Correlation Between Electrovibration Perception Magnitude and the Normal Force Applied by Finger

Xingwei Guo[1,2], Yuru Zhang[1,2], Dangxiao Wang[1,2](✉), Lei Lu[1,2], Jian Jiao[1,2], and Weiliang Xu[2,3]

[1] State Key Lab of Virtual Reality Technology and Systems, Beihang University, Beijing 100083, China
hapticwang@buaa.edu.cn

[2] Beijing Advanced Innovation Center for Biomedical Engineering, Beihang University, Beijing 100083, China

[3] Department of Mechanical Engineering, The University of Auckland, Auckland 1142, New Zealand

Abstract. Electrovibration has been used to render the surface texture on tactile devices. To understand how the rendering performance is related to the normal force applied to the surface of the device by a finger, we investigated the influence of the applied normal force on electrovibration perception magnitude. We conducted a magnitude estimation experiment to observe how the electrovibration perception relates to the applied normal force ranging from 0.5 to 5 N. We measured the frictional force on a finger together with the normal force and calculated the friction induced by the electrostatic force. We found that the electrovibration perception magnitude increased with the increased applied normal force. Similarly, the friction induced by the electrostatic force increased with the applied normal force. This study demonstrates that the applied normal force has a large influence on the electrovibration perception, which needs to be considered in virtual texture rendering on electrovibration-based tactile devices.

Keywords: Haptics · Electrovibration · Applied normal force

1 Introduction

As the use of touch screen becomes increasingly popular, tactile displays on surface have drawn great interest from academia and industry. Such haptic interfaces allow users to perceive virtual objects by touch on the screen, which would greatly enhance user experience and task performance in the interaction with the virtual world. Thus far, a wide assortment of the tactile displays has been developed [1–4], one of which is electrovibration-based display which relies on electrostatic force to render virtual texture.

Since electrovibration was discovered, various electrovibration-based devices have been developed. Strong and Troxel firstly developed a tactile display on electrode-array using electrovibration [5]. TeslaTouch was realized on a commercial transparent touch screen [2], which demonstrate that electrovibration could be easily combined with the

D. Prattichizzo et al. (Eds.): EuroHaptics 2018, LNCS 10893, pp. 91–101, 2018.
https://doi.org/10.1007/978-3-319-93445-7_9

widely used touch screen. Senseg and Tanvas developed commercial techniques that apply electrovibration to touch screens such as smartphones and tablets. Recently, some flexible tactile devices based on electrovibration were developed to extend the application of electrovibration [6–8].

Electrovibration effect was modeled by the parallel-plate capacitor [9, 10]. The major parameters that affect the electrostatic force are: voltage across the finger and the electrode, insulator properties, fingertip skin properties, and contact area [11]. In [12], Vezzoli et al. improved the capacitor model for electrovibration effect by taking into account the frequency dependence. Meyer et al. [13] investigated dependence of the friction induced by the electrostatic force on the frequency and amplitude of the actuation voltages. Recently, Shultz et al. [10] modeled the electrovibration according to the voltage difference across the air gap between human fingertip and the insulator layer of the touch screen. Kang et al. [14] explored how to achieve low voltage operation of an electrovibration tactile display. They compared three types of input voltage signals and showed that the dc-offset was the best way to decrease the activated voltage.

A number of researchers have investigated the electrovibration effect with respect to the input voltage and insulator properties [15–19]. Strong and Troxel [5] found that the intensity of the electrovibration sensation was primarily dependent on the voltage peak rather than the current intensity. Kaczmarek et al. [20] investigated voltage polarity effect in electrovibration. Their results showed that tactile sensation of electrovibration was more sensitive to negative or biphasic pulses than that for positive pulses. Bau et al. [2] measured the absolute thresholds of the voltage signals with respect to five frequencies. They found that the absolute threshold formed a U-shaped curve. Furthermore, Vardar et al. explored the effect of input voltage waveform on the haptic perception of electrovibration on touch screens [15]. Wijekoon et al. [16] investigated the electrovibration sensation intensity with respect to input voltage signal using a fixed 6-point Effect Strength Subjective Index (ESSI). Their experimental results showed that there were significant correlations between intensity perception and signal amplitude. Agarwal et al. [21] studied the relationship between the input voltage and the insulator thickness. They performed psychophysical measurements to determine the dependence of absolute threshold of the voltage signals on polyimide dielectric layers of varying thickness. The result showed that the thickness had little effect on the absolute threshold.

When users interact with the electrovibration-based display, their fingers apply a normal force to the surface of the display. Although the normal force was not included in the model of electrostatic force, some research works have studied its effect on the electrovibration perception. Zophoniasson et al. [22] studied the influence of the applied normal force on the absolute thresholds of the input voltage of an electrovibration-based device. They divided the applied force into three levels: the light level (from 0.2 N to 1.5 N), the medium level (from 1.5 N to 3.0 N) and the high level (from 3.0 N to 7.0 N). Their result showed that the applied normal force had an effect on the absolute threshold of the voltage amplitude at 240 Hz, 360 Hz, and 540 Hz.

Apart from the above efforts, little work has been done in studying the effect of the applied normal force on electrovibration perception intensity. In this study, we conducted a psychophysical experiment to investigate the effect of applied normal force on electrovibration perception magnitude. Meanwhile, the force data were recorded to explore the relationship between the electrostatic force and the applied normal force ranging from 0.5 N to 5 N.

The remainder of this paper is organized as follows: in Sect. 2 we present a psychophysical experiment for estimating the electrovibration perception magnitude as the applied normal force changes. In Sect. 3, we present the result of the magnitude estimation and the measured friction induced by the electrostatic force. In Sect. 4, we discuss the experimental results. Finally, we conclude in Sect. 5.

2 Methods

The aim of the experiment is to explore the perceived magnitude of electrovibration with respect to the normal force applied by fingertip. At three frequencies of the input voltage participants rated the magnitude of electrovibration perception under 10 levels of the applied normal force. The applied normal force considered in this study ranges from 0.5 N to 5 N, which is the normal range when using electrovibration-based tactile devices [22].

2.1 Participants

Eight participants from Beihang University took part in the experiment (aged 23-30 years old, average 27 years old). They were right-handed by self-report. All of them have no sensorimotor impairment with their right hands. Each participant cleaned his or her index finger prior to beginning the experiment. To decrease the friction effect due to skin moisture, participants were asked to use talcum powder to dry their fingertip.

2.2 Experimental Apparatus

The apparatus used for the experiment is shown in Fig. 1, in which 3 M touch screen was used as the tactile display because of its availability and stability. The screen consists of three layers. A high sensitivity transducer is necessary for measuring the friction induced by the electrostatic force. ATI Nano17 was chosen for this purpose, which has 1/300 N resolution and has a resonant frequency of 7200 Hz and is capable of measuring three dimensional forces. The sensor was mounted under the 3 M touch screen to measure the normal force and lateral force simultaneously. The force data were captured by a data acquisition board (National Instruments PCI-6220, Austin, Texas) at a sampling rate of 1 kHz. A carriage is mounted on the sliding rail (HIWIN MGNR15C, Taiwan), which allows participants to rest the wrist. The carriage can slide along the x axis of the sensor.

To help participants to maintain a stable applied normal force while sliding their finger on the surface, visual feedback was provided on computer monitor. As shown in Fig. 2, the blue bar moves up and down in real time indicating the error of the actual applied normal force from the desired value. Participants maintained the desired applied normal force by keeping the force error as small as possible (see Fig. 2).

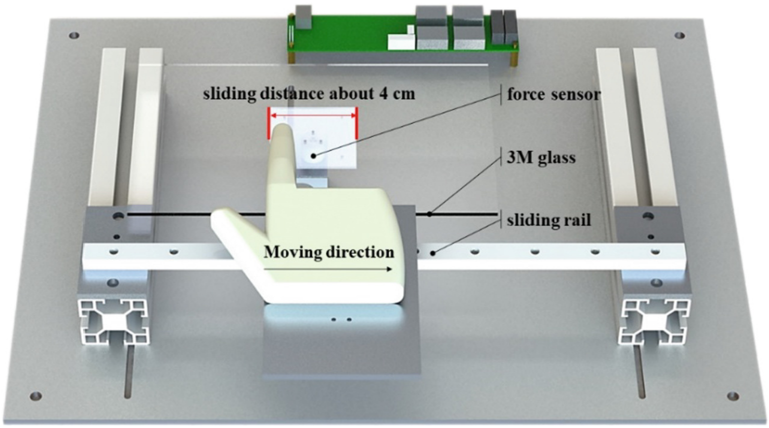

Fig. 1. Experimental apparatus

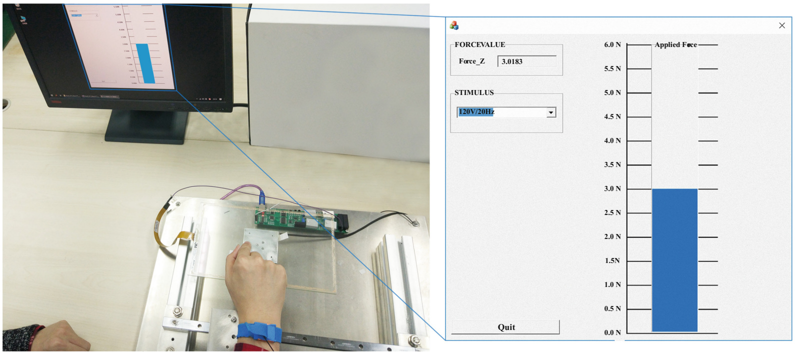

Fig. 2. Illustration of the experiment of perception magnitude estimation (left) and the interface of the visual feedback (right) (Color figure online)

The input voltage is generated by a microcomputer (Silicon Laboratories, C8051F320, USA) and amplified by a special amplification circuit. The frequency error of the input voltage signal is no more than ±0.2% and the amplitude error of the voltage is no more than ±4%. The finger is grounded through the skin via a copper foil band.

2.3 Stimuli

Vardar et al. showed the participants were more sensitive to stimuli induced by square wave voltage than sinusoidal one [15]. Thus, no bias square wave voltage was used in this study at the three frequencies of input voltage (20 Hz, 120 Hz, 220 Hz). As the frequency of electrostatic force is twice the voltage frequency [13], the 120 Hz lies in the range of the most sensitive frequency, which is around 200–300 Hz [23]. The other two are outside the range. The voltage magnitude was chosen as 120 V, which is higher enough than the absolute detection threshold [15]. To ensure small fluctuations in the applied normal force, the voltage signal is turned on every 500 ms, each time for 250 ms, as shown in Fig. 3. Zophoniasson et al. showed when users experience the electrovibration device the highest applied normal force was around 5 N [22]. Therefore, we evaluated the perception magnitude of electrovibration under 10 different applied normal forces (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 N).

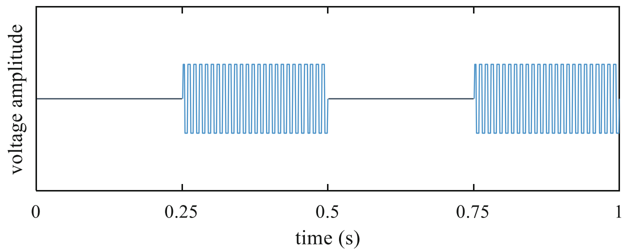

Fig. 3. Sample of the supply signal

2.4 Procedure

We used the method described in [24] to estimate the magnitude of the electrovibration perception. Before the experiment, participants were trained to maintain a stable normal force during finger sliding. During the training, each participant slides the fingertip on the device surface while watching the visual feedback on the computer. To reduce the task difficulty, the finger slides within a short distance of about 4 cm (Fig. 1). The average duration of the training session is about 20 min.

In the experiment, participants sat comfortably in front of the apparatus and wore a grounded band on right wrist, which rested on the sliding carriage (Fig. 2). Their right index finger pressed on the 3 M touch screen and kept desired normal force and then slid the finger. When sliding the finger on the 3 M touch screen, participants kept the applied normal force steady with the help of the visual feedback. The sliding was repeated 5 times for each level of applied normal force. Then participant was asked to rate the electrovibration perception by assigning a number to the estimated magnitude. Participants could use any number they think appropriate to them. They assigned successive numbers in such a way that represent their subjective impression. There is no limitation to the sets of numbers participants may use. A random order of 10 applied force levels were presented for each participant. To make the participants focus on the estimation task, they were asked to speak out their assigning number while the experimenter recorded the number. The normal force and tangential force were recorded during the sliding.

The experiments were performed in three sessions, which formed based on the types of the input signal (20 Hz, 120 Hz 220 Hz). The duration of each session was about 6–10 min. Participants were asked to take a two-minute break between sessions. Before each session, participants were asked to clean their fingers and use talcum powder to reduce finger humidity.

3 Results

3.1 Magnitude Estimation

The raw data of the magnitude estimation need to be normalized because participants were free to choose their own sets of numbers. We normalized the data by using a geometric mean, as recommended by Han et al. [25]. To determine the effect of applied normal force on electrovibration perception magnitude, one-way ANOVA was conducted on the normalized data at each frequency.

The normalized rating scores of magnitude estimation are shown in Fig. 6. The result shows that the average scores increase with the applied normal force. One-way ANOVA analysis of the score shows that the applied normal force has a significant effect on electrovibration perception magnitude (square wave (120 V, 20 Hz): $F(9,63) = 30.37$, $p < 0.001$; square wave (120 V, 120 Hz), $F(9, 63) = 15.38$, $p < 0.001$; and square wave (120 V, 220 Hz), $F(9, 63) = 13.62$, $p < 0.001$).

3.2 Friction Induced by the Electrostatic Force

The magnitude estimation experiments showed that the larger the applied normal force was, the stronger the perceived magnitude was. To better understand the reason behind this, we analyzed the friction induced by the electrostatic force during the experiments.

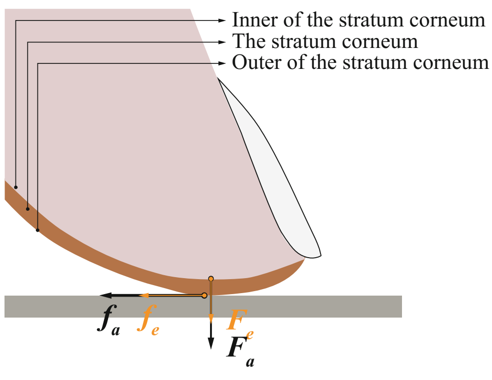

Fig. 4. Electrovibration principle and force analysis

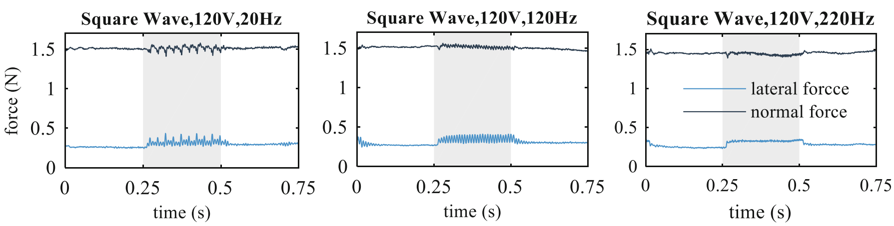

Fig. 5. Sample of the raw force data at three frequencies (20 Hz, 120 Hz, 220 Hz)

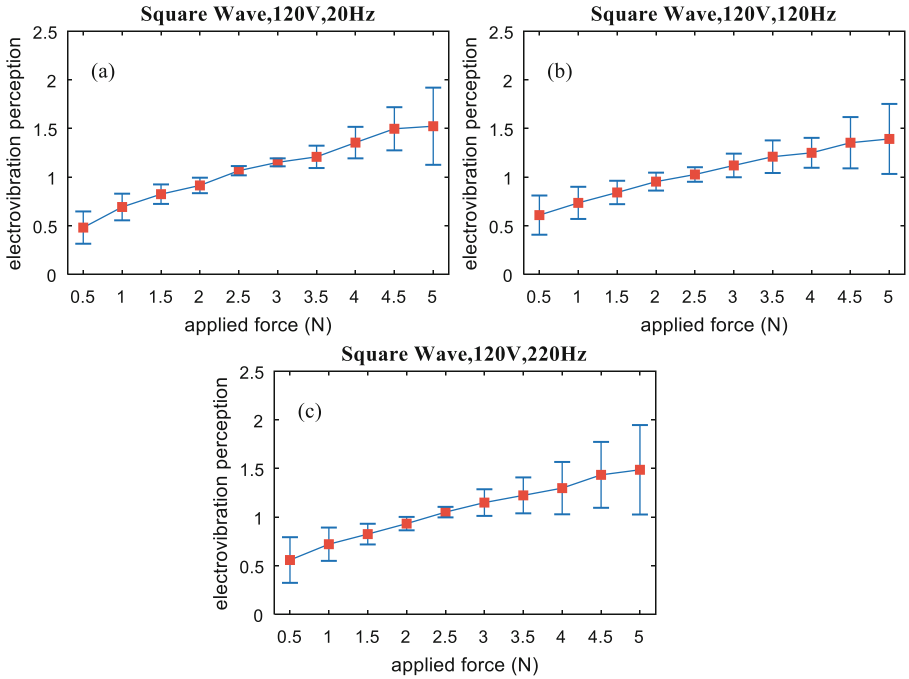

Fig. 6. The mean and standard deviation of the magnitude estimation of electrovibration perception at the three frequencies.

As shown in Fig. 4, the lateral force on the fingertip consists of two parts:

$$f = f_a + f_e \tag{1}$$

where f_a is the Coulomb friction, f_e is the friction induced by the electrostatic force. We measured the lateral force when the input voltage signal was turned on and off. Thus, the friction induced by the electrostatic force can be calculated by

$$f_e = f - f_a = f_{v \neq 0} - f_{v=0} \tag{2}$$

where $f_{v \neq 0}$ is the lateral force when the input voltage is turned on, $f_{v=0}$ is the lateral force when the input voltage is turned off. A sample of the normal and lateral force data at three frequencies (20 Hz, 120 Hz, 220 Hz) is shown in Fig. 5. The gray area represents the input voltage is turned on.

Figure 7(a–c) show the mean and the standard deviation of the applied normal force of individual participant. The largest standard deviation among the eight participants is 0.08 N, showing that the deviation from the specified normal force is small, which suggests that participants could keep the applied normal force constant during the short-distance (4 cm) sliding. As shown in Fig. 7(e–f), the friction induced by the electrostatic force increases with the applied normal force. The smallest means of the three frequencies are within 0.04 to 0.05 N, the largest means are within 0.19 to 0.29 N, which illustrates that the friction induced by the electrostatic force changes largely as the applied normal force increases.

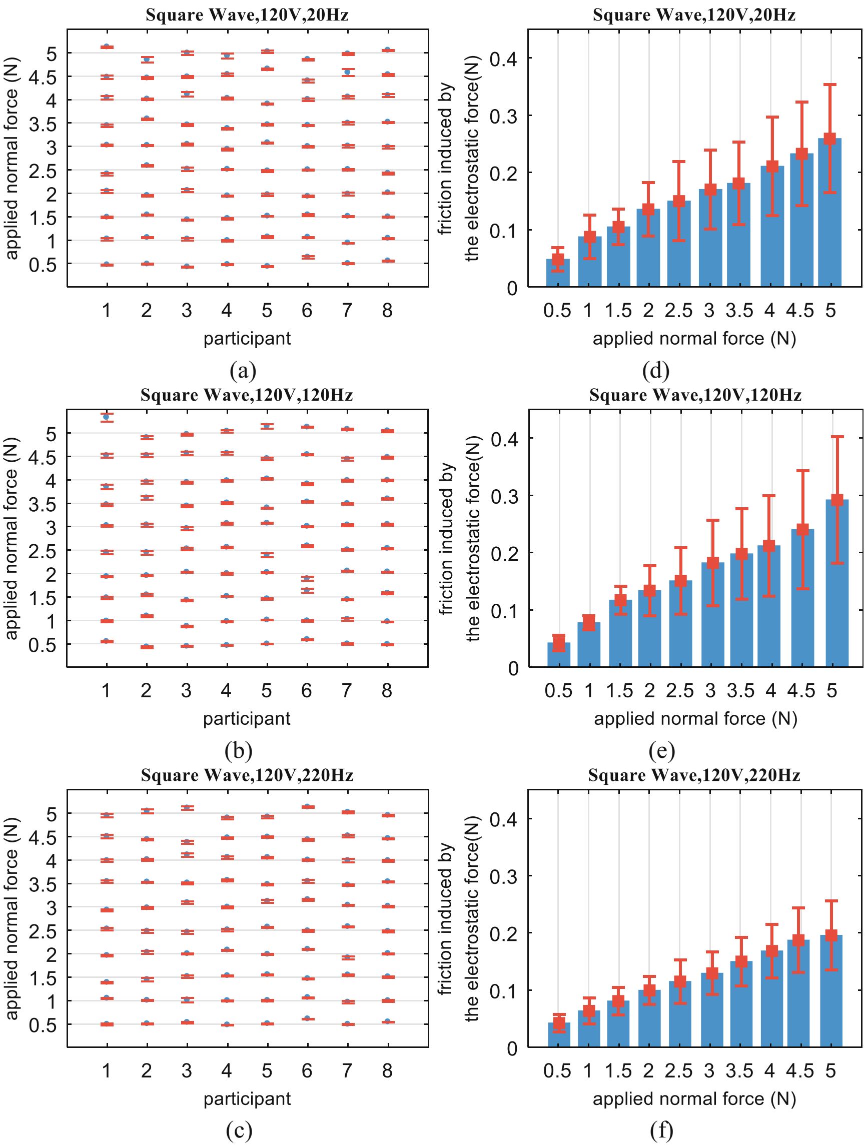

Fig. 7. The mean and deviation of the applied normal force (a–c). Relation between the friction induced by the electrostatic force and the applied normal force (d–f).

4 Discussion

The results of the magnitude estimation experiment suggest that the applied normal force has a significant effect on the perception of the friction induced by the electrostatic force. This result is drawn when the applied normal force changes from 0.5 N to 5.0 N, which is the normal range when the uses interact with the tactile displays. Although the applied normal force is not explicit in the model of electrostatic force, it needs to be considered when applying the model.

We measured electrovibration perception magnitude with respect to the applied normal force ranging from 0.5 to 5 N. The results showed that the electrovibration perception magnitude increased significantly with the increased applied normal force at three frequencies of the input voltage (20 Hz, 120 Hz and 220 Hz). To understand the reason behind this result, we measured the corresponding friction induced by the electrostatic force. Figure 7 shows a positive correlation between the friction induced by the electrostatic force and the applied normal force, which supports the relationship between the electrovibration perception magnitude and the applied normal force. Our finding at the voltage frequency of 220 Hz is consistent with what Zophoniasson et al. [22] claimed that the absolute voltage thresholds decreased with increased applied force at 240 Hz, 360 Hz, and 540 Hz. However, our results do not agree with the results at 100 Hz and 160 Hz in [22], which showed no applied force effect on the absolute threshold of the voltage. This discrepancy would need to be investigated further in the future.

The model of electrostatic force indicates a linear relationship with the contact area of the finger [9, 10]. Previous researches showed that the finger contact areas became roughly constant when the applied normal forces is above 2 N [26, 27]. Our result in Fig. 7 shows the friction induced by the electrostatic force continues to increase with the applied normal force in the range of 0.5 N–5 N. This fact suggests that the applied normal force affects not only the contact area but also other factors in the model of electrostatic force. We speculate that the applied force may affect the thickness of the air gap in the model. Future work needs to be done to confirm the speculation.

It is noted that the tangential force on the fingertip consists of two parts (see in Eq. (1)): the Coulomb friction (f_a) and the friction induced by the electrostatic force (f_e). Thus, the participants perceived the two parts when estimating the magnitude of electrovibration. Because f_a is a low-frequency friction and f_e is a relative high-frequency friction, the perceptual difference between the two is distinct. In fact, the participants can easily differentiate the two types of friction, which is supported by the similar trends of the estimated score (Fig. 6) and the friction induced by the electrostatic force (Fig. 7(d–f)). However, the Coulomb friction may affect the accuracy of the magnitude estimation. Furthermore, we observed that there is less deviation around 2.5 N in Fig. 6, which needs further investigation.

5 Conclusion

Aiming to investigate how the electrovibration perception magnitude is influenced by the applied normal force, we measured the electrovibration perception magnitude as well as the friction induced by the electrostatic force with respect to different applied normal forces. The experimental data indicated that both the magnitude and the friction induced by the electrostatic force increase with an increased applied normal force. The result implies that the applied normal force has a strong influence on the electrovibration perception magnitude, and thus needs to be considered in virtual texture rendering on electrovibration devices.

Acknowledgment. This research is supported by the National Key Research and Development Plan under Grant No. 2017YFB1002803, and the National Natural Science Foundation of China under the grant No. 61532003.

References

1. Nakamura, T., Yamamoto, A.: A multi-user surface visuo-haptic display using electrostatic friction modulation and capacitive-type position sensing. IEEE Trans. Haptics **9**, 311–322 (2016)
2. Bau, O., Poupyrev, I., Israr, A., Harrison, C.: TeslaTouch: electrovibration for touch surfaces. In: Proceedings of the 23nd Annual ACM Symposium on User Interface Software and Technology, UIST 2010, New York, USA, pp. 283–292 (2010)
3. Mullenbach, J., Johnson, D., Colgate, J.E., Peshkin, M.A.: ActivePaD surface haptic device. In: 2012 IEEE Haptics Symposium (HAPTICS), Vancouver, BC, Canada, pp. 407–414 (2012)
4. Chubb, E.C., Colgate, J.E., Peshkin, M.A.: ShiverPaD: a glass haptic surface that produces shear force on a bare finger. IEEE Trans. Haptics **3**, 189–198 (2010)
5. Strong, R.M., Troxel, D.E.: An electrotactile display. IEEE Trans. Man-Mach. Syst. **11**, 72–79 (1970)
6. Radivojevic, Z., Beecher, P., Bower, C., Haque, S., Andrew, P., Hasan, T., et al.: Electrotactile touch surface by using transparent graphene. In: Proceedings of the 2012 Virtual Reality International Conference, Laval, France, 28–30 March 2012
7. Radivojevic, Z., Beecher, P., Bower, C., Cotton, D., Haque, S., Andrew, P., et al.: Programmable electrostatic surface for tactile perceptions. In: SID Symposium Digest of Technical Papers, vol. 43, pp. 407–410 (2012)
8. Guo, X., Zhang, Y., Wang, D., Jiao, J.: Absolute and discrimination thresholds of a flexible texture display. In: 2017 IEEE World Haptics Conference (WHC), pp. 269–274 (2017)
9. Vodlak, T., Vidrih, Z., Vezzoli, E., Lemaire-Semail, B., Peric, D.: Multi-physics modelling and experimental validation of electrovibration based haptic devices. Biotribology **8**, 12–25 (2016)
10. Shultz, C.D., Peshkin, M.A., Colgate, J.E.: Surface haptics via electroadhesion: expanding electrovibration with Johnsen and Rahbek. In: 2013 World Haptics Conference (WHC), Chicago, USA, pp. 57–62 (2015)
11. Bau, O., Poupyrev, I.: REVEL: tactile feedback technology for augmented reality. ACM Trans. Graph. **31**, 11 (2012)

12. Vezzoli, E., Amberg, M., Giraud, F., Lemaire-Semail, B.: Electrovibration modeling analysis. In: Auvray, M., Duriez, C. (eds.) EUROHAPTICS 2014. LNCS, vol. 8619, pp. 369–376. Springer, Heidelberg (2014). https://doi.org/10.1007/978-3-662-44196-1_45
13. Meyer, D.J., Peshkin, M.A., Colgate, J.E.: Fingertip friction modulation due to electrostatic attraction. In: 2013 World Haptics Conference, Daejeon, South Korea, pp. 43–48 (2013)
14. Kang, J., Kim, H., Choi, S., Kim, K.D., Ryu, J.: Investigation on low voltage operation of electrovibration display. IEEE Trans. Haptics **10**, 371–381 (2017)
15. Vardar, Y., Güçlü, B., Basdogan, C.: Effect of waveform on tactile perception by electrovibration displayed on touch screens. IEEE Trans. Haptics **10**, 488–499 (2017)
16. Wijekoon, D., Cecchinato, M.E., Hoggan, E., Linjama, J.: Electrostatic modulated friction as tactile feedback: intensity perception. In: Isokoski, P., Springare, J. (eds.) EuroHaptics 2012. LNCS, vol. 7282, pp. 613–624. Springer, Heidelberg (2012). https://doi.org/10.1007/978-3-642-31401-8_54
17. Ilkhani, G., Aziziaghdam, M., Samur, E.: Data-driven texture rendering on an electrostatic tactile display. Int. J. Hum.-Comput. Interact. **33**, 756–770 (2017)
18. Wu, S., Sun, X., Wang, Q., Chen, J.: Tactile modeling and rendering image-textures based on electrovibration. Vis. Comput. **33**, 637–646 (2017)
19. Kim, S.-C., Israr, A., Poupyrev, I.: Tactile rendering of 3D features on touch surfaces. In: Proceedings of the 26th Annual ACM Symposium on User Interface Software and Technology, St. Andrews, Scotland, United Kingdom, pp. 531–538 (2013)
20. Kaczmarek, K.A., Nammi, K., Agarwal, A.K., Tyler, M.E., Haase, S.J., Beebe, D.J.: Polarity effect in electrovibration for tactile display. IEEE Trans. Biomed. Eng. **53**, 2047–2054 (2006)
21. Agarwal, A.K., Nammi, K., Kaczmarek, K.A., Tyler, M.E., Beebe, D.J.: A hybrid natural/artificial electrostatic actuator for tactile stimulation. In: 2nd Annual International IEEE-Embs Special Topic Conference on Microtechnologies in Medicine & Biology Proceedings, New York, USA, pp. 341–345 (2002)
22. Zophoniasson, H., Bolzmacher, C., Anastassova, M., Hafez, M.: Electrovibration: influence of the applied force on tactile perception thresholds. In: 2017 Zooming Innovation in Consumer Electronics International Conference (ZINC), Novi Sad, Serbia, pp. 70–73 (2017)
23. Israr, A., Choi, S., Tan, H.Z.: Detection threshold and mechanical impedance of the hand in a pen-hold posture. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, pp. 472–477 (2006)
24. Jones, L.A., Tan, H.Z.: Application of psychophysical techniques to haptic research. IEEE Trans. Haptics **6**, 268–284 (2013)
25. Han, S.H., Song, M., Kwahk, J.: A systematic method for analyzing magnitude estimation data. Int. J. Ind. Ergon. **23**, 513–524 (1999)
26. Liu, X., Carré, M.J., Zhang, Q., Lu, Z., Matcher, S.J., Lewis, R.: Measuring contact area in a sliding human finger-pad contact. Skin Res. Technol. **24**, 31–44 (2018)
27. Elizabeth Tomlinson, S.: Understanding the friction between human fingers and contacting surfaces. The University of Sheffield, UK (2009)