HAPTICS SYMPOSIUM '16, APRIL 8–11, 2016, PHILADELPHIA, PENNSYLVANIA, USA
978-1-5090-0903-9/16/$31.00 ©2016 IEEE

Identification of Primitive Geometrical Shapes Rendered Using Electrostatic Friction Display

Reza Haghighi Osgouei[1], Jin Ryong Kim[2], and Seungmoon Choi[1]

Abstract— **Electrostatic displays are an effective platform in enabling programmed haptic feedback on a touchscreen using variable friction. In this work, we investigate the extent to which users can correctly recognize 3D primitive geometrical shapes rendered using only the tangential friction force produced by an electrostatic display. The algorithm for that was based on a previous study that demonstrated using a force-feedback interface that lateral force has a dominant role in shape perception. The main findings of this study are two-fold: 1) Users do not naturally associate electrovibration patterns to primitive shapes unless guidance or context for that is given; and 2) Users can map electrovibration patterns to primitive shapes with moderately high accuracy if they are asked to do so. These results provide some promise that electrostatic displays can further improve the user experience of exploring the visual content displayed on a touchscreen.**

I. Introduction

Touchscreens are a versatile device that displays visual content and takes touch input simultaneously. However, it lacks the ability of providing programmed tactile feedback, which can be essential for more natural interaction. This limitation has been addressed by several approaches, and they are generally called surface haptics technology. This technology modulates the friction between a user's fingertip and a touchscreen surface in order to create a variety of tactile sensations when the finger explores on the touchscreen. This functionality allows the user to see and feel the digital content simultaneously with richer haptic information, leading to improved user experience and/or usability.

There exist two major approaches in surface haptics. One is to apply ultrasonic vibration to the touchscreen surface, which creates a thin air film between the user's finger and the screen and thereby decreases the friction [1], [2], [3], [4]. The other approach relies on the electrostatic force induced between the user's finger and an insulating surface on the touchscreen by supplying high AC voltage, which effectively increases the surface friction [5], [6], [7]. Such electrovibration displays have the advantages that they require only electrical components and that the friction can be controlled uniformly on the screen, which are particularly attractive for mobile devices with a provision of adequate amplifiers.

The phenomenon of electrovibration was first introduced by Mallinckrodt et al. [8] in 1953. They accidentally discovered that an insulated surface supplied by an alternating voltage source of 110 V elicits rubber-like sensations when the surface is scanned by the finger. Later on, Strong et al. [9] developed the first electrotactile display using a stimulator array with a number of small electrodes. These early findings have recently been elaborated for application to touchscreens, beginning from TeslaTouch [5]. TeslaTouch was the first embodiment of electrovibration on a touchscreen, and many interesting and useful applications of TeslaTouch were also presented. At the moment, there exist a few commercial solutions for electrostatic displays. FeelScreen [10] from Senseg is one of the first commercial electrostatic development kit for tablets. Tanvas [11] is also commercializing surface haptics by utilizing similar technology to Feelscreen with the ability for position-dependent friction modulation.

One of the unique properties of electrostatic friction is that it creates clearly perceptible stimuli only when the surface is laterally scanned, but not when the finger is stationary on or presses against the surface. This fundamental limitation has confined the application of electrostatic friction display mostly to texture rendering. In [7], a data-driven approach for texture rendering using an electrostatic display was proposed. In this work, acceleration data was first recorded as the dominant feature of surface texture and then played back by modulating friction on the electrostatic display, similarly to data-driven rendering of surface textures using mechanical vibration [12], [13]. In [14], authors presented a high-fidelity surface haptic display for texture rendering. They adopted a non-contact position sensor and a low-latency rendering scheme to reproduce fine-grained textures.

Another challenge researchers have addressed is rendering 3D features using only the friction force produced by an electrostatic display [6]. To this end, the early findings that tangential force alone can be sufficient for rendering surface textures [15] and simple 3D features (bumps and holes) [16], have been central assets. In particular, Robles-De-La-Torre and Hayward demonstrated that in active exploration of physical shapes, the lateral force applied to the sliding finger from the surface plays the main role in the perception of the shapes [16]. They investigated the accuracy of physical shape recognition and localization using a one-DOF (degree of freedom) haptic interface without any visual information. Different combinations of physical and virtual geometries (bump, hole, and flat surface) were presented to participants, e.g., a virtual bump combined with a physical flat surface. The virtual shapes were rendered using lateral force only. It was reported that participants could accurately identify the shapes of virtual shapes in all the conditions. This study

This work was supported by a Giga Korea Project (GK15C0100; Development of Interactive and Realistic Massive Giga-Content Technology) of the Ministry of Science, ICT and Future Planning, Republic of Korea.

[1]R. H. Osgouei, and S. Choi are with the Haptics and Virtual Reality Laboratory, Department of Computer Science and Engineering, POSTECH, Pohang, Geyongbuk, Republic of Korea. {haghighi, choism}@postech.ac.kr.

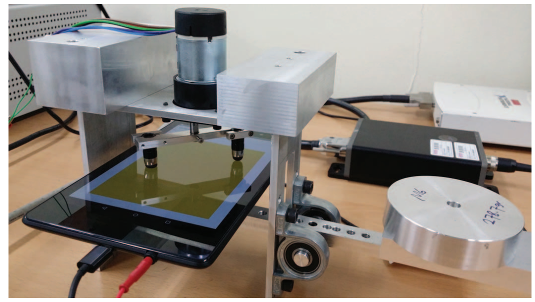
[2]J. R. Kim is with the Electronics and Telecommunications Research Institute, Daejeon, Republic of Korea. jessekim@etri.re.kr.

was a foundation to the gradient-based algorithm of Kim et al. [6] for rendering 3D features on a touch surface using electrovibration. They compared the user preference of three types of force profiles, height, slope, and rectangular, for a visual bump displayed on the screen. Results indicated that the slope profile was the best match to the visual bump. They generalized this finding to develop a 2D gradient-based rendering algorithm for 3D features and applied the algorithm to many user interface examples.

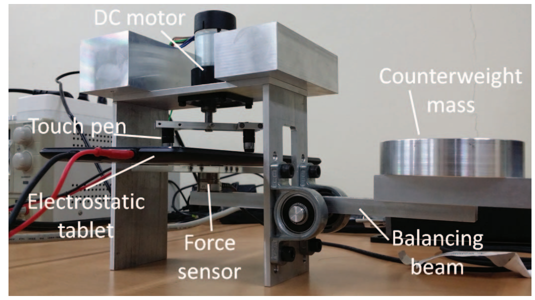
The study we report in this paper was motivated by our on-going research for an integration of a multi-focus autostereoscopic 3D visual display and an electrostatic display onto a touchscreen. Multi-focus displays provide greatly superior 3D visual perception than regular touchscreens, and we have been seeking the methods to further enhance 3D perception by means of haptic feedback. The present study was carried out for the following two research questions:

- Q1 *Can users identify primitive 3D features, such as bumps and holes, from electrovibration alone without any visualization?*
- Q2 *How close is the recognition performance to that of the case using an active kinesthetic interface?*

These objectives are in contrast to the work of Kim et al. [6] that was concerned more with matching electrovibration patterns to visual shapes.



(a) Top view



(b) Bottom view

Fig. 1: Rotary tribometer.

II. Device Characterization

In this study, we used a Feelscreen development kit (Senseg, Finland) for a tablet, in which an electrostatic display was overlaid on a commercial tablet (Google Nexus 7). This device can provide strong and clear sensations of electrovibration. Its software development kit (SDK) supported nine haptic effects (called haptic grains) that resulted in noticeably different friction patterns. The intensity of haptic grain could be controlled using a normalized value (0.0–1.0). However, the Feelscreen SDK did not allow completely-customable input, e.g., a sinusoidal wave with certain frequency and amplitude, and the characteristics of generated friction forces was unknown. Therefore, it was necessary to characterize FeelScreen's various haptic grains, and we built a tribometer for that purpose.

A. Tribometer

Our tribometer is similar to those used in the research of electrostatic displays [17], [18], but also has a few differences. The previous studies required great care in controlling the electrical skin impedance of fingertip since it depends greatly on person, temperature, and moisture. In particular, the skin moisture level can change even in a short period of use. We found that the electrostatic display of Feelscreen also responded to some touch pens. The sensations of electrovibration resulted from the use of such a touch pen and the bare finger were very similar. Hence, our tribometer uses a touch pen instead of the human fingertip for data collection in order for precisely regulation of the measurement condition. Our tribometer is also rotary for a simpler mechanical design whereas the previous studies used linear scanning movements.

Our tribometer consists of a DC motor (RB-35GM, DnJ, Korea) with a touch pen attached to its shaft using a holder and a six-axis force/torque sensor (Nano 17, ATI Technologies, USA) placed under the tablet (Fig. 1). The length of the pen holder is 6 cm, which makes the rotation radius 3 cm. A balancing beam with a counterweight on the opposite end of the touch pen is used to adjust the normal pressure. The beam is pivoted at the middle to provide free vertical movement. The counterweight mass ($\simeq$ 470 g) is selected to approximate the normal pressure of human hand. The rotation velocity ($\simeq$ 6.5 cm/s) is chosen for the usual human hand velocity during surface scanning. The force data is sampled at 10 KHz using a 16-bit data acquisition board (NI USB-6251, National Instruments, USA).

B. Output Characteristics

To characterize the output friction force of Feelscreen, we customized an Android application, originally developed by Senseg, that aligned a number of vertical edges in the landscape orientation (Fig. 2). When each edge was crossed by the rotating touch pen of the tribometer, a haptic grain was played back with the designated intensity. A representative data of the measured tangential and normal forces is presented in Fig. 3 (haptic grain EDGE-SOFT; intensity 1.0). The upper panel shows that whenever an edge was crossed by the touch pen, a vibratory tangential force occurred with the peak-to-peak (p-p) amplitude of approximately 0.25 N (averaged over 50 largest p-p amplitudes). Vibratory forces were also observed in the normal direction, but their p-p amplitude was much lower (less than 0.05 N). Therefore, the

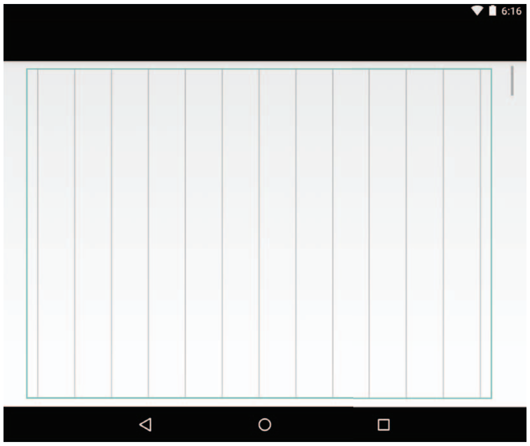


Fig. 2: Graphical user interface for device characterization. When each vertical line is crossed, a haptic grain is rendered.

tangential force should be the dominant sensory cue for the perception of haptic effects. These output behaviors are in good agreement with those reported in the previous related work [17].

We then identified the relationship between the input intensity (0.0–1.0) and the magnitude of the resulting tangential force. While changing the input intensity from 0.1 to 1.0 with a step size of 0.1, we collected 20 seconds of force data (corresponding to seven full rotations of the tribometer's shaft). After applying a low-pass Butterworth filter with a cut-off frequency of 500 Hz, we computed the p-p amplitudes in the tangential force and then averaged the 50 largest p-p amplitudes. The average p-p amplitude showed a quadratic relationship to the input intensity, as demonstrated in Fig. 4 (haptic grain: EDGE-SOFT). Assuming that the input voltage to the electrostatic film of Feelscreen is linearly proportional to the input intensity, this result conforms to the classic theory of electrovibration that the output force magnitude is in proportion to the square of input voltage [8].

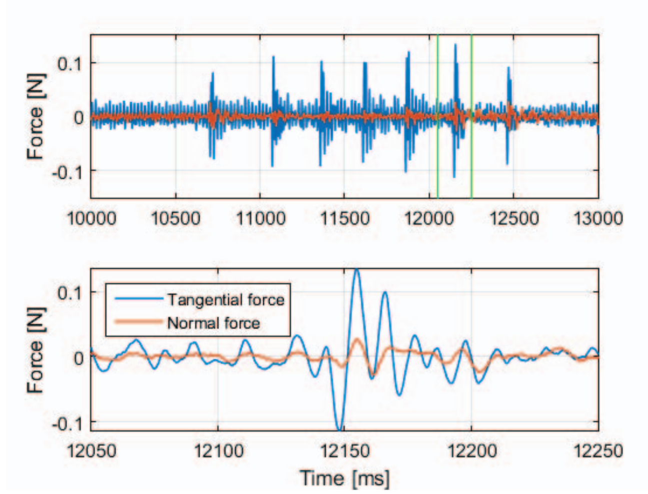


Fig. 3: Example of force measurements. Blue: tangential force and red: normal force. Upper panel: the data collected during a full rotation and lower panel: the highlighted region with two vertical lines in the upper panel.

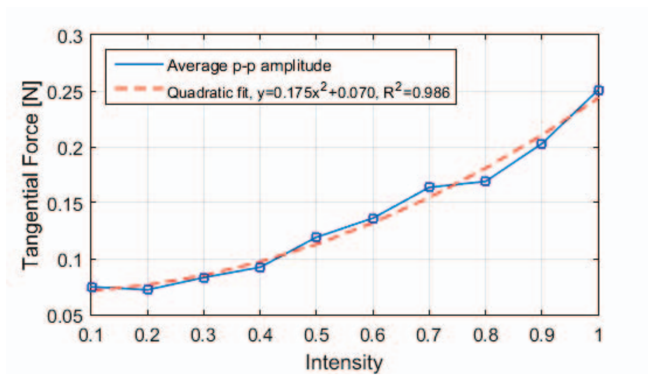


Fig. 4: Peak-to-peak amplitude of tangential force vs. input intensity.

III. Methods

As stated earlier, this perceptual experiment aimed to assess how well users can recognize primitive 3D geometrical shapes when they are provided with depictions of the shapes using only the friction force produced by an electrovibration display. This idea was motivated by the prior work [16] that had demonstrated that rendering tangential force alone can be extremely effective in recognizing geometrical shapes such as bumps and holes. This method was also implemented using a force-feedback haptic interface for inclusion in the experiment as the baseline.

A. Force Profiles

Following [16], we designed two basic 3D geometries, Gaussian bump and hole, as well as a flat surface for the experiment. The Gaussian profiles had a length of 5 cm and a height of 0.8 cm. They were computed using (1) with $\mu = 0$ and $\sigma = 0.5$:

$$y(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right). \qquad (1)$$

An exemplar Gaussian bump is shown in Fig. 5. The bumps and holes used in the experiment had a width of approximately 2.6 cm.

1) For Force-Feedback Device: To compute force profiles for Gaussian bumps and holes, we followed the footstep introduced in [16]. Assuming the user applies force $\mathbf{F_s}$ at position $\mathbf{p}(x, y)$ when exploring a friction-less physical surface, the surface returns $\mathbf{F_p} = -\mathbf{F_s}$ (Fig. 5). From the surface slope at the contact point, the relation between tangential (F_{px}) and normal (F_{py}) components of the returned force can be expressed by

$$\begin{aligned} F_{px} &= -F_{py}\tan(\alpha(x)), \\ \tan(\alpha(x)) &= \frac{dy}{dx} = -\frac{1}{\sigma^2}xy, \end{aligned} \qquad (2)$$

where $\alpha(x)$ is the angle of $\mathbf{p}(x, y)$.

The normal force F_{py} applied by the user was measured using a force sensor in [16]. However, impedance-type force

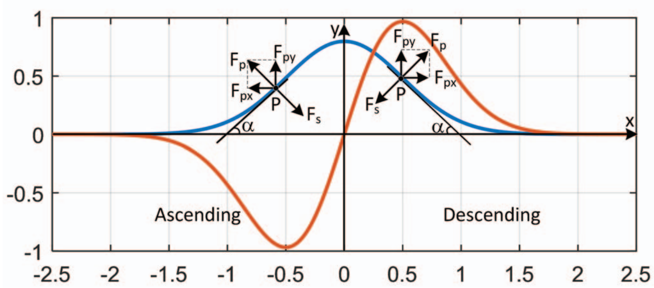
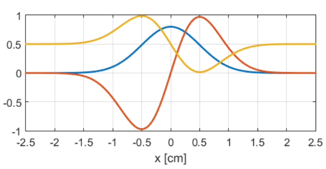
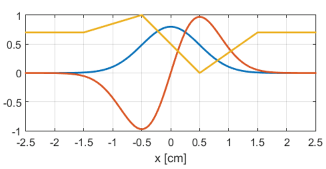


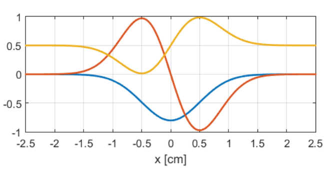
Fig. 5: Gaussian bump (blue) and the corresponding force profile (red) taken from [16]. The scanning direction is from left to right.



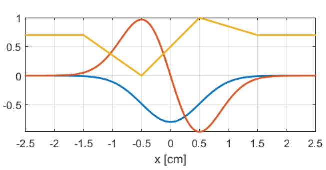
(a) Bump, IP0.5.



(b) Bump, IP0.7.



(c) Hole, IP0.5.



(d) Hole, IP0.7.

Fig. 6: Profiles for the electrostatic display. Blue: geometry [cm], red: force [N], and orange: intensity.

feedback devices and electrostatic displays generally do not have a force or a pressure sensor. Hence, we assumed in our experiment that $F_{py} = 1\,\text{N}$ based on pilot experiments we conducted using the human hand. An example of the computed tangential force profile for a Gaussian bump is plotted in Fig. 5. When the scanning direction is from left to right (in the direction of positive x-axis), the tangential force F_{px} resists the movement during ascending and assists the movement during descending. The force changes its direction at zero slope, right at the summit of the bump.

A computer program was developed using CHAI3D to render the computed force profiles with a force-feedback device using two types of algorithms based on force field and friction, respectively. In the force field-based algorithm, the tangential force profile is directly sent to the force-feedback device. In the friction-based algorithm, the dynamic friction coefficient of a virtual surface is adjusted based on the force profile using a mapping explained in Section III-A.2.

Five experimental conditions were formed by combining three geometries (bump, hole, and flat surface) and the two rendering algorithms (force field-based and friction-based), as summarized in TABLE I. Only the friction-based algorithm was used for the flat surface.

2) For Electrostatic Display: The tangential force profiles for a force-feedback device cannot be rendered using an electrostatic display since it cannot provide the active force assisting movement, e.g., when $F_{px} > 0$ in Fig. 5. This is the fundamental limitation of friction displays that are inherently passive. To handle this problem, we linearly map the normalized force of a force profile from -1.0 N to 1.0 N to the input intensity of the Feelscreen tablet from 1.0 to 0.0. This maps -1.0 N to the maximum friction, 0 N to the friction of the half intensity, and 1.0 N to the minimum friction (that of the touchscreen). This is the same technique used in [6]. Since the input intensity profile has the offset of 0.5, we call this method IP0.5 (see Fig. 6a and c). A similar mapping was also used to implement the friction-based rendering for a force-feedback device.

According to the results of device characterization (Fig. 4), the actual electrostatic friction for the input intensity of 0.5 is lower than 50% of the full scale force. The minimum friction force is about 0.075 N and the maximum is 0.25 N, and the half full scale force, 0.16 N, occurs around the input intensity of 0.7. This observation led to the design of another intensity profile IP0.7 that uses 0.7 as the offset. For the mapping, we approximate the Gaussian force profiles with piecewise linear intensity profiles (Fig. 6b and d).

We developed an Android application using min3d (an open-source engine based on OpenGL ES) to graphically render geometrical profiles (although hidden from the participants) and also to render intensity profiles in response to the user's touch position. Ten experimental conditions were prepared by combining three geometries (bump, hole, and flat surface) with the two intensity profiles (IP0.5 and IP0.7) and two haptic grains (HG1: EDGE-SOFT and HG2: AREA-GRAIN). The two haptic grains were chosen based on pilot experiments. A constant force profile with the maximum

TABLE I: Experimental conditions for force-feedback device.

Condition	Code name
1	FF-BUMP-FR
2	FF-BUMP-FF
3	FF-HOLE-FR
4	FF-HOLE-FF
5	FF-FLAT

FF: force-feedback device, FR: friction-based algorithm, and FF: force field-based algorithm.

TABLE II: Experimental conditions for electrostatic device.

Condition	Code name
1	EV-BUMP-IP0.5-HG1
2	EV-BUMP-IP0.7-HG1
3	EV-BUMP-IP0.5-HG2
4	EV-BUMP-IP0.7-HG2
5	EV-HOLE-IP0.5-HG1
6	EV-HOLE-IP0.7-HG1
7	EV-HOLE-IP0.5-HG2
8	EV-HOLE-IP0.7-HG2
9	EV-FLAT-HG1
10	EV-FLAT-HG2

EV: electrovibration, IP: intensity profile, and HG: haptic grain.

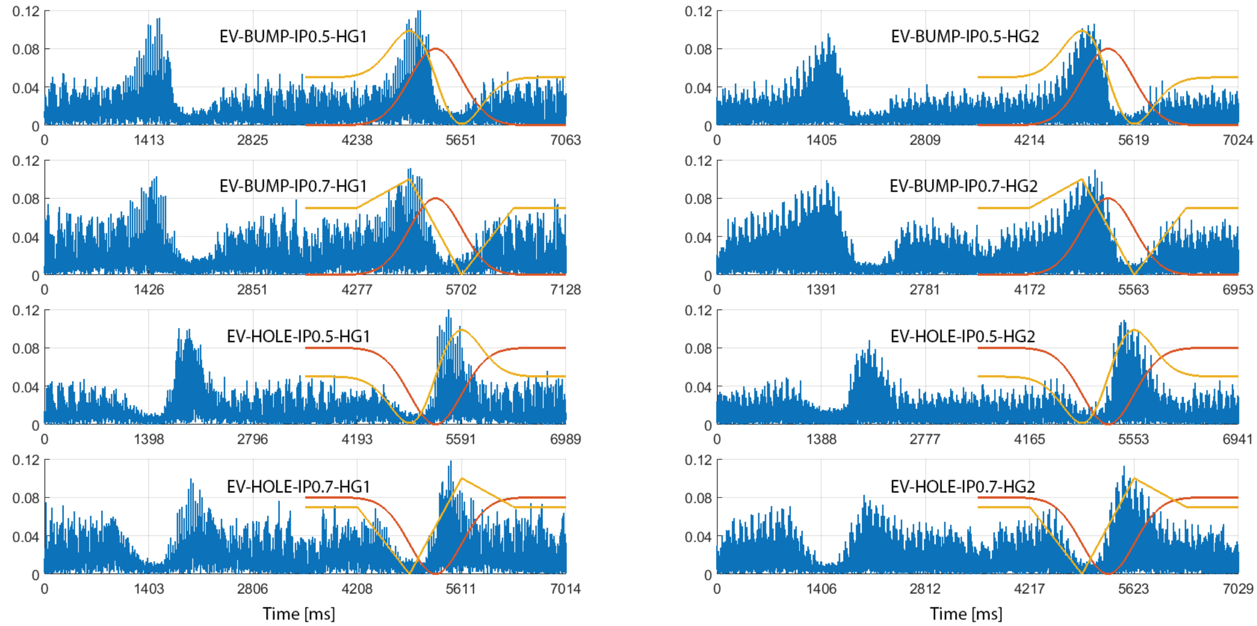


Fig. 7: Measured friction force profiles for each experimental condition. Blue: measured force profile [N] (only absolute values are shown for clarity), red: geometry profile, orange: intensity profile (scaled to show the trend).

intensity 1.0 is used for the flat surface. The ten experimental conditions are summarized in TABLE II.

The electrovibration stimuli measured using the tribometer are shown in Fig. 7 for the eight experimental conditions for bumps and holes. The geometry and intensity profiles are also shown for reference. It is clear that the induced electrostatic friction forces were in good match with the corresponding intensity profiles. The friction force patterns are clearly distinguishable between bumps and holes. The friction forces rendered using IP0.7 resulted in more symmetric profiles than those rendered using IP0.5.

B. Participants

Twelve participants (9 male, 3 female; M 22.7 years, SD 2.6 years) were recruited using an on-line public announcement. All of them were students enrolled at the authors' university. None of them reported noteworthy previous experiences of using kinesthetic haptic interfaces or electrostatic displays. They signed on an informed consent prior to the experiment. Each participant was compensated 10,000 KRW (9 USD) for their help.

C. Procedure

In the experiment, we used a PHANToM (1.0A; Geomagic, USA) as a force-feedback device and the Feelscreen tablet as an electrostatic display. Participants were randomly divided into two groups. The participants in group G1 first performed the five experimental conditions in Table I with the PHANToM, and then the ten experimental conditions in Table II with the Feelscreen tablet. These were switched for the participants in group G2. The order of the experimental conditions for the PHANToM and that for the Feelscreen tablet were randomized for each participant.

For each device, the experiment consisted of two parts. Part 1 was for open descriptions; participants were asked to freely describe their percept and experience in writing after exploring each stimulus. Nothing was provided to participants that could bias their perception. Part 2 was for a closed question; for each stimulus, participants chose one of the following four answers: 1) bump, 2) hole, 3) flat surface, and 4) none of them. They were instructed to select the shape that best describes their percept. Part 1 was performed first, followed by Part 2 using the same device after a short break.

During the experiment, the haptic device was placed inside a box with frontal access to a participant. A curtain covered the box to block the participant's view to prevent them from obtaining any visual cues. The experimenter could see the device from the back of the box and provided occasional guidance to the participant's pose and scanning speed when necessary. For the experiment with the Feelscreen tablet, participants were asked to hold a touch pen vertically and scan the surface from left to right. Each of the ten experimental conditions was presented only once. For the experiment with the PHANToM, the same touch pen was attached to the last vertical link of the PHANToM, and a seven-inch tablet was placed under the touch pen to enable similar scanning experiences. Participants were asked to hold the touch pen vertically and scan the surface from left to right. Each of the five experimental conditions was repeated twice. The numbers of bumps, holes, and flat surfaces were not known to participants in order to prevent guessing based on counting.

Prior to the experiment, participants were given enough time to practice and become familiar with the system. During the experiment, they were allowed to take rest whenever necessary. Participants' scanning velocity and vertical pressure were not controlled. They were free to adjust their own velocity and pressure for better perception; however it was supervised by the experimenter. The experiment took approximately one hour to finish for each participant.

IV. Results and Discussion

A. Open Descriptions

We compiled the participants' answers collected in the first part of the experiment. No noticeable differences were observed between the participants of group G1 and G2 in the open descriptions.

Most of the participants described the sensations of the force feedback rendered by the PHANToM using geometrical terms and figures. Frequently used words included bump, hole, protrusion, groove, convex or concave shape, ascent, and descent. Only one participant did not use any geometry-related term and instead used material-related terms, e.g., spring. These results reinforce the previous finding of [16] that the lateral force alone can render clearly identifiable primitive 3D shapes.

For the surfaces rendered using electrovibration, the majority of the participants described their sensations with terms related to vibration and friction, and sometimes texture. Only one participant mentioned geometrical terms (hole). It appears that electrovibration alone is not able to elicit strong illusions for the perception of 3D geometric shapes.

The time the participants spent to complete each experimental condition was shorter with the PHANToM than with the Feelscreen tablet. After just three or four scans with the PHANToM, the participants began to write down their descriptions. The Feelscreen tablet usually required six or seven scans for that.

B. Closed Selections

From the participants' responses collected in Part 2 of the experiment, the average correct recognition ratios of the geometrical shapes were computed for the two devices and are shown in Fig. 8. The correct recognition ratio for each device was calculated by dividing the total number of correct answers from all participants received in each experimental condition by the total number of answers in that condition. As expected, higher recognition performance was achieved with the PHANToM than with the Feelscreen tablet—91% vs. 64%. The Kruskal-Wallis test showed that the difference between the two devices was statistically significant ($p < 0.001$). The same test was performed between the two participant groups G1 and G2, but their recognition performance difference was not statistically significant ($p = 0.88$). These results suggest that when participants were given explicit guidance, they were able to associate the electrovibration patterns to the primitive 3D shapes at well above the chance level (25%). However, there existed a substantial performance difference (27%) from the best performance enabled by active force feedback.

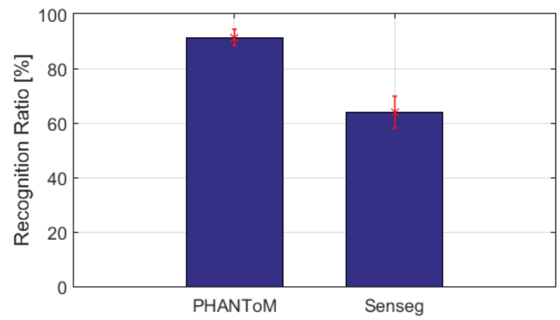


Fig. 8: Correct recognition ratios using the PHANToM (mean 91%) and the Feelscreen tablet (mean 64%). Error bars show standard errors.

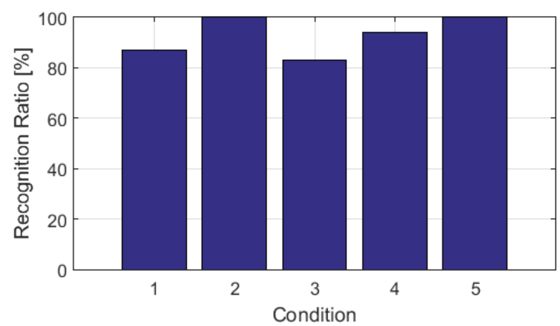


Fig. 9: Correct recognition ratios with the PHANToM for each experimental condition (see TABLE I).

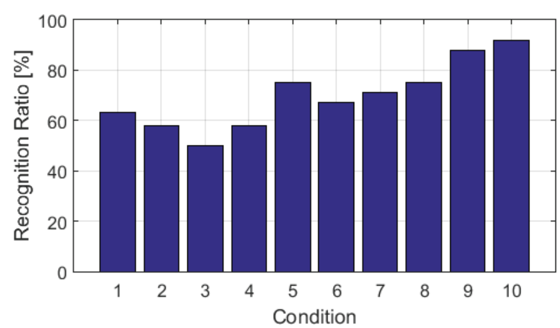


Fig. 10: Correct recognition ratios with the Feelscreen tablet for each experimental condition (see TABLE II).

Fig. 9 shows the average correct recognition ratios measured with the PHANToM for each experimental condition.[1] On average, bumps resulted in a higher ratio than holes (94% vs. 89%), which can be seen by comparing the ratios of conditions 1 and 2 and those of conditions 3 and 4. In addition, the force field-based algorithm showed higher performance than the friction-based algorithm (97% vs. 85%; compare the ratios of condition 1 and 3 to those of condition 2 and 4).

Similarly, the average correct recognition ratios measured with the Feelscreen tablet are presented in Fig. 10 for each

[1]Only one ratio was computable for each experimental condition. Hence no error bars are shown in Fig. 9 and 10. No statistical tests were performed with the data for the same reason.

experimental condition. The most prominent observation is that holes (conditions 5–8) gained more correct recognition than bumps (conditions 1–4) with 72% vs. 57%. The performance difference caused by the two different intensity profiles was negligible (IP0.5 66% vs. IP0.7 65%), and so was the recognition accuracy difference between the two haptic grains (HG1 69% vs. HG2 70%).

C. Summary and Discussion

The experimental results allow us to draw the following conclusions to the two research questions of this study:

Q1 *Can users identify primitive 3D features, such as bumps and holes, from electrovibration alone without any visualization?*
The answer is negative if no guidance or context implying association to geometric shapes is provided.

Q2 *How close is the recognition performance to that of the case using an active kinesthetic interface?*
If a hint to geometric shapes is given, users can associate electrovibration patterns to geometrical shapes at well above the chance level (64%), but the performance is clearly below the best performance (91%) achievable by active force feedback.

Lateral force feedback using electrovibration has two important differences from active force feedback. First, it conveys clear sensations of vibration, as predominantly mentioned in the participants' open descriptions. This seems to be one of the major reasons that preclude users from associating electrovibration patterns to geometrical shapes unless guided explicitly. Second, electrovibration does not allow the rendering of active tangential force that assists the movement when the gradient of a surface profile is negative. Although we tried to imitate this behavior using only friction, it seems that the effectiveness of that approach has a room for further improvement.

The similar performance between the two haptic grains HG1 and HG2 is an indication that the type of haptic grain is not a main factor for geometry recognition, although they may provide different feelings. Delivering noticeable friction fluctuations according to the intensity profiles appears to be sufficient. The same can be said to the effect of intensity profile on the basis of the similar recognition ratios of the two intensity profiles IP0.5 and IP0.7.

V. Conclusions

In this study, we compared an electrostatic tablet and a kinesthetic haptic interface in terms of their performance for rendering 3D shapes using only tangential force. Since the commercial electrostatic device used was a black box to us, we first characterized its input-output behavior of generating friction force. Then we carried out a perceptual experiment that assessed the user's recognition performance of primitive 3D shapes based on the tangential stimuli presented by the electrostatic tablet and a force-feedback interface. Experimental results demonstrated that users are not able to absolutely associate electrovibration patterns to the geometrical shapes without any contextual information. However, when such guidance was given, participants showed moderately high recognition performance of the primitive shapes, which is promising for the possibility of improving the user experiences of 3D visual content with the provision of electrovibration. The results obtained with the force-feedback device were used as the reference for the best performance.

For future work, we plan to extend this study for two topics. First, a variable friction display that modulates friction without clear sensations of vibration can be more beneficial for our purpose. Second, it is important to identify the range of the size of spatial features for which friction display is effective.

References

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

[2] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin, "T-pad: Tactile pattern display through variable friction reduction," in *Proceedings of the World Haptics Conference (WHC)*. IEEE, 2007, pp. 421–426.

[3] M. Biet, F. Giraud, and B. Lemaire-Semail, "Squeeze film effect for the design of an ultrasonic tactile plate," *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, vol. 54, no. 12, pp. 2678–2688, 2007.

[4] E. Chubb, J. Colgate, and M. Peshkin., "Shiverpad: a glass haptic surface that produces shear force on a bare finger," *IEEE Transactions on Haptics*, vol. 3, no. 3, pp. 189–198, 2010.

[5] 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*, 2010, pp. 283–292.

[6] 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*, 2013, pp. 531–538.

[7] G. Ilkhani, M. Aziziaghdam, and E. Samur, "Data-driven texture rendering with electrostatic attraction," in *Haptics: Neuroscience, Devices, Modeling, and Applications*. Springer, 2014, pp. 496–504.

[8] E. Mallinckrodt, A. L. Hughes, and W. Sleator Jr., "Perception by the skin of electrically induced vibrations." *Science*, 1953.

[9] R. M. Strong and D. E. Troxel, "An electrotactile display," *IEEE Transactions on Man-Machine Systems*, vol. 11, no. 1, pp. 72–79, 1970.

[10] "Senseg feelscreen development kit." [Online]. Available: http://www.senseg.com/

[11] "Tanvas." [Online]. Available: http://tanvas.co/

[12] J. M. Romano and K. J. Kuchenbecker, "Creating realistic virtual textures from contact acceleration data," *IEEE Transactions on Haptics*, vol. 5, no. 2, pp. 109–119, 2012.

[13] S. Shin, R. H. Osgouei, K.-D. Kim, and S. Choi, "Data-driven modeling of isotropic haptic textures using frequency-decomposed neural networks," in *Proceedings of the IEEE World Haptics Conference (WHC)*, 2015, pp. 131–138.

[14] M. Wiertlewski, D. Leonardis, D. J. Meyer, M. A. Peshkin, and J. E. Colgate, "A high-fidelity surface-haptic device for texture rendering on bare finger," in *Haptics: Neuroscience, Devices, Modeling, and Applications*. Springer, 2014, pp. 241–248.

[15] M. D. R. Minsky, "Computational haptics: The sandpaper system for synthesizing texture for a force-feedback display," Ph.D. dissertation, MIT, June 1995.

[16] G. Robles-De-La-Torre and V. Hayward, "Force can overcome object geometry in the perception of shape through active touch," *Nature*, vol. 412, no. 6845, pp. 445–448, 2001.

[17] D. J. Meyer, M. Peshkin, and J. E. Colgate, "Fingertip friction modulation due to electrostatic attraction," in *Proceedings of the IEEE World Haptics Conference (WHC), 2013*, 2013, pp. 43–48.

[18] E. Vezzoli, M. Amberg, F. Giraud, and B. Lemaire-Semail, "Electrovibration modeling analysis," in *Haptics: Neuroscience, Devices, Modeling, and Applications*. Springer, 2014, pp. 369–376.