the base surface more easily. Therefore, any further increase in groove width does not increase the penetration between the ridges, resulting in a drop in perceived roughness. Furthermore, it has been shown that the discrimination and roughness perception of macro-textures are not affected by finger velocity [35], [42], [43]. This finding further supports the notion that roughness perception of macro-textures is mediated by a spatial mechanism.

Nevertheless, contribution of temporal cues in the discrimination and roughness perception of macro-textures cannot be fully ignored. Morley et al. [36] have noted a drop in discrimination performance (Weber fraction increased from 5% to 10%) when the finger is pressed on the surface without sliding (i.e. static contact). This drop in discrimination is due to the lack of finger movements, which provide additional vibration cues enhancing the perception. Similarly, Kocsis et al. observed an increase in discrimination performance of linear gratings when they were explored with a rigid probe [44]. This was due to the efficient transfer of vibration cues as a result of an increase in the skin contact area (i.e. holding the probe increases the area in contact with the hand, as compared to a fingerpad exploring the same surface). Cascio and Sathian [39] observed a significant influence of temporal frequency on the discrimination and roughness perception of linear gratings for varying ridge width, but not for groove width.

1.2 Discrimination and Roughness Perception of Virtual Gratings

Tactile discrimination and roughness perception of virtual gratings are less studied, and the perceptual mechanisms behind them have not been fully understood yet. Obviously, better understanding of these mechanisms is important for effective rendering of virtual textures.

Roughness perception of virtual gratings was investigated using force feedback devices in [45]–[48]. The results suggest that a trend similar to that of real gratings can be observed if the device can resolve forces in 3D to simulate surface topography [48]. On the other hand, conflicting trends in roughness perception have been reported for force feedback devices which can only resolve 2D forces (in planar direction). Klatzky and Lederman [45], [46] utilized a haptic mouse that can modify sliding resistance only and found that perceived roughness increases with spatial period for the range varying from 0.08 to 8 mm. Smith et al. [47] rendered periodic gratings (varying from 1.5 to 8.5 mm in spatial period) using a force feedback device which could only display tangential forces resisting to the planar movements. Unlike [45], they observed a decrease in roughness perception when spatial period was increased. They also observed a strong influence of friction coefficient and tangential force on roughness perception.

The discrimination and roughness perception of periodic gratings, rendered on a surface using friction modulation techniques have been far less studied. Vardar et al. [12] investigated the roughness perception of periodic gratings displayed by electrovibration. They compared four waveforms; sine, square, triangular and saw-toothed waves with spatial periods varying from 0.6 to 8 mm. The width of periodic high friction regimes (analogous to ridge width) was taken as 0.5 mm, while the width of low friction regimes (analogous to groove width) was varied. The finger velocity was controlled indirectly by displaying a visual cursor moving at 50 $\mathrm{mm/s}$. The results showed that square waveform was perceived as the roughest, while there were no significant differences between the other three waveforms. The perceived roughness followed an inverted U-shaped trend as a function of spatial period with a peak value around 2 mm. The discrimination of periodic gratings, rendered on a touch surface by ultrasonic actuation was investigated in [7]. Four standard and eight comparison gratings in square waveform were rendered. The width ratio of high to low friction regimes was always kept constant. The finger velocity was not controlled. The results showed that the difference threshold (JND) increases with spatial period (0.2, 0.32, 0.47 and 0.8 mm for spatial period of 2.5, 3.5, 5 and 10 mm, respectively), but unlike real gratings [49], Weber fraction remained almost constant (varied between 8 and 10 %).

1.3 Problem Statement and Objectives

The above discussion shows that discrimination and roughness perception of real textures are extensively investigated, and the underlying perceptual mechanisms are relatively well-established. However, corresponding studies for virtual textures are limited, particularly the ones displayed by friction modulation techniques. In fact, there is no in-depth study exploring the roughness perception of virtual textures displayed by ultrasonic actuation. It has been shown that a step increase in friction casts a stronger perceptual effect as compared with a step fall in friction [50]. However, how multiple changes in friction affects the tactile perception of periodic gratings is yet to be established.

This study aims to explore the roughness perception of virtual periodic gratings at macro-scale, rendered on a glass surface by using ultrasonic actuation technique. Since it is important that the tactile stimuli must be discriminable (distinct) in the first place for the estimation of their

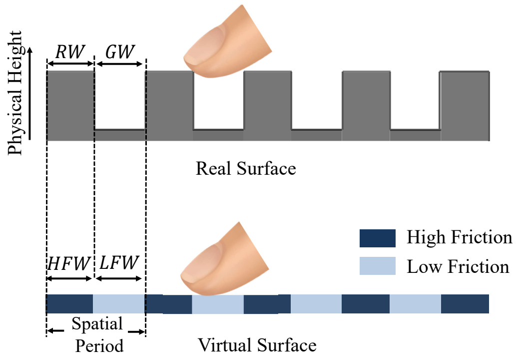


Fig. 1: Analogy between real textures and virtual textures rendered by ultrasonic actuation in our study.

TABLE 1: List of symbols

Name	Symbol
Vibration Amplitude	V_{amp}
Finger Velocity	f_v
Rendering Length	R_{length}
Spatial Period	SP
Temporal Frequency	ω
Relative Difference Between Spatial Periods	R_{diff}
Rising Friction Edge	RF
Falling Friction Edge	FF
Edge Sequence	E_{seq}
Rising Edge Followed by Falling Edge	$RF \rightarrow FF$
Falling Edge Followed by Rising Edge	$FF \rightarrow RF$
Distance Between Two Edges	Δx
Duration Between Two Edges	Δt
High Friction Width	HFW
Low Friction Width	LFW
Ridge Width	RW
Groove Width	GW
Waveform	W_{frm}
Dynamic Friction Coefficient	μ
Rate of Change in Friction Coefficient	$d\mu/dt$
Normal Force	F_n

roughness perception, we initially investigated the tactile discrimination of virtual edges and gratings. Consequently, the results of discrimination experiments were used in the design of the roughness perception experiment. Since friction modulation by ultrasonic actuation cannot render all the spatial cues (such as grating height) necessary for the activation of spatial neural mechanism, we hypothesized that roughness perception of virtual gratings will mainly rely on temporal cues. To test this hypothesis, we rendered a set of discriminable periodic gratings in different spatial periods and investigated their roughness perception. To create an analogy between virtual and real gratings, we define the width of high friction regime (HFW) as a counterpart of ridge width (RW), and width of low friction regime (LFW) as a counterpart of groove width (GW), as shown in Fig. 1. The hierarchy of the psychophysical experiments conducted in this study is given in Fig. 2. The symbols frequently used in the text are listed in Table 1.

2 Experimental Setup

Our variable friction tactile display was a 100 $\times$ 60 mm glass surface, actuated at 26.9 kHz using two piezoelectric actuators (7BB-35, Murata Manufacturing). A small piezoelectric patch (FT-10.5T, Kepo Electronic), calibrated by a Laser Doppler Vibrometer (OFV-551, Polytec), was utilized to measure the instantaneous vibration amplitude (V_{amp}) of the surface. The surface has a response time of 2 ms approximately. A high resolution force sensor (Nano17 Titanium, ATI Industrial Automation) was placed under the glass surface to measure the normal and tangential forces acting on the finger. A motorized stage was used to move the participant's finger at a constant velocity (f_v). For further details on the experimental setup, the readers are referred to [50].

3 EXP-1: Discrimination of Two Consecutive Virtual Edges

The purpose of this experiment was to estimate the spatial threshold distance between two consecutive virtual edges. An edge was rendered either by rising friction (RF) or falling friction (FF).

3.1 Participants

Twenty participants (5 females) volunteered to take part in the experiment. The average age of the participants was 28.8 ± 4.1 years. The participants used the index finger of their dominant hand during the experiments. Their finger and the surface were cleaned with alcohol before the start of each experimental session. To eliminate any perceptual bias due to the surrounding noise, the participants were asked to wear noise cancellation headphones, and white noise was played to their ears. There was a short training session at the start of each experiment to familiarize the participants with the experimental setup and procedures. The participants read and signed the consent form before the experiments. The form was approved by the Ethical Committee for Human Participants of Koc University.

3.2 Experimental Design

We considered three independent factors for the experimental design: finger velocity (f_v = 30 and 60 $\mathrm{mm/s}$), vibration amplitude (V_{amp} = 1 and 2 µm), and edge sequence (E_{seq} = $FF \rightarrow RF$ and $RF \rightarrow FF$). In $FF \rightarrow RF$, we varied low friction width (LFW) between two edges, while high friction width (HFW) was varied in $RF \rightarrow FF$ as elaborated in Fig. 3(a). Therefore, there were a total of 8 rendering conditions in this experiment.

3.3 Procedure

We rendered the first edge after moving participants' finger via the motorized stage for 20 mm (to ensure steady motion), as shown in Fig. 3(a). The distance (Δx) between two consecutive edges (i.e. low friction width or high friction width) was initially set to the maximum value of 15 mm, but then adjusted dynamically based on the participants' response. When the motion was stopped, participants were asked if they felt two distinct edges. If their response was "YES", we decreased distance by 2.5 dB, however, if they reported only one edge ("NO" response), we increased the distance by 2.5 dB. We presented the stimuli on the

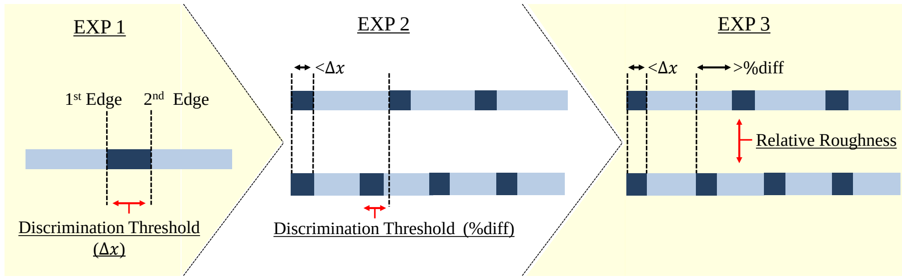


Fig. 2: Hierarchy of experiments in this study.

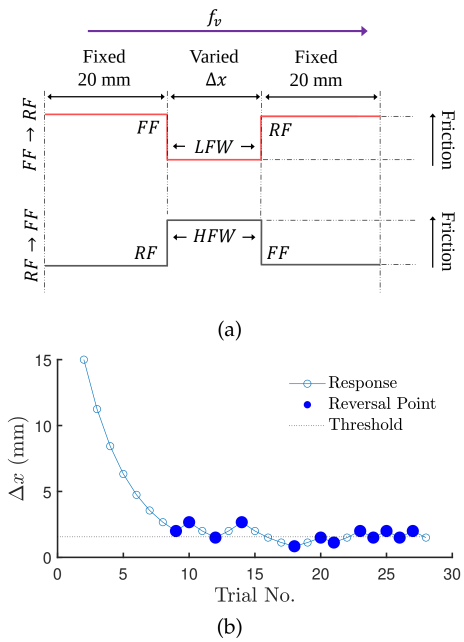


Fig. 3: Experimental procedure for evaluating the spatial threshold distance between two consecutive virtual edges (EXP-1); (a) desired edge sequences (E_{seq}), (b) an example for experimental trial.

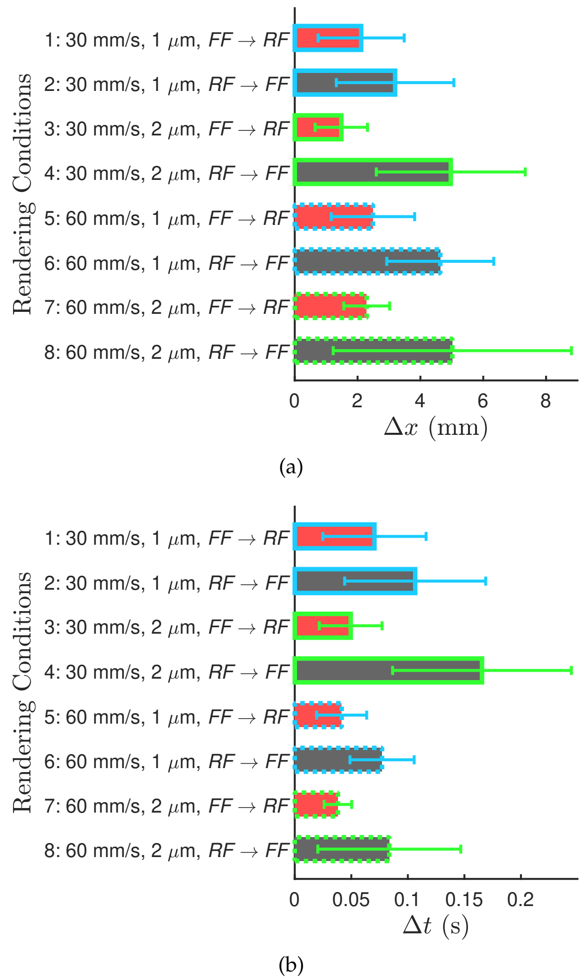


Fig. 4: Thresholds to discriminate two consecutive virtual edges in EXP-1 (mean values and standard deviations); a) spatial threshold and b) temporal threshold. Red and gray bars are for $FF \rightarrow RF$ and $RF \rightarrow FF$, solid and dotted bars are for f_v of 30 and 60 $\mathrm{mm/s}$, blue and green bars are for V_{amp} of 1 and 2 µm, respectively.

rightward and leftward direction of their finger scan. The process was repeated for twelve reversals. If they could not detect two edges even after a distance of 15 mm, we restarted the experiment (twice only) after a short break. They were allowed to repeat a trial only once. They had to lift their finger up at the end of each scan to wait for the next one. We implemented this protocol to remove any build up stress on their finger during tangential motion. It took 5 to 7 minutes for participants to reach a threshold value under each rendering condition. To reduce the learning effect, we permuted the order of rendering conditions by which participants performed the experiment. Each participant completed the experiment in two days (four rendering conditions per day).

We calculated the spatial threshold distance (Δx) by averaging the last eight reversals of each trial (see Fig. 3(b)). The spatial threshold distance was converted to temporal threshold duration (Δt) by dividing it with finger velocity (f_v). We performed three-way repeated measure ANOVA to analyze the effects of independent factors finger velocity, vibration amplitude, and edge sequence on spatial threshold distance. For pair-wise comparisons, the significance level for each comparison was adjusted by Bonferroni correction.

3.4 Results

During the experiment, 8 participants had difficulty in detecting two consecutive edges under the condition of

$RF \rightarrow FF$. Some of them reported that they could feel a sharp rise in friction followed by a slower decrease, which they could not classify it as an edge. On the other hand, all 20 participants performed well under the condition of $FF \rightarrow RF$ and their responses converged to a spatial threshold distance (Δx). For further analysis, we only considered the results of 12 participants (5 females) who showed converging response under all rendering conditions. The discrimination thresholds in spatial and temporal domains (Δx and Δt) for all rendering conditions are shown in Fig. 4(a) and Fig. 4(b), respectively. The mean thresholds against all independent factors are listed in Table 2.

- The results showed that the effect of finger velocity (f_v) on spatial threshold distance was not significant (see Table 3 for ANOVA results).
- The spatial threshold distance was significantly lower for $FF \rightarrow RF$, as compared with $RF \rightarrow FF$.
- There was no significant effect of vibration amplitude (V_{amp}) on spatial threshold distance. However, we observed an interaction between vibration amplitude and edge sequence (E_{seq}). A post-hoc pairwise comparisons (based on estimated marginal means) showed that vibration amplitude affected $RF \rightarrow FF$ ($p = 0.05$). This is evident when rendering conditions 2 and 4 are compared in Fig. 4(a).

TABLE 2: Mean thresholds to discriminate two consecutive virtual edges (EXP-1).

Independent Factors		$\Delta x \pm$ SEM (mm)	$\Delta t \pm$ SEM (s)
f_v	30 mm/s	2.94±0.35	0.10±0.01*
	60 mm/s	3.60±0.42	0.06±0.01*
V_{amp}	1 µm	3.11±0.33	0.07±0.01
	2 µm	3.40±0.42	0.08±0.01
E_{seq}	$FF \rightarrow RF$	2.14±0.26*	0.05±0.01*
	$RF \rightarrow FF$	4.45±0.57*	0.11±0.01*

*Statistically significant

TABLE 3: ANOVA results for the effect of independent factors on spatial threshold, Δx (EXP-1).

Effects	F-value	p-value
f_v	F(1,11)=3.00	0.11
V_{amp}	F(1,11)=0.84	0.38
E_{seq}	F(1,11)=25.9	<0.001*
$f_v \times V_{amp}$	F(1,11)=0.39	0.54
$f_v \times E_{seq}$	F(1,11)=0.05	0.82
$V_{amp} \times E_{seq}$	F(1,11)=12.7	0.004*

*Statistically significant

3.5 Discussion

In EXP-1, we measured the spatial threshold distance (Δx) between two consecutive edges under $FF \rightarrow RF$ as 2 mm. Interestingly, this value is approximately equal to the two-point discrimination resolution of human index finger [51]. Tactile perception of virtual edges rendered by ultrasonic actuation was also investigated by Gueorguiev et al. [52] in temporal domain. However, they did not control finger velocity, while vibration amplitude was actively maintained at 1.25 µm. They reported a temporal threshold duration of 0.05 s. Hence, our results supported their observation, as we also found temporal threshold duration (Δt) of 0.05 s under $FF \rightarrow RF$. In case of $RF \rightarrow FF$, the threshold value was higher, indicating that it was more difficult for the participants to discriminate two edges under this condition. As shown in Fig. 10 (see the shaded window), $FF \rightarrow RF$ produced a sharper change in friction response as compared with $RF \rightarrow FF$. This was due to the slower dynamics of rising friction (RF) than that of falling friction (FF), which is in line with earlier findings [50], [53]. Hence, it is not surprising that participants detected two consecutive edges more easily under $FF \rightarrow RF$.

4 EXP-2: Discrimination of Virtual Periodic Gratings

The goal of the second experiment was to estimate the difference threshold between spatial periods of two periodic gratings.

4.1 Participants

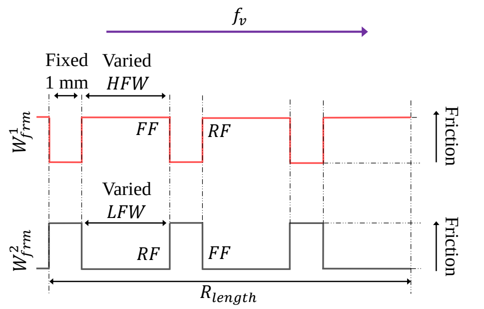
Eleven participants (4 females) with an average age of 30.2 ± 2.9 years participated in the experiment. The experimental and ethical protocols followed in this experiment were the same as in EXP-1.

4.2 Experimental Design

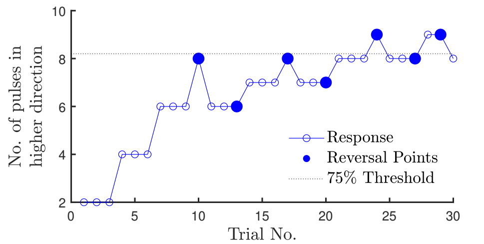
We considered three independent factors; rendering length ($R_{length} = 20$, 30, and 40 mm), finger velocity ($f_v = 30$ and 60 mm/s), and waveform ($W_{frm} = W^1_{frm}$ and W^2_{frm}). The vibration amplitude (V_{amp}) was fixed to 1 µm. Therefore, there were a total of 12 rendering conditions. In waveform W^1_{frm}, we fixed low friction width (LFW) and varied high friction width (HFW), while in waveform W^2_{frm}, we fixed high friction width and varied low friction width (Fig. 5(a)). The fixed width in both waveforms was 1 mm, which was below the spatial threshold distance estimated in EXP-1. This ensured that two edges across fixed width were perceived as a single pulse by the participants. Therefore, in waveform W^1_{frm}, we rendered a multiple sequence of consecutive edges $FF \rightarrow RF$ (i.e. a series of pulses resulting in high friction between fingerpad and the touch surface on average). In waveform W^2_{frm}, we rendered a multiple sequence of $RF \rightarrow FF$ (i.e. a series of pulses resulting in low friction between fingerpad and the touch surface on average), as depicted in Fig. 5(a).

4.3 Procedure

We rendered gratings with higher and lower number of friction pulses on the alternative directions (rightward and leftward) of finger scan. At the start of the experiment, we rendered one vs. two pulses on the alternative directions but then monotonically increased/decreased the number of pulses by two in each direction based on participants' response while keeping the difference as one always. The direction in which we rendered a higher number of pulses was randomized during each trial. Participants had to identify the direction (rightward or leftward) in which they felt more number of friction pulses. We used three up and one down transformed staircase method as elaborated in [54], which converges on the 75% correct level. Hence, if



(a)



(b)

Fig. 5: Experimental procedure for evaluating the difference threshold between spatial periods of two virtual gratings in EXP-2. (a) Types of desired waveforms (W_{frm}), (b) an example for experimental trial.

participants gave three correct answers, we increased the number of pulses in alternative directions to three vs. four, five vs. six, seven vs. eight, and so on. In case of a wrong answer, we decreased the number of pulses by two in each direction. The step size was reduced to one pulse after the first reversal. The experiment was stopped after seven reversals. Similar to EXP-1, participants were allowed to repeat any trial only once, and we permuted the order of rendering conditions by which participants performed the experiment. Each participant completed the experiment in three days (four rendering conditions per day).

We estimated the convergent value for lower and higher number of pulses by averaging the last five reversals as shown in Fig. 5(b), and then rounded it to the nearest integer. Then, we calculated the spatial periods SP^{high} and SP^{low} corresponding to the lower and higher number of pulses, respectively. To interpret the results, we calculated the absolute difference between spatial periods ($\Delta SP = SP^{high} - SP^{low}$), mean spatial period ($\overline{SP} = (SP^{high} + SP^{low})/2$), and the relative difference between spatial periods ($R_{diff} = \Delta SP/\overline{SP} \times 100$) at the threshold level. We performed three-way repeated measure ANOVA to analyze the effects of independent factors of rendering length (R_{length}), finger velocity (f_v) and, waveform (W_{frm}) on relative difference (R_{diff}). During the statistical analysis, we adjusted the degree of freedom using Greenhouse-Geisser correction whenever the sphericity assumption was violated.

4.4 Results

The mean thresholds for all independent factors are tabulated in Table 4. The results showed that:

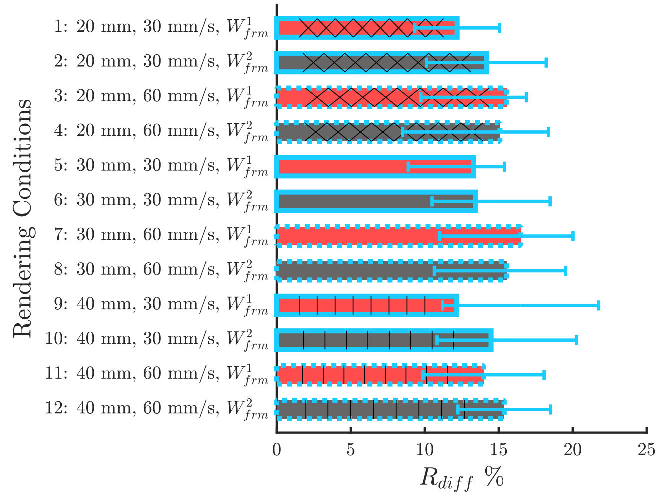


Fig. 6: Relative difference between spatial periods to discriminate virtual periodic gratings in EXP-2. Red and gray bars are for W_{frm}^1 and W_{frm}^2, solid and dotted bars are for f_v of 30 and 60 mm/s, respectively. Cross, plain and vertical hatched bars are for R_{length} of 20, 30 and 40 mm, respectively.

TABLE 4: Mean thresholds to discriminate virtual periodic gratings (EXP-2).

Independent Factors		$\Delta SP \pm$ SEM (mm)	$\overline{SP} \pm$ SEM (mm)	$R_{diff} \pm$ SEM (%)
R_{length}	20 mm	0.44±0.05*	2.9±0.16*	14.2±0.8
	30 mm	0.73±0.10*	4.4±0.32*	14.7±1.1
	40 mm	0.84±0.09*	5.6±0.32*	14.0±0.8
f_v	30 mm/s	0.58±0.07*	4.0±0.26*	13.3±0.8*
	60 mm/s	0.76±0.08*	4.6±0.26*	15.3±0.9*
W_{frm}	1	0.64±0.07	4.2±0.23	14.0±0.7
	2	0.71±0.09	4.4±0.28	14.7±0.9

*Statistically significant

- Increasing the rendering length, R_{length}, also increased the absolute difference between spatial periods, ΔSP, ($F(2, 20) = 12.5, p < 0.001$) and mean spatial period, $\overline{SP}$, ($F(2, 20) = 52.9, p < 0.001$) required to differentiate two virtual gratings. However, the relative difference between spatial periods, R_{diff}, remained the same with no significant effect of rendering length ($F(2, 20) = 0.37, p = 0.69$), as shown in Fig. 6.
- The relative difference (R_{diff}) slightly increased with increasing finger velocity (f_v).
- ANOVA test revealed no significant effect of waveform on relative difference (R_{diff}), and no significant interaction between the independent factors.

4.5 Discussion

The results of EXP-2 showed that a relative difference (R_{diff}) of 14% in spatial period was necessary to differentiate virtual periodic gratings. Biet et al. [7] have reported a Weber fraction of 9% for the discrimination of two periodic square gratings rendered by ultrasonic actuation. Several factors might have contributed to the difference; we used a staircase method, and the two gratings being compared in our study were always differed by one spatial period only, which makes it more difficult to differentiate them.

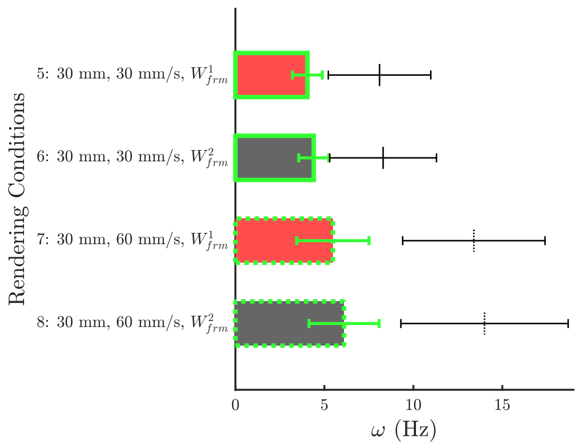


Fig. 7: Maximum temporal frequencies (mean and standard deviation) obtained by counting the pulses. Black error bars show the mean temporal frequencies obtained in EXP-2.

On the other hand, spatial period was altered explicitly using the method of constant stimuli in [7]. Furthermore, we controlled the finger velocity (f_v), and the participants were allowed to explore a stimulus only twice. However, finger velocity was not controlled, and there was no limit on exploration time in [7]. Nevertheless, the spatial discrimination thresholds of virtual square gratings tested in our study and [7] are both higher than the real ones [36].

We also observed that the relative difference in spatial period (R_{diff}) increased as finger velocity was increased. This could be due to the viscoelastic properties of fingerpad as suggested in [50]; at higher finger velocity, the deformation in fingerpad could not follow the consecutive changes in friction. However, the increase in R_{diff} due to the increase in finger velocity was small and this topic requires further investigation.

One may argue that the participants might have confused spatial discrimination with counting of the pulses in EXP-2. To elucidate, we conducted a separate counting experiment under the rendering conditions of 5, 6, 7, and 8. We rendered two to eight pulses over the same rendering length of 30 mm (corresponding to the spatial period varying from 15 to 3.75 mm) in random order with 10 repetitions, and asked the participants to explicitly count the number of bumps. We then fitted a psychometric curve to the correct responses and calculated the threshold at 75% accuracy level. As shown in Fig. 7, the maximum temporal frequencies obtained in the counting experiment were always lower than the mean temporal frequencies (f_v/SP) obtained in EXP-2 (discrimination experiment). Therefore, it is implausible that the participants have discriminated the gratings by explicitly counting the pulses in EXP-2.

We observed that the effect of waveform (W_{frm}) was not significant in the discrimination of virtual gratings. Based on the results of our earlier study which showed that RF was perceived stronger than FF [50], we had expected that rendering a series of pulses $RF \rightarrow FF$ (waveform W_{frm}^2) would produce stronger tactile cues, as compared to vice versa (waveform W_{frm}^1). However, the difference in perception between a single step change in friction (RF vs. FF) in [50], and multiple consecutive changes in the current study is justifiable. In [50], a single step change in friction was rendered on the glass surface in the middle of the exploration area. Hence, travel distance for finger after the change was sufficiently long. As a result, contact forces between finger and glass surface reached a steady-state value under both RF and FF. On the other hand, the step changes in friction in the current study were closely rendered. Therefore, contact forces between finger and glass surface could not reach a steady-state value. This resulted in weaker contrast in friction under waveform W_{frm}^2 as compared with waveform W_{frm}^1.

5 EXP-3: Roughness Perception of Virtual Gratings

We investigated the roughness perception of virtual gratings in spatial and temporal domains.

5.1 Participants

Eleven participants (3 females) with an average age of 29.7 ± 3.9 years participated in this experiment. The experimental and ethical protocols followed in this experiment were the same as in EXP-1.

5.2 Experimental Design

To investigate the roughness perception, we selected three independent factors: spatial period (SP), finger velocity (f_v = 30 and 60 $\mathrm{mm/s}$), and waveform ($W_{frm} = W_{frm}^1$ and W_{frm}^2). We have chosen seven different spatial periods in macro-texture range, varying from 2.5 to 7.4 mm with an increment of 20% as shown in Fig. 8. The increment (20%) was selected as higher than the relative threshold value estimated in EXP-2. We fixed the rendering length (R_{length}) to 30 mm, and the vibration amplitude (V_{amp}) to 1 µm in this experiment. Hence, there were 28 rendering conditions, repeated 10 times, making a total of 280 trials for each participant.

5.3 Procedure

We rendered each stimulus on the rightward scan first. Then, participants lifted their finger up and the same stimulus was repeated on the leftward scan. We monitored the mean normal force ($\overline{F_n}$) in both scans. If the magnitude of mean normal force was outside the desired range (0.25 $\pm$ 15% N), the participants were prompted to repeat the trial. We have chosen a mean normal force of 0.25 N because this was the most comfortable force reported by a number of participants during the preliminary experiments. On the completion of each trial, participants were asked to rate the roughness they perceived using any positive value with no constraints on its limit (a higher number for rougher surface). They were allowed to repeat each stimulus twice only. The trials were randomized, while the same randomization pattern was used for each participant. The experiment took approximately 45 minutes, and participants completed it in two sessions.

For the analysis, we first normalized the roughness estimates of each participant. For that, we divided the scores of each participant by his/her geometric mean, and

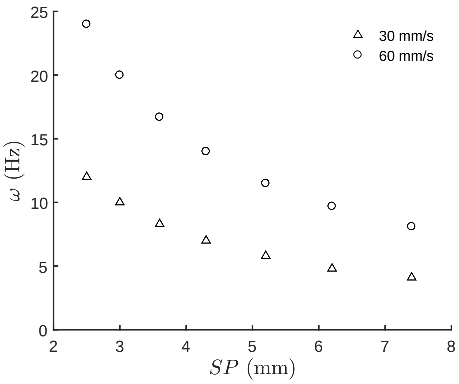


Fig. 8: Spatial period (SP) and temporal frequency (ω=SP/f_v) of virtual gratings rendered in roughness perception experiment (EXP-3).

TABLE 5: ANOVA results for the effect of independent factors on roughness perception (EXP-3).

Effects	F-value	p-value
SP	F(1.1,11.3)=23.1	<0.001*
f_v	F(1,10)=6.90	0.025*
W_{frm}	F(1,10)=8.90	0.014*
$f_v \times W_{frm}$	F(1,10)=2.4	0.06
$SP \times f_v$	F(6,60)=6.80	0.01*
$SP \times W_{frm}$	F(6,60)=5.80	0.01*

*Statistically significant

then multiplied it with the overall geometric mean of all participants. We performed three-way repeated measure ANOVA to analyze the effects of finger velocity, waveform, and spatial period on normalized roughness scores. We adjusted the degree of freedom using Greenhouse-Geisser correction whenever necessary. For pair-wise comparisons, the significance level was adjusted by Bonferroni correction.

We also analyzed the force data recorded during the experiment to calculate some metrics based on friction coefficient. To calculate friction coefficient ($\mu = F_t/F_n$), we took a window of duration $t^{total} = R_{length}/f_v$, starting from the moment we rendered the first edge. The mean value of friction coefficient ($\overline{\mu}$) was calculated by averaging μ for the interval of t^{total}. To analyze the rate of change in friction coefficient ($d\mu/dt$), we computed RMS value of $d\mu/dt$ for each spatial period, and then calculated the overall average for all spatial periods ($\overline{d\mu/dt}$). Finally, we used Spearman correlation to investigate the relation between roughness perception and friction metrics.

5.4 Results

The mean roughness scores of participants in spatial and temporal domains are reported in Fig. 9(a) and Fig. 9(b), respectively. We performed linear regression by taking spatial period (SP) and finger velocity (f_v) as independent factors, and roughness scores as dependent factor. The results showed that:

- Perceived roughness can be modeled by a linear function of spatial period and finger velocity ($R^2 = 0.81, F(2,27) = 53.2, p < 0.001$). The results of multiple linear regression (see Table 6) showed that perceived roughness decreased with spatial period, and increased with finger velocity (see Table 5 for ANOVA results).
- The participants perceived waveform W^1_{frm} significantly rougher than waveform W^2_{frm}.
- There was a significant interaction effect between spatial period and finger velocity, and spatial period and waveform on perceived roughness. Post-hoc pairwise comparisons (based on estimated marginal means) showed that effect of waveform was significant for spatial periods $SP \geq 3$ mm ($p = 0.04$), and effect of finger velocity was significant for spatial periods $SP \geq 4.6$ mm ($p = 0.001$).
- The modulated friction profile for waveform W^1_{frm} resembled to the desired square signal more than that of W^2_{frm} (Fig. 10).

TABLE 6: Results of linear regression (EXP-3).

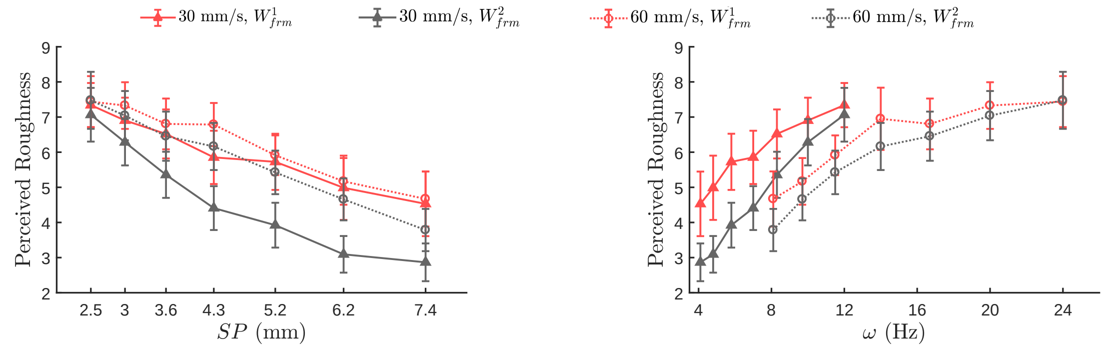
Model	Unstandardized Coefficients	Standardized Coefficients (β)	p-value
const.	7.84	–	<0.001
SP	-0.70	-0.86	<0.001
f_v	0.025	0.28	0.004

5.5 Discussion

The results of EXP-3 showed that perceived roughness decreased with increasing spatial period (SP), and the decrease was sharper for waveform W^2_{frm}. A similar decrease in roughness perception with increasing spatial period has been reported for virtual gratings rendered by electrovibration [12], and also for a force feedback device that can display tangential forces only [47]. On the other hand, roughness perception of real periodic textures increases with increasing groove width, but decreases slightly with ridge width [34]–[40], [55], though a decrease in roughness perception with increasing spatial period was observed for real linear gratings when the ridge height was low [41]. Therefore, the difference in perception between the real textures in the earlier studies and the virtual textures in studies [12], [47] and also our study is not surprising due to the missing spatial cues on texture height in virtual textures rendered by friction modulation.

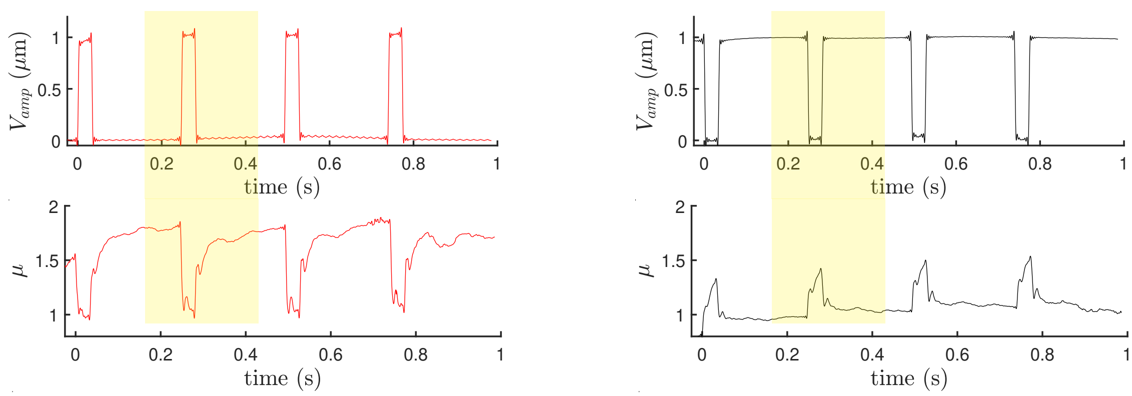
Correlation analysis showed a moderate positive correlation ($r_s = 0.58, n = 308, p < 0.001$) between perceived roughness and rate of change in friction coefficient ($\overline{d\mu/dt}$), as also reported earlier by others for real [56] and virtual periodic gratings [12]. On the other hand, a significant correlation between friction coefficient and roughness perception was reported in [47], though we observed a weak correlation in our study ($r_s = 0.30, n = 308, p < 0.001$). As shown in Fig. 11, waveform W^1_{frm} resulted in higher friction coefficient and rate of change in friction coefficient on average as compared with waveform W^2_{frm}. This explains why waveform W^1_{frm} was perceived rougher than W^2_{frm} (Fig. 9). Similarly, higher finger velocity produced stronger rate of change in friction coefficient, which resulted in an increase in perceived roughness.

The results of our experiment also showed that, despite doubling of finger velocity (f_v), the maximum perceived roughness remained almost the same (see roughness scores for spatial period of 2.5 mm rendered at temporal frequency of $\omega = 12$ and 24 Hz in Fig. 9(b)). Therefore, the results rejected our initial hypothesis that the perception of virtual



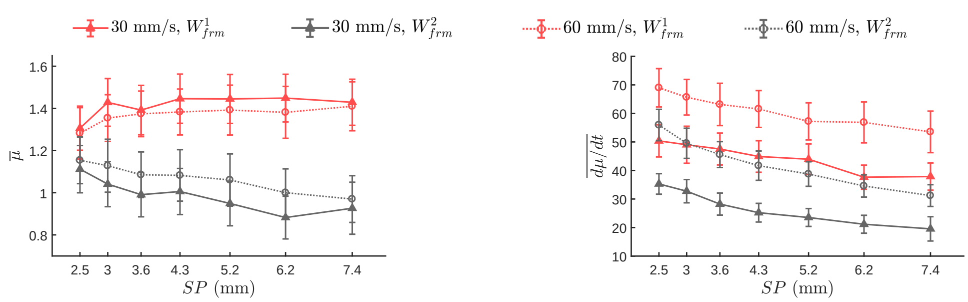
(a) (b)

Fig. 9: Perceived roughness (mean values and standard errors) of virtual gratings in spatial (a) and temporal (b) domains (EXP-3).



(a) (b)

Fig. 10: Vibration amplitude and friction coefficient recorded at 30 mm/s for a) W^1_{frm} and b) W^2_{frm}.



(a) (b)

Fig. 11: Friction metrics (mean values and standard errors).

periodic textures is more dominantly governed by temporal cues since spatial cues in normal direction cannot be rendered directly by friction modulation.

6 General Discussion

We investigated the roughness perception of virtual gratings displayed on a touch surface by periodically changing the friction between the human finger and the surface using ultrasonic actuation. Each experiment in our study feeds into the next one and at the end, the main parameters affecting the roughness perception of virtual gratings were determined. In EXP-1, we first investigated the discrimination of two consecutive virtual edges, constructed by RF followed by FF and FF followed by RF, to gain insight on how our perception was affected by the order of friction changes. In EXP-2, we concentrated on discrimination of virtual periodic gratings, constructed by a series of consecutive high and low friction regions. We fixed the vibration amplitude and varied the rendering length, finger velocity, and waveform. The aim was to investigate how those parameters affected the thresholds in discriminating virtual periodic gratings. To that end, we mainly focused on the relative difference between spatial periods. Finally, in EXP-3, we investigated the roughness perception of virtual gratings in spatial and temporal domains. In particular, we investigated the effects of spatial period, finger velocity, and waveform on roughness perception. The spatial periods used in EXP-3 were selected based on the findings of EXP-2. The results showed that roughness perception of periodic gratings was better defined in spatial domain despite the missing spatial cues on grating height. Therefore, our results support the earlier finding that rendering of virtual textures at macro scale via friction modulation based on finger position is a better choice than finger velocity [11].

In fact, effect of spatial cues on roughness perception of virtual square gratings raises several questions regarding the underlying neural mechanism. The maximum value of temporal frequency in our experiments was significantly lower than the sensitivity range of PC afferents (80 Hz and above, [57]). Yet, Vardar et al. [13] showed that PC afferents play an important role in the detection of square gratings rendered by electrovibration at low frequencies (< 60 Hz) since a low-frequency square wave has also high frequency components stimulating the PC afferents. However, if the decrease in roughness perception was primarily mediated by PC afferents, then one should expect a dominant effect of temporal frequency, as observed in [39], which was not the case in our experiment. Similarly, it is less likely that SA1 afferents have played a significant role in the tactile perception of virtual gratings in our experiment due to missing spatial cues on grating height. On the other hand, it has been shown that all afferent classes are excited by a tactile stimuli in typical contact interactions of fingertip [58], [59], and it is known that humans are good at integrating the information coming from different afferent classes to create a meaningful percept. For example, Moscatelli et al. [60] have shown that humans can estimate the length of spatial paths from the tactile slips. Similarly, it is quite possible that our participants were able to resolve successive micro-slips to spatial periods by integrating their finger velocity. They might have used this information to construct their roughness judgment. However, further investigation is indeed required to better understand the underlying neural mechanism.

On the other hand, we should point out that effect of spatial cues on roughness perception is likely to be valid within our tested range of spatial periods only. A trend of flattening or decrease in roughness perception at smaller spatial periods (i.e higher temporal frequencies) is reported for virtual textures in [12], [48]. Similarly, Ahmaniemi et al. [61] investigated the perception of virtual textures displayed by a hand held vibrotactile actuator. They reported that the textures created with a carrier frequency of 10 Hz were perceived rougher than those of 20 Hz. Therefore, an inverted U-shaped trend is likely to be observed when micro textures are investigated, which is the topic of our future studies (Fig. 12).

7 Conclusion and Future Work

In this study, we investigated the spatial discrimination of virtual edges and roughness perception of virtual square gratings generated by consecutive virtual edges, all in macro-scale. We observed that virtual edges were detected by the participants if the distance between them (spatial threshold) was more than 2 mm, provided that the first edge was rendered by a fall in friction and second one by a rise in friction. In the case of opposite edge sequence, the mean distance between the edges was above 4 mm. We also found that a relative difference of 14% in spatial period is necessary in perceived roughness for the discrimination of virtual gratings. Finally, we investigated the roughness perception of virtual gratings for different spatial periods. The results showed that the roughness perception of square gratings followed a decreasing trend with increasing spatial period, and rate of change in friction coefficient was more strongly correlated with roughness perception than friction coefficient itself. The results also suggested that spatial period played a significant role in roughness perception of virtual gratings rendered by ultrasonic actuation despite the missing spatial cues in the direction normal to the touch surface.

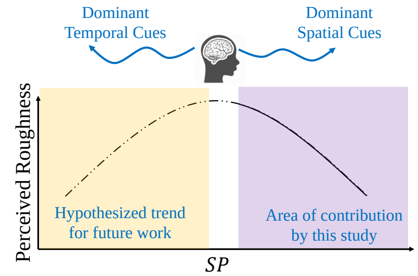


Fig. 12: A hypothetical curve explaining the roughness perception of virtual textures.

Our results are valid for macro-textures having a spatial period greater than 2 mm. The open-loop nature of our system prevented us from studying finer textures. Future work involves investigating the roughness perception of virtual textures over a wider range (see Fig. 12). Furthermore, possible effect of vibrotactile masking on tactile discrimination and roughness perception is another avenue that we would like to explore. We hope that this will shed further light on the mechanisms behind our perception of friction and change in friction rendered on touch surfaces.

References

[1] V. Levesque, L. Oram, K. MacLean, A. Cockburn, N. D. Marchuk, D. Johnson, J. E. Colgate, and M. A. Peshkin, "Enhancing physicality in touch interaction with programmable friction," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, (New York, NY, USA), pp. 2481–2490, 2011.

[2] T. Watanabe and S. Fukui, "A method for controlling tactile sensation of surface roughness using ultrasonic vibration," in *Proceedings of IEEE International Conference on Robotics and Automation*, vol. 1, pp. 1134–1139 vol.1, May 1995.

[3] M. Wiertlewski, R. Fenton Friesen, and J. E. Colgate, "Partial squeeze film levitation modulates fingertip friction," *Proceedings of the National Academy of Sciences*, vol. 113, no. 33, pp. 9210–9215, 2016.

[4] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "Teslatouch: Electrovibration for touch surfaces," in *Proceedings of the 23rd Annual ACM Symposium on User Interface Software and Technology*, UIST '10, (New York, NY, USA), pp. 283–292, ACM, 2010.

[5] C. D. Shultz, M. A. Peshkin, and J. E. Colgate, "Surface haptics via electroadhesion: Expanding electrovibration with Johnsen and Rahbek," in *IEEE World Haptics Conference (WHC)*, pp. 57–62, June 2015.

[6] M. Biet, F. Giraud, and B. Lemaire-Semail, "Implementation of tactile feedback by modifying the perceived friction," *Eur. Phys. J. Appl. Phys.*, vol. 43, no. 1, pp. 123–135, 2008.

[7] M. Biet, G. Casiez, F. Giraud, and B. Lemaire-Semail, "Discrimination of virtual square gratings by dynamic touch on friction based tactile displays," in *Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pp. 41–48, March 2008.

[8] D. J. Meyer, M. A. Peshkin, and J. E. Colgate, "Modeling and synthesis of tactile texture with spatial spectrograms for display on variable friction surfaces," in *IEEE World Haptics Conference (WHC)*, pp. 125–130, June 2015.

[9] J. Kim, K. J. Son, and K. Kim, "An empirical study of rendering sinusoidal textures on a ultrasonic variable-friction haptic surface," in *12th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI)*, pp. 593–596, Oct 2015.

[10] F. Kalantari, L. Grisoni, F. Giraud, and Y. Rekik, "Finding the minimum perceivable size of a tactile element on an ultrasonic based haptic tablet," in *Proceedings of the ACM International Conference on Interactive Surfaces and Spaces*, ISS '16, (New York, NY, USA), pp. 379–384, ACM, 2016.

[11] E. Vezzoli, T. Sednaoui, M. Amberg, F. Giraud, and B. Lemaire-Semail, "Texture rendering strategies with a high fidelity - capacitive visual-haptic friction control device," in *Haptics: Perception, Devices, Control, and Applications* (F. Bello, H. Kajimoto, and Y. Visell, eds.), pp. 251–260, Springer International Publishing, 2016.

[12] Y. Vardar, A. Isleyen, M. K. Saleem, and C. Basdogan, "Roughness perception of virtual textures displayed by electrovibration on touch screens," in *IEEE World Haptics Conference (WHC)*, pp. 263–268, June 2017.

[13] Y. Vardar, B. Guclu, and C. Basdogan, "Effect of waveform on tactile perception by electrovibration displayed on touch screens," *IEEE Transactions on Haptics*, vol. 10, pp. 488–499, Oct 2017.

[14] Y. Rekik, E. Vezzoli, L. Grisoni, and F. Giraud, "Localized haptic texture: A rendering technique based on taxels for high density tactile feedback," in *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*, CHI '17, (New York, NY, USA), pp. 5006–5015, ACM, 2017.

[15] R. F. Friesen, R. L. Klatzky, M. A. Peshkin, and J. E. Colgate, "Single pitch perception of multi-frequency textures," in *IEEE Haptics Symposium (HAPTICS)*, pp. 290–295, March 2018.

[16] C. Bernard, J. Monnoyer, and M. Wiertlewski, "Harmonious textures: The perceptual dimensions of synthetic sinusoidal gratings," in *Haptics: Science, Technology, and Applications* (D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli, eds.), pp. 685–695, Springer International Publishing, 2018.

[17] W. Ben Messaoud, M.-A. Bueno, and B. Lemaire-Semail, "Textile fabrics' texture: From multi-level feature extraction to tactile simulation," in *Haptics: Perception, Devices, Control, and Applications* (F. Bello, H. Kajimoto, and Y. Visell, eds.), pp. 294–303, Springer International Publishing, 2016.

[18] G. Ilkhani, M. Aziziaghdam, and E. Samur, "Data-driven texture rendering on an electrostatic tactile display," *International Journal of Human–Computer Interaction*, vol. 33, no. 9, pp. 756–770, 2017.

[19] J. Jiao, Y. Zhang, D. Wang, Y. Visell, D. Cao, X. Guo, and X. Sun, "Data-driven rendering of fabric textures on electrostatic tactile displays," in *IEEE Haptics Symposium (HAPTICS)*, pp. 169–174, March 2018.

[20] R. H. Osgouei, S. Shin, J. R. Kim, and S. Choi, "An inverse neural network model for data-driven texture rendering on electrovibration display," in *IEEE Haptics Symposium (HAPTICS)*, pp. 270–277, March 2018.

[21] S.-C. Kim, A. Israr, and I. Poupyrev, "Tactile rendering of 3D features on touch surfaces," in *Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology*, UIST '13, (New York, NY, USA), pp. 531–538, ACM, 2013.

[22] R. H. Osgouei, J. R. Kim, and S. Choi, "Improving 3D shape recognition with electrostatic friction display," *IEEE Transactions on Haptics*, vol. 10, pp. 533–544, Oct 2017.

[23] J. Ware, E. Cha, M. A. Peshkin, J. E. Colgate, and R. L. Klatzky, "Search efficiency for tactile features rendered by surface haptic displays," *IEEE Transactions on Haptics*, vol. 7, pp. 545–550, Oct 2014.

[24] Y. Zhang and C. Harrison, "Quantifying the targeting performance benefit of electrostatic haptic feedback on touchscreens," in *Proceedings of the International Conference on Interactive Tabletops & Surfaces*, ITS '15, (New York, NY, USA), pp. 43–46, ACM, 2015.

[25] F. Kalantari, E. Lank, Y. Rekik, L. Grisoni, and F. Giraud, "Determining the haptic feedback position for optimizing the targeting performance on ultrasonic tactile displays," in *IEEE Haptics Symposium (HAPTICS)*, pp. 204–209, Mar. 2018.

[26] F. Giraud, M. Amberg, and B. Lemaire-Semail, "Design and control of a haptic knob," *Sensors and Actuators A: Physical*, vol. 196, pp. 78 – 85, 2013.

[27] S. E. Emgin, A. Aghakhani, M. Sezgin, and C. Basdogan, "Haptable: An interactive tabletop providing online haptic feedback for touch gestures," *IEEE Transactions on Visualization and Computer Graphics*, pp. 1–1, 2018.

[28] M. Hollins, R. Faldowski, S. Rao, and F. Young, "Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis," *Perception & Psychophysics*, vol. 54, pp. 697–705, Nov 1993.

[29] M. Hollins, S. Bensmaïa, K. Karlof, and F. Young, "Individual differences in perceptual space for tactile textures: Evidence from multidimensional scaling," *Perception & Psychophysics*, vol. 62, pp. 1534–1544, Dec 2000.

[30] S. Bensmaïa and M. Hollins, "Pacinian representations of fine surface texture," *Perception & Psychophysics*, vol. 67, pp. 842–854, Jul 2005.

[31] S. Okamoto, H. Nagano, and Y. Yamada, "Psychophysical dimensions of tactile perception of textures," *IEEE Transactions on Haptics*, vol. 6, pp. 81–93, First 2013.

[32] A. I. Weber, H. P. Saal, J. D. Lieber, J.-W. Cheng, L. R. Manfredi, J. F. Dammann, and S. J. Bensmaia, "Spatial and temporal codes mediate the tactile perception of natural textures," *Proceedings of the National Academy of Sciences*, vol. 110, no. 42, pp. 17107–17112, 2013.

[33] M. Hollins and S. J. Bensmaïa, "The coding of roughness.," *Canadian Journal of Experimental Psychology*, vol. 61, no. 3, p. 184, 2007.

[34] M. M. Taylor and S. J. Lederman, "Tactile roughness of grooved surfaces: A model and the effect of friction," *Perception & Psychophysics*, vol. 17, pp. 23–36, Jan 1975.

[35] S. J. Lederman, "Tactual roughness perception: Spatial and temporal determinants.," *Canadian Journal of Psychology*, vol. 37, no. 4, pp. 498–511, 1983.

[36] J. W. Morley, A. W. Goodwin, and I. Darian-Smith, "Tactile discrimination of gratings," *Experimental Brain Research*, vol. 49, pp. 291–299, Feb 1983.

[37] K. Sathian, A. W. Goodwin, K. T. John, and I. Darian-Smith, "Perceived roughness of a grating: correlation with responses of mechanoreceptive afferents innervating the monkey's fingerpad.," *Journal of Neuroscience*, vol. 9, no. 4, pp. 1273–1279, 1989.

[38] T. Yoshioka, B. Gibb, A. K. Dorsch, S. S. Hsiao, and K. O. Johnson, "Neural coding mechanisms underlying perceived roughness of finely textured surfaces," *Journal of Neuroscience*, vol. 21, no. 17, pp. 6905–6916, 2001.

[39] C. J. Cascio and K. Sathian, "Temporal cues contribute to tactile perception of roughness," *Journal of Neuroscience*, vol. 21, no. 14, pp. 5289–5296, 2001.

[40] M. A. Lawrence, R. Kitada, R. L. Klatzky, and S. J. Lederman, "Haptic roughness perception of linear gratings via bare finger or rigid probe," *Perception*, vol. 36, no. 4, pp. 547–557, 2007.

[41] K. Drewing, "Low-amplitude textures explored with the bare finger: Roughness judgments follow an inverted U-shaped function of texture period modified by texture type," in *Haptics: Perception, Devices, Control, and Applications* (F. Bello, H. Kajimoto, and Y. Visell, eds.), pp. 206–217, Springer International Publishing, 2016.

[42] S. J. Lederman, "Tactile roughness of grooved surfaces: The touching process and effects of macro- and microsurface structure," *Perception & Psychophysics*, vol. 16, pp. 385–395, Mar 1974.

[43] M. Hollins and S. R. Risner, "Evidence for the duplex theory of tactile texture perception," *Perception & Psychophysics*, vol. 62, pp. 695–705, Jan 2000.

[44] M. B. Kocsis, S. A. Cholewiak, R. M. Traylor, B. D. Adelstein, E. D. Hirleman, and H. Z. Tan, "Discrimination of real and virtual surfaces with sinusoidal and triangular gratings using the fingertip and stylus," *IEEE Transactions on Haptics*, vol. 6, pp. 181–192, April 2013.

[45] R. L. Klatzky and S. J. Lederman, "The perceived roughness of resistive virtual textures: I. Rendering by a force-feedback mouse," *ACM Trans. Appl. Percept.*, vol. 3, pp. 1–14, Jan. 2006.

[46] S. J. Lederman, R. L. Klatzky, C. Tong, and C. Hamilton, "The perceived roughness of resistive virtual textures: II. Effects of

varying viscosity with a force-feedback device," *ACM Trans. Appl. Percept.*, vol. 3, pp. 15–30, Jan. 2006.

[47] A. M. Smith, G. Basile, J. Theriault-Groom, P. Fortier-Poisson, G. Campion, and V. Hayward, "Roughness of simulated surfaces examined with a haptic tool: effects of spatial period, friction, and resistance amplitude," *Experimental Brain Research*, vol. 202, pp. 33–43, 2010.

[48] B. Unger, R. Hollis, and R. Klatzky, "Roughness perception in virtual textures," *IEEE Transactions on Haptics*, vol. 4, no. 2, pp. 122–133, 2011.

[49] H. T. Nefs, A. M. L. Kappers, and J. J. Koenderink, "Amplitude and spatial-period discrimination in sinusoidal gratings by dynamic touch," *Perception*, vol. 30, no. 10, pp. 1263–1274, 2001.

[50] M. K. Saleem, C. Yilmaz, and C. Basdogan, "Psychophysical evaluation of change in friction on an ultrasonically-actuated touchscreen," *IEEE Transactions on Haptics*, vol. 11, no. 4, pp. 599–610, 2018.

[51] S. Y. Won, H. K. Kim, and K. S. Kim, "Two-point discrimination values vary depending on test site, sex and test modality in the orofacial region: a preliminary study," *J Appl Oral Sci.*, vol. 25, pp. 427–35, Aug 2017.

[52] D. Gueorguiev, E. Vezzoli, T. Sednaoui, L. Grisoni, and B. Lemaire-Semail, "The perception of ultrasonic square reductions of friction with variable sharpness and duration," *IEEE Transactions on Haptics*, pp. 1–1, 2019.

[53] D. J. Meyer, M. Wiertlewski, M. A. Peshkin, and J. E. Colgate, "Dynamics of ultrasonic and electrostatic friction modulation for rendering texture on haptic surfaces," in *2014 IEEE Haptics Symposium (HAPTICS)*, pp. 63–67, Feb 2014.

[54] J. J. Zwislocki and E. M. Relkin, "On a psychophysical transformed-rule up and down method converging on a 75% level of correct responses," *Proceedings of the National Academy of Sciences*, vol. 98, no. 8, pp. 4811–4814, 2001.

[55] K. Drewing, "Judged roughness as a function of groove frequency and groove width in 3D-printed gratings," in *Haptics: Science, Technology, and Applications* (D. Prattichizzo, H. Shinoda, H. Z. Tan, E. Ruffaldi, and A. Frisoli, eds.), pp. 258–269, Springer International Publishing, 2018.

[56] A. M. Smith, C. E. Chapman, M. Deslandes, J.-S. Langlais, and M.-P. Thibodeau, "Role of friction and tangential force variation in the subjective scaling of tactile roughness," *Experimental Brain Research*, vol. 144, no. 2, pp. 211–223, 2002.

[57] A. W. Freeman and K. O. Johnson, "A model accounting for effects of vibratory amplitude on responses of cutaneous mechanoreceptors in macaque monkey," *The Journal of Physiology*, vol. 323, no. 1, pp. 43–64, 1982.

[58] I. Birznieks, P. Jenmalm, A. W. Goodwin, and R. S. Johansson, "Encoding of direction of fingertip forces by human tactile afferents.," *Journal of Neuroscience*, vol. 21 20, pp. 8222–8237, 2001.

[59] H. P. Saal and S. J. Bensmaia, "Touch is a team effort: Interplay of submodalities in cutaneous sensibility," *Trends in Neurosciences*, vol. 37, no. 12, pp. 689–697, 2014.

[60] A. Moscatelli, A. Naceri, and M. O. Ernst, "Path integration in tactile perception of shapes," *Behavioural Brain Research*, vol. 274, pp. 355 – 364, 2014.

[61] T. Ahmaniemi, J. Marila, and V. Lantz, "Design of dynamic vibrotactile textures," *IEEE Transactions on Haptics*, vol. 3, pp. 245–256, Oct 2010.

Muhammad Khurram Saleem received his Ph.D. in Mechanical Engineering from Koc University, Turkey in 2019. He completed BS and MS in Mechatronics Engineering from University of Engineering and Technology Lahore, Pakistan. His research interests include haptics and mechatronic systems.

Cetin Yilmaz received his BS degree with high honors in Mechanical Engineering from Bogazici University in 2000. He pursued his graduate study at University of Michigan between 2000 and 2005. In 2001 and 2002 he completed his MS degrees in Mechanical Engineering and Mathematics, respectively. In 2005 he received his Ph.D. degree in Mechanical Engineering. Between 2005 and 2007 he worked as a postdoctoral researcher at University of Michigan. Currently, he is an Associate Professor of Mechanical Engineering at Bogazici University. His research interests include multi-body dynamics, acoustics and vibrations, phononic band gap structures, and design

Cagatay Basdogan received the Ph.D. degree in mechanical engineering from Southern Methodist University in 1994. He is a faculty member in the mechanical engineering and computational sciences and engineering programs of Koc University, Istanbul, Turkey. He is also the director of the Robotics and Mechatronics Laboratory at Koc University. Before joining Koc University, he worked at NASA-JPL/Caltech, MIT, and Northwestern University Research Park. His research interests include haptic interfaces, robotics, mechatronics, biomechanics, medical simulation, computer graphics, and multi-modal virtual environments. He is currently the associate editor in chief of IEEE Transactions on Haptics and serves in the editorial boards of IEEE Transactions on Mechatronics, Presence: Teleoperators and Virtual Environments, and Computer Animation and VirtualWorlds journals. He also chaired the IEEE World Haptics Conference in 2011.