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A Texture Display Using Vibrotactile and Electrostatic Friction Stimuli Surpasses One Based on Either Type of Stimulus

Ken Ito*, Shogo Okamoto*, Hatem Elfekey*, Hiroyuki Kajimto†, and Yoji Yamada*
*Department of Mechanical Science and Engineering, Nagoya University, Nagoya, Japan
†Department of Informatics, The University of Electro-Communications, Tokyo, Japan

***Abstract*—This study demonstrates that the simultaneous use of two types of representative principles for tactile texture displays, vibrotactile and electrostatic friction stimulation surpasses either type of stimulation. We used a set of sinusoidal grating scales with different surface spatial periods as simulated textured surfaces for testing the quality of texture displays. Experimental participants judged the best stimulus condition among the vibrotactile, electrostatic friction, and the conjunctive stimuli in terms of the reality perceived from the simulated texture stimuli. The use of vibrotactile and electrostatic stimuli in conjunction was judged to be the most realistic for the spatial periods of 1 and 2 mm, whereas noticeable differences among the three stimuli conditions were not reported for small spatial periods of 0.2 and 0.5 mm. The simultaneous use is effective for simulating the surfaces with middle-level asperity.**

I. INTRODUCTION

In the wake of the proliferation of touch panel interfaces for personal use, vibrotactile feedback techniques have been intensively studied to compensate for the lack of haptic sensation and to improve their usability. Thus far, many studies have demonstrated that vibrotactile feedback for actions such as button-pushing, dialing, sliding, and flicking [1], [2], [3] improves the usability of touch panel interfaces.

Unlike these successful vibrotactile feedback techniques for operative motions, the feedback techniques for surface textures still require technical progress. The main drawback of texture feedback is believed to be the lack of perceptual dimensions that the vibrotactile feedback can provide. In general, vibrotactile feedback excels at presenting roughness sensations [4], [5], [6], whereas some studies have devised supplementary techniques for friction and softness sensations [7], [8], [9], [10]. Roughness, friction, softness, and temperature constitute the perception of texture [11], and the vibrotactile roughness feedback combined with friction and softness/hardness cues can effectively present simulated materials [8], [12].

Ultimately, tactile texture displays should be able to simultaneously present roughness, friction, softness, and temperature stimuli. However, it is demanding to equip flat, rigid, and transparent touch panels with capabilities to present softness and temperature stimuli. Therefore, by combining vibrotactile and electrostatic friction stimuli that are suitable for touch panels, we have been developing tactile texture display to cover roughness and friction sensations [13]. The principles of each type of stimuli are described in section II. Thus far, no studies have attempted to combine the two types of stimuli for quality tactile textures. One study reported a tactile display that could deliver both types of stimulus [14] where the vibrotactile and friction stimuli were used for separately presenting fine texture and macroscopic geometry, respectively.

TABLE I
COMPLEMENTARY CHARACTERISTICS OF VIBROTACTILE AND ELECTROSTATIC TACTILE TEXTURE DISPLAYS.

	Vibrotactile	Electrostatic
Target texture	Surface roughness	Variable friction
Energy type	Active	Passive
Finger deformation	Normal direction	Shear direction

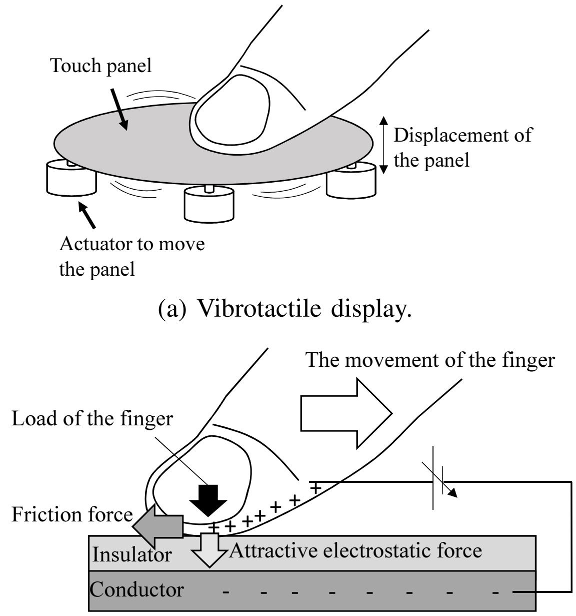
In the present study, through experiments to evaluate subjective experiences, we demonstrate that the texture display using vibrotactile and electrostatic friction stimuli in conjunction presents better quality textures than texture displays using either type of stimuli. We use grating scales with periodic surface patterns as testbeds. In our former study [13] using the grating scale with a spatial period of 3 mm, the combined tactile stimuli were superior to either type of stimuli in terms of perceived reality. However, it is still unknown whether the combined tactile stimuli are effective for finer textures for which the surface spatial period is lower than 3 mm. For acquiring further general conclusions, in the present study, we experimentally examine the effects of vibrotactile and electrostatic friction displays for fine textured surfaces.

II. PRINCIPLES OF VIBRO- AND ELECTROSTATIC TACTILE DISPLAY

We focused on two types of texture presenting mechanisms which are suitable for touch panels. These two have complementary characteristics and are summarized in Table I.

A. Vibrotactile display

Fig. 1(a) shows the mechanism of vibrotactile display. This tactile display presents tactile stimuli by actively deforming the finger pad in the normal direction by using actuators such as voice coil motors or piezoelectric actuators. Thus, the vibrotactile display actively stimulates the finger pad and does not require relative displacement in the tangential direction between the finger pad and the panel.



(a) Vibrotactile display.

(b) Electrostatic tactile display.

Fig. 1. Principles of vibrotactile and electrostatic tactile displays.

In terms of textures, generally, this type of display is good at presenting fine surface roughness [4], [5], [6], [15]. However, when it comes to the presentation of geometry or a macroscopically rough surface, the vibration feels unnatural. Although the vibrotactile display can present roughness textures without hand motion of the user [16], a stimulation method synchronized with the hand motion is more effective [4], [5], [6]. These general characteristics of vibrotactile texture display are summarized in Table I.

B. Electrostatic tactile display

Fig. 1(b) shows the mechanism of electrostatic display. It manipulates the friction between the finger pad and touch panel. The friction force can be varied by controlling the attractive electrostatic force which is induced by the applied voltage between the finger pad and conductor. The change in the friction force influences the tangential deformation of the skin. The finger stroking-motion is necessary for the user to experience the feedback from the display. According to this aspect, the electrostatic friction display is a passive-type tactile display.

In terms of textures, generally, this type of display is good at presenting textures with low surface roughness but having friction [17], [18] and geometry or a macroscopically rough surface [13], [19]. The characteristics of electrostatic friction display are summarized in Table I.

III. Integrated texture display using Vibrotactile and electrostatic stimuli

Fig. 2 shows the tactile display developed in this and our previous studies [13]. This display presents vibrotactile and electrostatic stimuli simultaneously. As previously mentioned, the conjunction of vibrotactile and friction stimuli is practically reasonable, provided that this technique is intended for popular information terminals, such as touch panels. There are various methods for the implementation of the two types of stimuli. In the present study, because it is a laboratory prototype, we used actuators and amplifiers that could deliver output stimuli large enough when compared to the perceptual threshold levels.

Vibrotactile stimuli were produced by four voice coil actuators (X-1741, Neomax Engineering Co. Ltd., Japan) located at the four corners of the top panel. The four actuators were synchronously driven by a current amplifier (ADS 50/5, Maxon Motor AG, Switzerland). Therefore, mechanical vibratory stimuli were produced along the normal to the top panel.

In Fig.2 (a), a voltage (V_e) is applied between the Indium Tin Oxide (ITO) panel layer and the conductor. Consequently, an electric force is generated between the ITO layer and the conductor. In doing so, an electrostatic stimulus was applied. An insulator (Kimotect PA8X, KIMOTO Co. Ltd., Japan, 8 μm) was fixed on the Indium Tin Oxide (ITO) plate. The voltage V_e was driven by a high-voltage amplifier (HJOPS-1B20, Matsusada Precision Inc., Japan).

A load cell (FS2050-0000-1500-G, TE Connectivity, Switzerland) was affixed beneath each voice coil motor. The center of the force on the panel was calculated at 1 kHz by using the four load cells and regarded as the finger position on the panel. Thus, the position and velocity of the finger were detected by the load cells.

The two amplifiers and four load cells were connected to a data acquisition board (TNS-6812, Interface Corporation, Japan) which was connected to a PC.

Our display presents tactile stimuli based on the position and velocity of the finger through the pad. Without finger movement, this display does not present tactile stimuli. The pad with a conductor film was introduced to qualify the frictional forces of the panel.

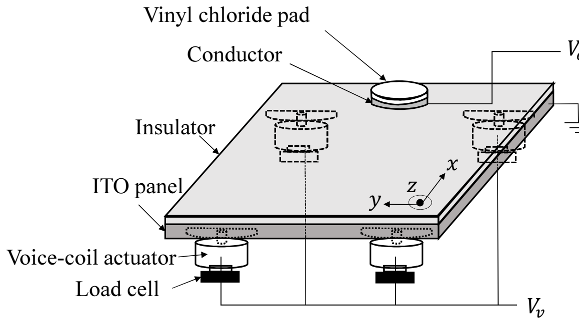
IV. Experiment: Comparison of reality perceived by tactile stimuli

A. Design and justification

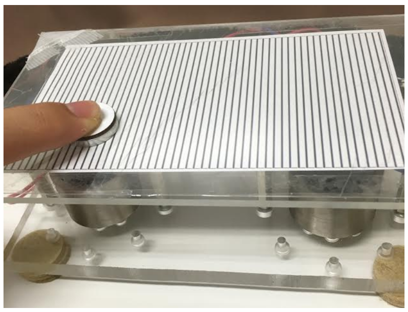
To evaluate the reality of simulated textures, a ranking task was selected because it is suitable for proving that a stimulus is more realistic than the other stimuli. Simple sinusoidal grating scales were selected for the evaluation because the grating scale has been used in a lot of research. It should be noted that additional experiments are necessary for coming to conclusions about the other types of textures.

B. Ranking task

Participants experienced three types of stimuli (1. combination of vibrotactile and electrostatic, 2. vibrotactile only, and 3. electrostatic only) through the pad and the grating scale with a round tube shown in Fig. 3. They were instructed to rank the three stimuli in the order of reality. Tie ranks were permitted. If a participant ranked a stimulus as first, the stimulus was perceived to match the specimen the most. They



(a) Schematic view of the structure.



(b) Photograph of the display. A picture of a grating scale is displaced beneath the transparent top panel.

Fig. 2. Overall structure of the tactile display for vibrotactile and electrostatic friction stimuli

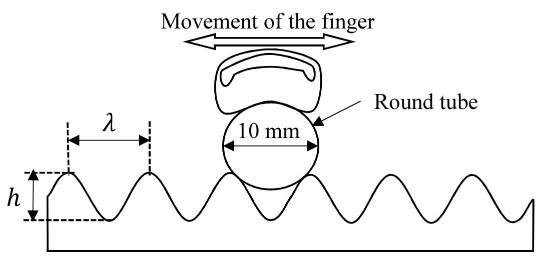


Fig. 3. Sinusoidal grating scale. Participants experienced the grating scale with the round tube.

could change the stimuli when they wanted and experience the three stimuli and specimen as many times as they wanted. They were instructed to move their finger at a normal speed (approximately 15 cm/s). The same tasks were repeated under each condition for four wave lengths.

C. Participants

Six volunteers (all students, non-experts, right handed, with an average age of 23.3) participated in this experiment. They were not informed about the objective of the research. They were ascertained that they can perceive stimuli or not before the experiment.

D. Sinusoidal grating scale (actual texture)

Fig. 3 shows an image of the sinusoidal grating scale, which was the actual target texture. Participants experienced it using the round tube shown in Fig. 3 because our display could not

TABLE II
λ AND h VALUES OF GRATING SCALE. λ AND h WERE SPACIAL WAVE LENGTHS AND HEIGHTS FROM THE BOTTOM OF THE GRATING SCALES.

λ [mm]	h [mm]
0.2	0.2
0.5	0.5
1.0	2.0
2.0	4.0

present the spatial deformation on the finger pad. The shape was a sinusoidal wave which was determined by λ and h shown in Fig. 3. Table II presents four combinations of λ and h. Four grating scales of each combination were prepared. A similar experiment was performed under the condition of $\lambda = 3$ mm in our previous research [13]. Thus, we selected four spatial wave lengths λ, which were each smaller than 3 mm. The values of h were large enough so that the round tube did not reach the bottom.

E. Roughness texture stimuli

We used the vibrotactile and electrostatic roughness texture stimuli of the grating scale. The presentation algorithm for each stimulus was the same as that used in numerous earlier studies.

1) Simulated vibrotactile texture: We used the presentation algorithm that had been already reported [6], [8], [20]. When the finger pad experiences the sinusoidal grating scale, deformation of the finger pad occurs. This deformation is a sinusoidal wave of the same amplitude and frequency as the experienced grating scale. Thus, the driving force F_v in the normal direction for vibrotactile stimulus was determined by

$$F_{\mathrm{v}}(t) = A \sin 2\pi \frac{x(t)}{\lambda} \tag{1}$$

where $x(t)$ and A are the position of the finger pad on the panel and maximum force respectively. This force causes the finger pad to deform in coordination with the finger motion, which is known to be effective in presenting surface roughness [6], [8], [20].

2) Texture stimulus by electrostatic stimuli: When the finger moves up the surface of the grating scale, the friction force becomes higher. When the finger moves down the surface of the grating scale, the friction force becomes lower. Hence, the phases of the stimuli for surface displacement and friction were separated by $\pi/2$ [21], [22]. Thus, the applied voltage for electrostatic was determined by

$$V_{\mathrm{e}}(t) = B \cos 2\pi \frac{x(t)}{2\lambda} \tag{2}$$

where B is the maximum value of the voltage. From the law of the static electricity attraction force and friction force, the friction force between the finger pad and panel was determined by

TABLE III

MAXIMUM DRIVING FORCE F_v AND ELECTROSTATIC FRICTION FORCE F_e

	Combination		Vib. only	Elec. only
λ [mm]	F_v [N]	F_e [N]	F_v [N]	F_e [N]
0.2	1.69	0.70	2.01	0.80
0.5	1.78	0.84	2.19	0.91
1.0	1.90	0.88	2.25	0.95
2.0	2.01	0.99	2.35	1.08

$$F_e(t) = \mu\left\{W + kV_e^2(t)\right\} \quad (3)$$

$$= \mu\left\{W + \frac{kB^2}{2}(1+\cos 2\pi\frac{x(t)}{\lambda})\right\} \quad (4)$$

where μ, W, and k are the coefficient of friction, load of the finger, and constant involving the electrostatic force, respectively. The first member of (3), which is W, expresses the load of the finger, and the second member expresses the electricity attraction force; k mainly depends on the area of the electrode, the relative dielectric constant of the insulator, and thickness of the insulator.

3) Texture simulated by vibrotactile and electrostatic friction stimuli: This type of texture stimulus was designed based on the combination of vibrotactile and electrostatic stimuli.

4) Perceived magnitude of simulated textures: The gain parameters A and B in (1) and (2), respectively, partly determine the magnitude of perceived textures. Hence, they should be carefully adjusted. The direct measurement of normal and shear forces when a finger slided on a grating scale was one of options to adjust gains, however, it is very sensitive and depends on the environment of the measurement. Thus, the experimenters determined these parameters manually such that the simulated textures felt close to the actual grating scale for each λ value. As a result, the three types of perceived strengths of texture stimuli were the same under the condition of each spatial wave length λ.

The maximum generative forces F_e and F_v are listed in Table III. The ranges for F_e were evaluated under the onset of a pressing force W of 1 N. The intensity of the combination of the two stimuli was lower than the intensity of each single stimulus as a result of tuning by experimenters.

V. RESULTS

Fig. 4 shows the experimental results. Each graph shows the ranks assigned to each stimulus condition by individual participants under each condition of the four spatial wave lengths.

For an overall analysis, we conducted ANOVA on the number of times that each simulated texture was ranked first. The analysis conducted was a two-way ANOVA involving the type of simulated stimulus and λ value as the two factors. The type of stimulus was found to be significant in influencing the most favored stimulus ($F_0(2,6) = 5.14$, $p < 0.01$).

For each λ value, we used the Wilcoxon rank sum test to evaluate the priority of the combination stimulus. There were significant differences between the combination stimulus and vibrotactile stimulus under the conditions of wave length λ = 1.0 and 2.0 mm. As an overall trend, the smaller the wave length of the grating scale, the smaller is the difference between each stimulus. The results for each λ value are described below.

A. λ = 0.2 mm

For the stimuli with λ 0.2 = mm, every stimulus was ranked first at least once. There were no significant differences.

B. λ = 0.5 mm

For the stimuli with λ 0.5 = mm, every stimulus was ranked first at least once, the same as λ = 0.2 mm. There were no significant differences. The combination stimulus was ranked first the most.

C. λ = 1.0 mm

For the stimuli with λ 1.0 = mm, there was a significant difference between the combination stimulus and vibrotactile stimulus. However, there was no significant difference between the combination stimulus and vibrotactile stimulus. The vibrotactile stimulus was not ranked first and the ranks that were assigned to the electrostatic friction stimulus were divided into two.

D. λ = 2.0 mm

For the stimuli with λ 2.0 = mm, there was a significant difference between the combination stimulus and vibrotactile stimulus. However, there was no significant difference between the combination stimulus and electrostatic friction stimulus.

VI. DISCUSSION

Although we had expected the conjunction of two types of stimuli to be more effective across wide λ values than the individual stimuli, in our experiments, the superiority of tactile stimuli depended on the fineness of the surface roughness. When the surface was fine with λ values being 0.2 – 0.5 mm, the superiority was opaque. In contrast, for a coarser surface roughness with λ values greater than 1 mm, the stimuli combining the vibrotactile and electrostatic friction stimuli exhibited a better performance than either the vibrotactile or electrostatic friction stimuli. The reasons explaining such results are discussed below.

A. Fine roughness textures are well presented by either vibrotactile or electrostatic friction displays

For fine surface roughness with $\lambda <$ 1 mm, the roughness perception is largely mediated by skin vibration caused in scanning the surface [15]. Both the vibrotactile and electrostatic friction stimuli are good at presenting vibratory stimulus. One speculation is that the skin vibration derived from surface displacement and that derived from friction are perceptually close for fine roughness. Consequently, two types of tactile stimuli are equally capable of presenting fine roughness textures.

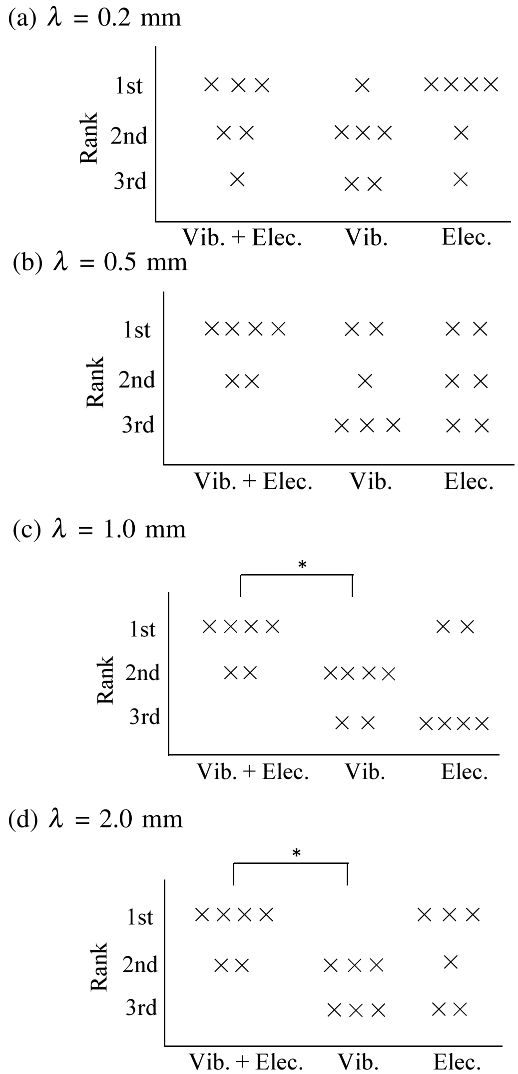


Fig. 4. Experimental results. Frequencies of ranks for each stimulus. $*$ indicates $p < 0.05$.

B. *Texture displays using vibrotactile and electrostatic friction stimuli in conjunction are superior to those based on either type of stimulus*

When $\lambda = 1.0$ and 2.0 mm, the stimulus combining the two types of stimuli was judged better than the individual vibrotactile stimuli. In our previous report [13], the combined stimuli were better than single types of stimulus when $\lambda = 3.0$ mm. Collectively, the combination of the two types of stimuli is effective when $\lambda = 1-3$ mm. The perception of coarse surfaces with such λ values is mediated by spatially distributed cues, rather than skin vibration [11]. An intuitive explanation of these results is as follows. Only with the vibrotactile stimulation, is the friction associated with surface roughness missing, whereas the information on surface displacement is delivered. In contrast, the electrostatic friction stimulation lacks the information on surface displacement. Actual textures involve both surface displacement and friction. The combination of friction and surface displacement presented spatial cues such as the friction field on the surface and might have enhanced the perceived reality of textures in our experiments.

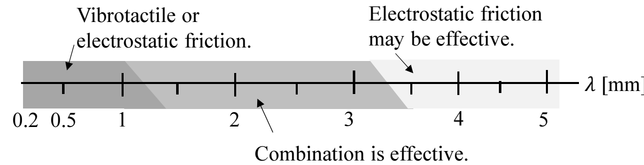


Fig. 5. Type of tactile stimuli that deliver natural texture feelings. For λ smaller than 1 mm, either of vibrotactile or electrostatic friction stimuli is satisfactory. For λ of 1–3 mm, the combined stimulus is superior. For $\lambda >$ 3 mm, electrostatic friction stimuli may be better.

Fig. 5 shows the summary of the present and our past studies [13]. For grating scales with $\lambda = 0.2-0.5$ mm, either vibrotactile or electrostatic friction display is effective. For those with $\lambda = 1-3$ mm, the display combining the two types of stimuli is recommended. Regarding much lower or higher λ values, further studies are necessary; however, our prediction is as follows. For greater λ values, both types of stimuli are not effective because the surfaces have macroscopically distributed information, for which texture displays are no longer effective. Nonetheless, electrostatic friction stimuli may be still better [18] than vibrotactile stimuli. For λ values lower than 0.2 mm, the methods used in the present study may not be effective because the resultant temporal frequencies of the stimuli easily overcome the rendering capability of the computer.

VII. Conclusion

To improve the quality of textures presented by a tactile display, we combined two complementary types of texture presenting methods, vibrotactile and electrostatic displays. We prepared grating scales with four different wave lengths and presented virtual texture of those wave lengths. As the result of a ranking task, there were no significant differences in the small wave-length conditions, but there was a significant difference between combination and vibrotactile stimuli in the long wave length conditions. Therefore, we proposed an effective stimulus presenting method under each wave length.

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