2017 IEEE World Haptics Conference (WHC)
Fürstenfeldbruck (Munich), Germany
6–9 June 2017

Tactile Perception of Change in Friction on an Ultrasonically Actuated Glass Surface

Muhammad Khurram Saleem[1], Cetin Yilmaz[2] and Cagatay Basdogan[1#]

Abstract— **We conducted psychophysical experiments to investigate human haptic perception when they experience a step change in friction on an ultrasonically actuated glass surface under two experimental conditions; sliding finger and stationary finger pressed on the surface. During the experiments, the forces acting on the subjects' finger and the out of plane vibrations of the touch surface were measured by a force and a piezoelectric sensor, respectively. The results showed that stationary finger more easily detected falling friction, whereas, sliding finger was more sensitive to rising friction at higher actuation levels. Moreover, sliding finger was twice more sensitive to changes in friction than stationary finger. Finally, we found that the rate of change of contact forces were best correlated with the subjects' perception of change in friction under both experimental conditions.**

I. Introduction

Touch displays have permeated our daily lives. They have dominated the conventional displays due to their ease to configure depending upon the application. On the other hand, touch displays commercially available today cannot provide tactile feedback, which is known to augment human perception and task performance. During the last decade, various techniques have emerged to mimic human tactile sense on touch surfaces. One important technique for displaying tactile effects on a touch surface is to control the friction force between the fingertip and the surface using electrostatic actuation [1]. This method increases the friction coefficient between the finger and the surface when an alternative voltage is applied to the conductive layer of the touch surface. Another eminent technique is to use ultrasonic actuation. This approach was first proposed by Watanabe et al. [2]. Primarily, it decreases the friction coefficient between the fingertip and the surface by actuating the surface mechanically at an ultrasonic resonance frequency. The tactile stimuli can be rendered on the surface by modulating the vibration amplitude [3] [4]. Although, both techniques use different principles for the actuation, they are basically friction modulators.

The friction between a finger and a surface is perceived through a complex bio-mechanical process. To improve the effectiveness of touch displays, it is important to characterize human perception of friction on those surfaces through psychophysical experiments. However, the number of research studies in this area are limited, but even less for the ultrasonically actuated surfaces. Watanabe et al. [2] observed that a change in friction via ultrasonic actuation creates a sensation of a rough surface. They reported that the strength of roughness is related to the slew rate of rise and fall in vibration amplitude. The ability of humans to discriminate virtual gratings on a friction-based tactile display was evaluated by Biet et al. [5]. They found that discrimination performance of the subjects for real and virtual gratings remained close for the range of spatial periods (0.25 to 1 cm) tested in their study. They reported an average JND of 9% for the discrimination. They suggested that faster transition between grooves and ridges is important for better discrimination. Using the Tactile Pattern Display (TPaD), Samur et al. [6] conducted discrimination experiments to evaluate the minimum detectable difference in friction coefficient. The subjects were asked to identify the stimulus with higher friction based on two stimuli presented in a sequential order. An average JND of 18% was reported for the friction difference. Messaoud et al. [7] conducted psychophysical experiments to determine the absolute detection threshold for change in friction coefficient. According to their results, the friction contrast is closely related to the perception of change in surface friction. Moreover, they reported that humans can perceive a difference when the frictional contrast exceeds 0.19. Recently, Monnoyer et al. [8] found that humans can detect falling friction (FF) more easily than rising friction (RF) while pressing on an ultrasonically actuated tactile surface. Here, FF creates a sensation of key click. The authors argue that this perception is due to the release of the stress in finger pad when surface friction is reduced. The vivid difference reported in [8] between RF and FF when finger is stationary and pressed on a touch display has motivated us to investigate if the same phenomenon occurs when finger slides over the surface. Here the research questions are, how does the sensitivity to the change in friction differ when there is a relative motion between finger and the surface (sliding) and no relative motion (stationary)? What are the important parameters that affect our tactile perception in both cases?

Using a glass surface actuated ultrasonically, we evaluate the effect of RF and FF under the experimental conditions of sliding and stationary fingers.

II. Experimental Setup

The experimental setup consists of a 100x60 mm^2 glass surface of 1.4 mm thickness actuated at an ultrasonic frequency of 26.9 kHz. The distance between the nodal lines is approximately 11 mm, creating an area of 11x60 mm^2

[1]College of Engineering, Robotics and Mechatronics Laboratory, Koc University, 34450, Istanbul, Turkey
[2]Department of Mechanical Engineering, Bogazici University, 34342, Istanbul, Turkey
[#]Corresponding Author, cbasdogan@ku.edu.tr

978-1-5090-1425-5/17/$31.00 ©2017 IEEE

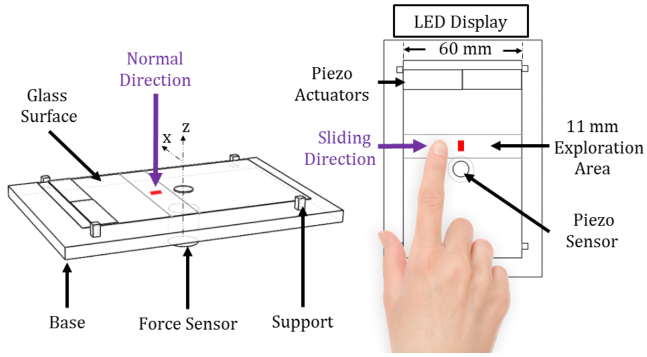

Fig. 1. Illustration of the experimental setup.

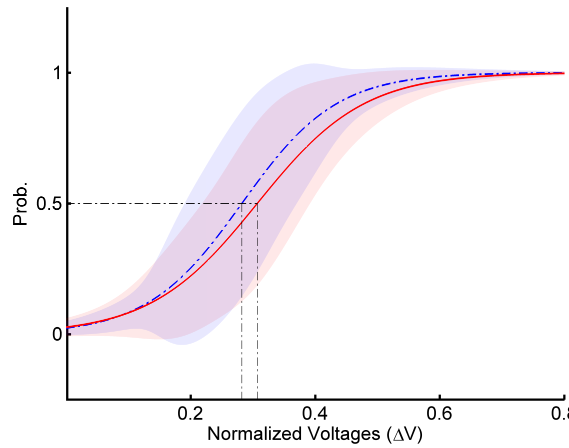

Fig. 2. Psychometric response for the sliding experiment (Blue-dotted: RF, Red-solid: FF). Black-dotted lines show mean 50% threshold levels.

between two nodal lines for haptic exploration (Fig. 1). We actuate the tactile surface by two piezoelectric patches (7BB-35, Murata Manufacturing) driven by an amplifier(PZD700A M/S, Trek). A force sensor (Nano17 Titanium, ATI Industrial Automation) capable of resolving 1.5 mN is used to measure the normal and lateral forces acting on finger during the experiments. To acquire the vibration amplitude, a small piezoelectric patch (FT-10.5T, Kepo Electronic) is used as a sensor. We use an analog RMS-circuit with the patch to record the vibration amplitude data at a lower sampling rate. The piezoelectric sensor is calibrated by a Laser Doppler Vibrometer (LDV) (OFV-551, Polytec). Two separate data acquisition cards (PCI-6034E, National Instruments) and (PCIe-6321, National Instruments) running at 5k samples/seconds are used to record the force and vibration data, respectively. We use an IR-frame running at 100 sample/seconds to record finger position during the experiments. For reliable sampling time and rendering, we use Simulink Real-Time running on a Windows-based personal computer.

III. Human Experiments

A. Human perception to step change in friction while finger is sliding

1) Experimental Design: The purpose of this experiment is to determine the perceptual sensitivity of human finger to a step change in friction during sliding motion. The psychophysical experiment is based on the method of constant stimuli, as elaborated by Jones et al. [9]. There are two experimental conditions: rising friction (RF) and falling friction (FF). RF is a step increase in friction and FF is a step decrease in friction. We render each condition with different stimuli levels by altering the actuation voltage (ΔV) applied to the piezoelectric patches. Preliminary experiments are conducted to select 10 linearly distributed stimuli levels. Each stimulus is repeated 10 times, hence each subject completes 200 trials (2 conditions x 10 levels x 10 repetitions). The trials are displayed in a random order, while the same order is displayed to each subject. During each trial, the subjects are asked to explore the area of 11x60 mm^2 (see Fig. 1) on the glass surface only once and respond to the following question; "Do you feel any haptic effect?". They answer the question by choosing either 'YES' or 'NO' button, displayed on a computer screen. We render the step change in friction in the middle of the exploration region (see the 'RED' mark in Fig. 1). Before the experiment begins, the subjects are asked to wash their hands. They are instructed to adjust their finger pressure as if they are moving their finger over a smart phone. As the compliance of fingertip depends on the loading direction [10], the subjects are instructed to move their finger only from left to right direction. Furthermore, we use a LED display to show a reference speed of 50 $\mathrm{mm/sec}$ to the subjects to keep their scan speed approximately constant, (We found that subjects were able to maintain an average speed of 49.6±12.6 $\mathrm{mm/s}$ during the experiment). The subjects are instructed to wear noise cancellation headphones. A white noise is played through the headphones to prevent any biasing due to unwanted sounds of the setup and the surroundings. Each subject is given a training session to make her/him familiar with the setup. Ten subjects participated in the experiment (average age: 27±3). The experiment took 30 to 40 minutes to complete for each subject.

2) Results: We fitted a logistic function to the mean responses of the subjects for RF and FF. The R^2 value of the fit was greater than 0.98 for both RF and FF. Fig. 2 shows the mean responses and the standard deviations. RF showed slightly lower threshold than FF. Two-way-ANOVA repeated measures showed that the difference was not significant ($F(1, 9) = 3.683, p = 0.087$).

For an ultrasonically actuated surface, vibration amplitude is the key parameter in rendering haptic effects. The user's finger can damp the vibrations. If the damping is high, a closed loop control might be necessary to achieve the desired amplitude (stimulus level) [11]. We wanted to make sure that the slight perceptual difference between RF and FF was not due to a difference in vibration amplitudes while the subjects' finger was crossing the friction boundary ('RED' mark in Fig. 1). We measured the difference in the vibration amplitudes when the step change in friction occurred. We observed a linear relation between vibration amplitude and the normalized voltages ($R^2 > 0.99$), as shown in Fig. 4(a). There was no significant difference between the slopes of the linear lines constructed for RF and FF. Furthermore, the standard deviations were low. Therefore, we can safely state that the slight perceptual difference between RF and FF in our experiment was not due to a difference in vibration amplitude. Furthermore, the response time for achieving the desired vibration amplitude was not significantly different for RF and FF; 2.3±0.35 ms and 2.8±0.35 ms, respectively. The response time is the duration in which the RMS of vibration amplitude varies between 10% to 90% of its maximum value.

To evaluate the forces acting on the subjects' finger, we considered a time window of 250 ms, centered around the time instant when the step change in the friction was rendered. To ensure proper contact, we rejected the data of a trial if the average normal force was less than 0.05 N. The noise in data was removed by a low-pass filter having a cutoff frequency of 600 Hz. The cutoff frequency was selected based on the frequency range that the mechanoreceptors in human finger are sensitive to vibrotactile stimuli (0.3-500 Hz) [12]. Using the recorded lateral (L) and normal (N) force, we computed the instantaneous coefficient of friction $\mu = L/N$. The average coefficients for low and high friction, μ_{low} and μ_{high}, were computed when the vibration was 'ON' and 'OFF', respectively (see Fig. 3). Finally, the tactile friction contrast $TFC = 1 - \mu_{low}/\mu_{high}$ was calculated as suggested in [13]. We fitted an exponential function to the mean response of TFC as suggested in [14]. The R^2 values of the fitted curves were greater than 0.97 for RF and FF (Fig. 4(b)). TFC of RF was slightly higher than that of FF. We also looked into the normal and the lateral force contrast, defined as, $NFC = 1 - N_{low}/N_{high}$ and $LFC = 1 - L_{low}/L_{high}$. NFC was (-0.032±0.11) and (-0.030±0.13) for RF and FF, respectively and independent of the actuation voltage. On the other hand, LFC followed the same exponential trend as TFC with $R^2 > 0.96$. We also calculated RMS of rate of change of normal force (dN/dt), lateral force (dL/dt), and kinetic friction coefficient ($d\mu/dt$). For this purpose, we considered a time window of 50 ms starting from the point when the step change in friction was rendered. We fitted a third order polynomial to the average RMS values to estimate the perceptual thresholds. The results showed no difference between RF and FF for RMS of dL/dt (Fig. 4(d)). However, the RMS of dN/dt was significantly higher for FF than that of RF (Fig. 4(e)). Table I tabulates the values of various force metrics at different threshold levels.

To investigate which force metric is correlated with the perceptual choice of the subjects at the 50% threshold level, we used point-biserial method. It computes the correlation between the dichotomous user response (YES/NO) and non-dichotomous values in the data. We conducted this analysis for each subject by considering her/his individual threshold value. First, the data for each force metric was normalized to [0,1]. Then co-relation between each metric and the subjects'

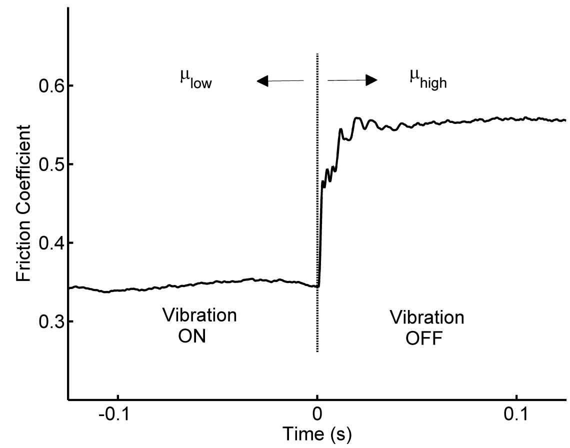

Fig. 3. Exemplification of μ_{low} and μ_{high}. Vertical line indicates the time when finger crosses the 'RED' mark (see Fig. 1)

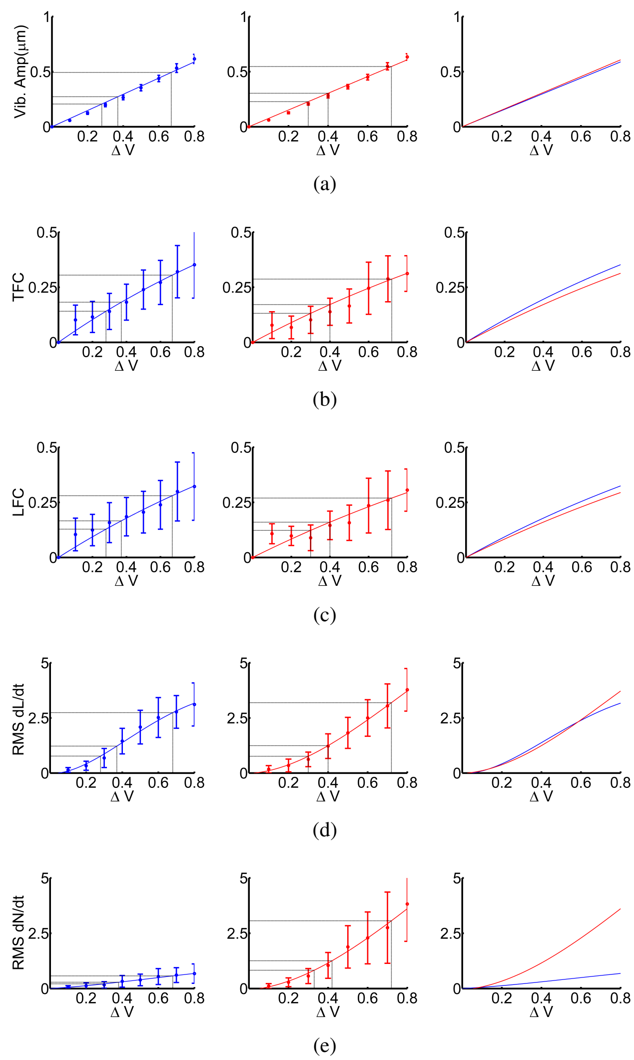

Fig. 4. Trends of various metrics as a function of change in normalized voltage for the sliding experiment. Blue: RF (left), Red: FF (mid), superimposed mean curves (right). Dotted lines indicate 50, 75, 100% thresholds obtained from the psychometric curves.

TABLE I

MEAN VALUES AND STANDARD DEVIATIONS AT DIFFERENT THRESHOLD LEVELS FOR THE SLIDING EXPERIMENT

	Edge Type	50%	75%	100%
Vib. Amp (μm)	RF FF	0.21±0.02 0.22±0.02	0.27±0.02 0.30±0.02	0.5±0.04 0.55±0.04
TFC	RF FF	0.14±0.08 0.13±0.06	0.18±0.08 0.16±0.07	0.31±0.10 0.27±0.13
LFC	RF FF	0.13±0.09 0.12±0.06	0.17±0.09 0.16±0.06	0.28±0.13 0.27±0.13
RMS dL/dt	RF FF	0.77±0.4 0.76±0.3	1.22±0.4 1.24±0.3	2.74±0.75 3.19±1.0
RMS dN/dt	RF FF	0.21±0.15 0.83±0.3	0.29±0.15 1.26±0.6	0.57±0.3 3.06±1.61
RMS $d\mu/dt$	RF FF	2.97±2 6.11±2.8	4.20±2.0 8.9±6.7	8.4±6.0 18.57±11

response was evaluated by the correlation coefficient, r_{pb}. The paired t-test was used to check the significance of correlations. In case of RF, RMS of dL/dt strongly correlated ($r_{pb} = 0.63{\pm}0.13$) to the response of seven subjects with $p < 0.005$ followed by $d\mu/dt$ for six subjects with $p < 0.05$ ($r_{pb} = 0.58{\pm}0.6$). Similarly, In case of FF, RMS of dL/dt moderately correlated ($r_{pb} = 0.51{\pm}0.13$) to the response of eight subjects ($p < 0.05$).

In the sliding finger experiment, we found that the difference between RF and FF was not significant when subjects were asked about the existence of a frictional change (absolute detection experiment). However, during an informal interview after the experiment, some of the subjects reported that they made a decision more easily when they experienced RF. This made us to consider a discrimination experiment to further explore the difference between RF and FF for the case of sliding finger. This time, the subjects were asked about the strength of change. We conducted this experiment with four subjects. We rendered RF and FF at five different voltage amplitudes, starting from 75% threshold level of the original sliding finger experiment (ΔV = 0.4) and increasing linearly up to ΔV = 1.6. Each voltage amplitude was repeated five times. To eliminate any bias, we rendered RF and FF randomly on the left and right sides of the exploration area with respect to the 'RED' mark (Fig. 1). During each trial, we asked the subjects to move their finger from left to right and right to left and choose the direction in which they felt a stronger change. Surprisingly, the subjects preferred RF over FF and the difference in their response was significant ($p < 0.05$). Fig. 5 shows the mean response and the standard deviations with respect to the normalized voltages above the 75% threshold level.

B. Human perception to step change in friction while finger is stationary

1) Experimental Design: This experiment re-evaluates the haptic click sensation when finger is pressed on the ultrasonically actuated surface [8]. We use the method of constant stimuli to make our results inline with our sliding experiment and also with the only study on this topic in the literature [8]. The experimental conditions and the number of trials per subject are the same as in the sliding finger experiment. In each trial, the subjects are asked to press on the surface at the location marked as 'RED' dot (see Fig. 1). Therefore, the spatial location at which we render a step change in friction is the same in both sliding and stationary finger experiments. We change the friction when the normal force exceeds 3 mN. The LED display turns 'ON' to indicate that the haptic click has been rendered and the subjects respond to the question, "Do you feel a haptic click? Similar to the first experiment, the subjects are instructed to wash their hands and wear noise cancellation headphones. There is a training session to familiarize the subjects with the haptic click sensation. Eight subjects participated in the second experiment (average age: 27±3). All of them have also participated in the first experiment. The experiment took 15 to 25 minutes to complete for each subject.

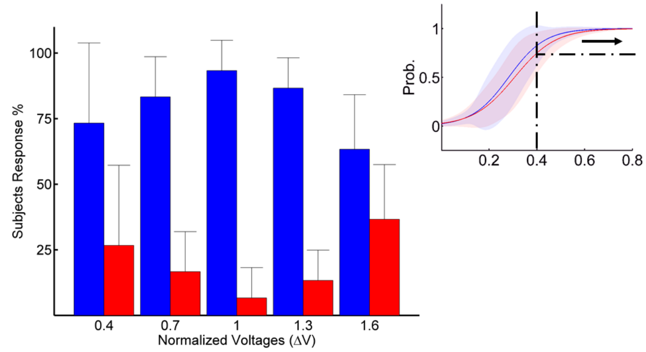

Fig. 5. Strength of frictional change perceived above threshold level. Blue: RF, Red: FF. Sub-figure shows the stimulus levels in reference to Fig. 1

2) Results: The psychometric responses for RF and FF are shown in Fig. 6. The R^2 values for the fit were 0.5 and 0.94 for RF and FF, respectively. The subjects' response didn't follow a typical psychometric behavior for RF and the mean response was unable to achieve 75% threshold. The difference between RF and FF was large. Two-way ANOVA showed that the curves for RF and FF were statistically different ($F(1, 7) = 13.887, p < 0.01$). Our results are in accordance with the earlier work [8].

As in the case of sliding finger experiment, we checked the vibration amplitudes for RF and FF (Fig. 7(a)). RF showed slightly higher slope than FF. The response times for achieving the desired vibration amplitudes were 2.8±0.3 ms and 2.4±0.5 ms, for RF and FF, respectively.

The force data in the lateral direction was very small, therefore, not reported here. Similar to the first experiment, we calculated the RMS of the rate of change of force in the normal direction dN/dt and correlation coefficient for each force metric. For FF, RMS of dN/dt moderately correlated ($r_{pb} = 0.46{\pm}0.11$) to the response of four subjects with $p <$ 0.05. On the other hand, there was no correlation with dN/dt for RF.

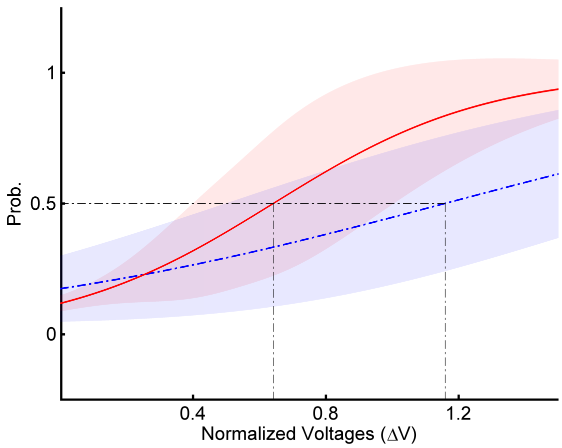

Fig. 6. Psychometric response for the stationary finger experiment. (Blue-dotted: RF, Red-solid: FF). Black-dotted lines indicate 50% thresholds.

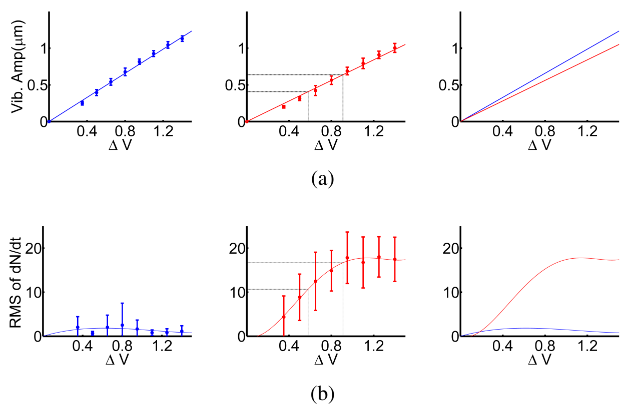

Fig. 7. Trends of various metrics as a function of the change in normalized voltage for the stationary finger experiment. Blue: RF (left), Red: FF (mid), superimposed mean curves (right). Dotted lines indicate 50, 75% thresholds obtained from the psychometric curve.

IV. Discussion

The results showed that, FF created a haptic sensation in both experiments, while RF could only stimulate the sliding finger. The subjects showed more sensitivity to the change in friction in the sliding finger experiment as compared to the stationary finger experiment, which can be ascertained from the psychometric curves (Fig. 2 and 6). For the sliding finger, the mean vibration amplitude to attain a threshold level of 75% was 0.27±0.02 μm and 0.30±0.02 μm for RF and FF, respectively. However, in the case of stationary finger, the corresponding value was 0.78±0.06 μm for FF and not available for RF.

Although the vibration amplitudes in our experiments showed very little variance, the corresponding forces showed high variance. High variation in the contact forces may arise from the variation in the moisture level between the subject's finger and the surface and also the scanning velocities [13] [15].

We calculated TFC at 75% threshold level as 0.18±0.10 and 0.17±0.10 for RF and FF, respectively. These values are closer to the ones reported in [7].

We found that the rate of change of lateral force (RMS of dL/dt) was best correlated with the subjects' response at the 50% threshold level for the case of sliding finger while the same was true for the rate of change of normal force (RMS of dN/dt) in the case of stationary finger. Smith et al. [16] suggests that RMS of lateral force plays an important role in human perception of roughness, which supports our results.

The slightly stronger effect of RF in the sliding experiments might be due to the nonlinear and viscoelastic behavior of the finger pad. In a user study conducted by Shull et al. [17], the subjects were asked to estimate the angle of torsional stretch applied to their forearm. The results showed that viscoelastic and hysteresis effects were evident in the perception of skin stretch at higher torques only, where the perceived angles were higher than the actual ones for some of the subjects. The same could happen at higher actuation levels in our experiments. Therefore, the subjects perceived the strength of RF more than FF despite similar stimuli levels. However, the underlying mechanisms for the difference between RF and FF will be further investigated in our future studies.

V. Conclusion

We conducted psychophysical experiments to investigate the haptic perception of FF and RF displayed on an ultrasonically actuated surface under the experimental conditions of sliding and stationary finger. The sensitivity of the subjects to perceive FF was almost twice higher in the case of sliding finger when compared to that of stationary finger. Based on the detection experiment, RF was equally perceivable as FF when finger was sliding and almost unperceivable when finger was stationary (pressed on the surface). On the other hand, the discrimination experiment performed with four subjects showed that the tactile effect of RF was significantly stronger than that of FF at stimulus levels significantly above threshold.

The correlation analysis showed that the rate of change of contact forces were best correlated with the subjects' perception. (dL/dt for sliding finger and dN/dt for stationary finger). This will be further explored in our future research.

References

[1] O. Bau, I. Poupyrev, A. Israr, and C. Harrison, "Teslatouch: electrovibration for touch surfaces," in *Proceedings of the 23nd annual ACM symposium on User interface software and technology*, pp. 283–292, ACM, 2010.

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

[3] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin, "T-pad: Tactile pattern display through variable friction reduction," in *EuroHaptics Conference, 2007 and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics 2007. Second Joint*, pp. 421–426, IEEE, 2007.

[4] M. Biet, F. Giraud, and B. Lemaire-Semail, "Implementation of tactile feedback by modifying the perceived friction," *The European Physical Journal Applied Physics*, vol. 43, no. 1, pp. 123–135, 2008.

[5] M. Biet, G. Casiez, F. Giraud, and B. Lemaire-Semail, “Discrimination of virtual square gratings by dynamic touch on friction based tactile displays,” in *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on*, pp. 41–48, IEEE, 2008.

[6] E. Samur, J. E. Colgate, and M. A. Peshkin, “Psychophysical evaluation of a variable friction tactile interface,” in *IS&T/SPIE Electronic Imaging*, pp. 72400J–72400J, International Society for Optics and Photonics, 2009.

[7] W. B. Messaoud, M.-A. Bueno, and B. Lemaire-Semail, “Relation between human perceived friction and finger friction characteristics,” *Tribology International*, vol. 98, pp. 261–269, 2016.

[8] J. Monnoyer, E. Diaz, C. Bourdin, and M. Wiertlewski, “Ultrasonic friction modulation while pressing induces a tactile feedback,” in *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pp. 171–179, 2016.

[9] L. A. Jones and H. Z. Tan, “Application of psychophysical techniques to haptic research,” *IEEE Transactions on Haptics*, vol. 6, no. 3, pp. 268–284, 2013.

[10] B. Delhaye, P. Lefevre, and J.-L. Thonnard, “Dynamics of fingertip contact during the onset of tangential slip,” *Journal of The Royal Society Interface*, vol. 11, no. 100, p. 20140698, 2014.

[11] 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.

[12] D. Kline, “The psychology instruction project (pip),” (accessed on December 30, 2016).

[13] P.-H. Cornuault, L. Carpentier, M.-A. Bueno, J.-M. Cote, and G. Monteil, “Influence of physico-chemical, mechanical and morphological fingerpad properties on the frictional distinction of sticky/slippery surfaces,” *Journal of The Royal Society Interface*, vol. 12, no. 110, p. 20150495, 2015.

[14] T. Sednaoui, E. Vezzoli, B. Dzidek, B. Lemaire-Semail, C. Chappaz, and M. Adams, “Experimental evaluation of friction reduction in ultrasonic devices,” in *World Haptics Conference (WHC), 2015 IEEE*, pp. 37–42, IEEE, 2015.

[15] S. M. Pasumarty, S. A. Johnson, S. A. Watson, and M. J. Adams, “Friction of the human finger pad: influence of moisture, occlusion and velocity,” *Tribology Letters*, vol. 44, no. 2, p. 117, 2011.

[16] 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.

[17] P. Shull, K. Bark, and M. Cutkosky, “Skin nonlinearities and their effect on user perception for rotational skin stretch,” in *Haptics Symposium, 2010 IEEE*, pp. 77–82, IEEE, 2010.