Response Surface of Softness Perceived via Frictional Tactile Stimuli on Flat Touch-display

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Abstract: An electrostatic frictional tactile display is used to present softness on a rigid flat-panel display. The display controlled the friction force of a finger sliding on it. However, the effects of representative stimulus parameters, those are, the finger's sliding velocity and wavelength which determined the spatial change of friction on the panel, are unknown, whereas the low-frequency fluctuation of surface friction is known to be important for softness presentation. This study experimentally specified the response surface of subjective softness as a function of the stimulus wavelength and finger's sliding velocity, involving ten participants. Consequently, the response surface was established, with a local maximum at the wavelength and sliding velocity of 10.55 mm and 198.6 mm/s, respectively. This stimulus condition was considered effective for the softness presentation.

Keywords: *Haptics, Softness, Tactile display, Electrostatic force, Friction force*

1. INTRODUCTION

The presentation of softness on a rigid flat-panel display is challenging because the surface touched by the fingers is rigid. Controlling the contact area [1–5] or force [2] between the finger pad and the haptic display device according to the pressing motion of the finger is a general approach for presenting softness. However, these methods are not suitable for flat and hard liquid crystal display panels because their surfaces do not deform. To overcome this difficulty, our research team proposed a method which control frictional forces when a finger slides on hard flat-panel displays to present illusory softness [6, 7].

When a finger slides over an object's surface, the friction force and its fluctuation are affected by the softness of the object [8–11]. Further, when people explore soft objects, they adopt sliding motions as well as the pushing motion [12–14]. Based on the relationship between friction and compliance, our research team controlled the friction force on a flat panel and presented softness perceptions [6, 7]. Electrostatic forces were used to control the friction force and low-frequency fluctuations (approximately 10–20 Hz) of frictional stimuli were perceived as soft [6, 7]. However, the most effective frequency of the fluctuation is unknown. Furthermore, as described in Section 3.3., frequency depends on the sliding velocity of the finger and spatial period of the stimuli. To optimize softness presentation, the effects of these parameters on subjective softness need to be investigated. In this study, as a preliminary step for optimization, the response surface of subjective softness as a function of the spatial period of frictional change and the sliding velocity of the finger was experimentally determined.

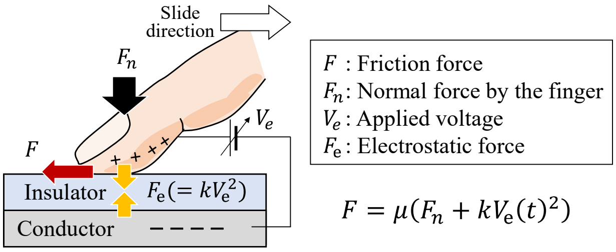

Figure 1: Principle of electrostatic friction force. Adapted from [15].

2. APPARATUS: ELECTROSTATIC FRICTIONAL TACTILE DISPLAY

2.1 Principle: Electrostatic friction force

Figure 1 shows a schematic of the principle of an electrostatic tactile display presenting the frictional force using electrostatic adhesion. The friction force F between a finger and the display is determined by the coefficient of friction μ between them and the finger's normal force F_n. When a finger touches the surface of a conducted display, the electrostatic force F_e attracts the finger skin to the display, leading to an increase in friction.

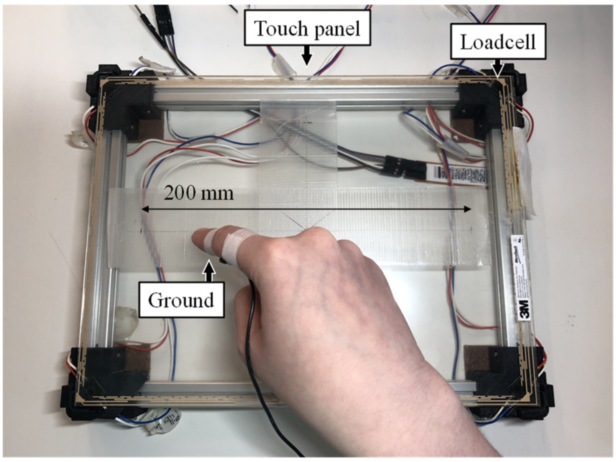

Figure 2: Experimental apparatus.

The relationship between the electrostatic force and the applied voltage is expressed as

$$F_{\mathrm{e}} = kV_{\mathrm{e}}(t)^2, \tag{1}$$

where k is an electrostatic coefficient that depends on the dielectric constant, insulating film thickness, and contact area [16]. Using this relationship, the frictional force is dynamically controlled.

2.2 Hardware

Figure 2 shows the experimental setup and electrostatic frictional tactile display used in the experiment. A load cell (FSS015WNSX, Honeywell International Inc., USA) was placed at each corner of the panel to calculate finger movement. Signals from the load cells were sampled at 250 Hz.

A capacitive touch panel (SCT3250EX, 3M Touch Systems, USA) was modified to present the electrostatic force. The voltage signal to the panel was amplitude-modulated with a carrier frequency of 2 kHz and then conditioned using an amplifier (HJOPS-1B20, Matsusada Precision Inc., Japan). The maximum applied voltage was adjusted for individual participants and ranged from 200 to 300 V. The ground of the panel was attached to the middle phalanx of the index finger using a surgical tape to fully present the electrostatic friction force.

3. EXPERIMENTAL METHODS

3.1 Participants

Ten paid university students (seven males and three females in their 20s) participated in the experiment after providing written informed consent.

3.2 Ethical statement

This study was approved by Institutional Review Board, Hino Campus, Tokyo Metropolitan University (H22-031).

Table 1: Combinations of the wavelength and sliding velocity of the stimuli used in the experiment.

λ (mm)	5.00	7.93	7.93	15.00	15.00	15.00	22.07	22.07	25.00
v (mm/s)	150.0	79.3	220.7	50.0	150.0	250.0	79.3	220.7	150.0

3.3 Stimuli

The voltage level applied to the electrostatic tactile display was determined as follows:

$$V_{\mathrm{e}}(t) = A\sin\left(2\pi\frac{x(t)}{2\lambda}\right) \tag{2}$$

where $x(t)$ is the horizontal position of the finger on the display panel, and λ is the spatial wavelength of the stimulus. A is the gain of the stimulus and was adjusted such that each participant felt the frictional changes satisfactorily.

Five different wavelengths λ and sliding velocities v were selected in order to investigate their effects on the perceived softness based on the central composite design. The ranges of λ and v values were determined through a preliminary experiment involving the authors and their colleagues, such that the most effective parameter set would be included within the ranges. Following the central composite design, the λ values were either 5.0, 7.9, 15.0, 22.1, or 25.0 mm, and the v values were 50.0, 79.3, 150.0, 220.7, or 250.0 mm/s. A total of nine combinations of λ and v were used for the experiment, as listed in Table 1. With these combinations, participants were expected to experience temporal frequencies, that is, v/λ, ranging from 3.3 to 30 Hz on their fingertip.

3.4 Procedures

The participants slid the index finger of their dominant hand along a 200 mm straight line on the surface of the electrostatic tactile display, as shown in Figure 2. The participants controlled their own slide speed with the help of a guide monitor on which a black square moved along a 200 mm horizontal line in a reciprocal manner. The black square moved at five constant velocities (50.0, 79.3, 150.0, 220.7, and 250.0 mm/s), same as v mentioned in Section 3.3. The participants were instructed to keep their finger motion synchronized with the black square displayed on the guide monitor.

Stimuli of five different wavelengths (5.0, 7.9, 15.0, 22.1, and 25.0 mm) were presented to the participants as they slid their fingers on the display. The combinations of λ and v were selected from Table 1 in a randomized order.

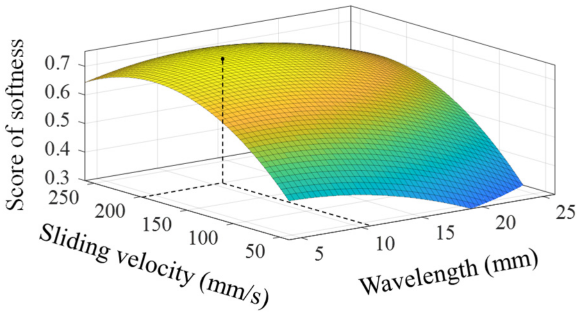

Figure 3: Response surface approximated from the experimental results. The dot plotted on the surface is the local maximum point on the surface (λ = 10.55 mm, $v =$ 198.6 mm/s). Mean value of each of the nine stimuli conditions were used for the computation.

Table 2: Constants of response surface.

a_{20}	a_{11}	a_{02}	a_{10}	a_{01}	a_{00}
-6.48×10^{-4}	5.26×10^{-5}	-1.38×10^{-5}	3.54×10^{-3}	4.91×10^{-3}	0.282

Each combination of λ and v was presented twice for each individual participant. Hence, 18 trials (9 stimulus combinations × 2 repetitions) were performed for each. After each trial, the participants scored the stimulus using a 10-graded scale ranging from 0 (as hard as a glass panel) to 9 (soft) to indicate how soft the surface felt. The participants were asked, "How soft was the surface?" A score of 0 was defined as the hardness of the glass touch panel without an electrostatic stimulus applied. If the surface felt softer than that at a score of 0, the participants scored it 1 or greater. The participants experienced the stimulus repeatedly in each trial until they were confident in the score.

Prior to the main experiment, participants completed a practice session. They experienced each stimulus combination once during the practice session. The experiment took at most 30 min, including instruction and practice. A break was taken if required. A pink noise was played through a headset during the experiment.

3.5 Analysis

The scores for the nine stimulus combinations were normalized within participants by dividing the raw scores by the highest score. Using the mean of the nine normalized scores among the participants, a response surface was computed with λ and v being the explanatory variables and the softness scores (z) being the objective variable by using the least-squares method. A total of nine mean values were used to determine the response surface. The model of the response surface is as follows:

$$z = a_{20}\lambda^2 + a_{11}\lambda v + a_{02}v^2 + a_{10}\lambda + a_{01}v + a_{00} \quad (3)$$

where a_{20}, a_{11}, a_{02}, a_{10}, a_{01}, and a_{00} are the coefficients of their respective terms.

4. RESULTS

The combination of λ and v with the highest mean softness score was λ = 7.93 mm and $v =$ 220.7 mm/s. The approximated response surface is shown in Figure 3, and the constants are listed in Table 2. The adjusted coefficient of determination for the response surface was $R^2 = 0.81$. The local maximum value of the response surface was at λ = 10.55 mm and $v =$ 198.6 mm/s.

5. DISSCUSSIONS

The response surface exhibited the highest score of softness at λ = 10.55 mm and $v =$ 198.6 mm/s, and the score decreased as the distance from this point increased, as shown in Figure 3. A verification experiment is required to determine whether this stimulus combination is felt softer than the other combinations.

According to the response surface, as the v values change, the λ values for achieving the highest softness values also change. For instance, for $v =$ 50.0, 150.0 and 250.0 mm/s, the response surface exhibited maximums at λ = 4.35, 8.52, and 12.70 mm, respectively. The frequency of friction can be simplified as $f = v/\lambda$, and the corresponding frequencies are 11.5, 17.6, and 19.7 Hz, respectively. At the maximum softness score, that is, λ = 10.55 mm and $v =$ 198.6 mm/s, the frequency is 18.5 Hz. Hence, the effective frequency of frictional stimuli for softness presentation may lie between 10 and 20 Hz, aligning with earlier studies [6, 7].

As a limitation of the experimental protocol, the concept of softness was not precisely defined, and the participants could have had different images of softness. Cavdan et al. [17] suggested four types of different softness perceived by humans. This may have resulted in a greater deviation in participants' answers.

6. CONCLUSION

In this study, to investigate the effects of stimulus parameters on the softness experienced when sliding a finger on an electrostatic friction panel, the response surface of the subjective softness as a function of the surface wavelength and finger's sliding speed was experimentally specified. The response surface exhibited the local maximum at λ = 10.55 mm and $v =$ 198.6 mm/s, which generated a frictional fluctuation of 18.5 Hz. Future studies should optimize the parameters for softness presentation and investigate why such parameters effectively evoke subjective softness.

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