# Surface Texture Display Combining Friction and Vibrotactile Stimuli for Realistic Natural Materials

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***Abstract*—Surface tactile displays are touch panel interfaces capable of presenting tactile sensations. Typically, these systems implement either electrostatic friction stimuli or vibrotactile stimuli. In this study, we investigated the advantages of simultaneously presenting both types of stimuli using virtual textures modeled after natural materials. In the experiment, four types of natural material textures—fabric, wallpaper, woven straw, and artificial grass—were virtually rendered and presented to participants. Ten participants compared three virtual stimulation conditions presented in random order: electrostatic friction only, vibrotactile only, and a combined stimulation. The results showed that the combined stimulation was consistently rated as more realistic than either single modality alone. This finding contributes to the development of surface texture displays with high realism.**

***Index Terms*—Surface texture display, Vibrotactile stimuli, Electrostatic stimuli**

## I. Introduction

A surface tactile display is a touch panel interface capable of presenting tactile stimuli [1]. Previous studies have mainly adopted either variable friction stimulation [2], [3] or vibrotactile stimulation for this type of interface. Both types of stimulation can be combined in one device [4]–[8]. Variable friction stimulation creates tactile sensations by controlling the distribution of friction on the panel surface, while vibrotactile stimulation mechanically actuates the panel to deform the skin on the finger, thus providing haptic feedback.

This study focuses on the realism of tactile textures rendered by surface tactile displays. Prior research has demonstrated that combining both types of stimulation can enhance the perceived realism of virtual grating textures, which are characterized by regular roughness patterns [5], [6]. However, the effects of combined stimulation on natural-like textures remain unclear.

Therefore, in this study, we generated four types of natural-like textures under three stimulation conditions: combined stimulation, friction-only, and vibrotactile-only. The virtual texture stimuli were created based on contact force profiles recorded during the exploration of real natural-like textures. The results of this experiment contribute to the development of techniques for generating more realistic virtual textures.

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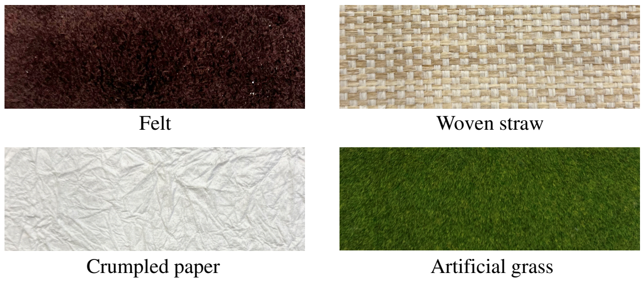


Fig. 1. Natural materials tested in the experiment.

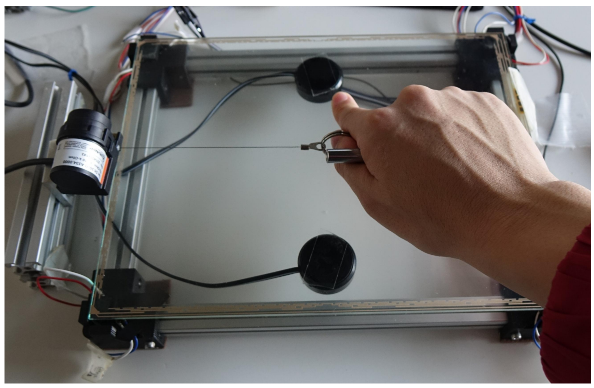

Fig. 2. Surface texture display used in this study.

## II. Methods

### A. Textural Data

The natural material textures used in this experiment were fabric, wallpaper, woven straw, and artificial grass, as shown in Fig. 1. During the exploration of these textures using fingers, tangential and normal forces, as well as finger motion, were measured using a custom-built two-axis force measurement device developed by our group [9], with a sampling frequency of 2 kHz. This device enabled precise measurement of kinetic information by integrating high-precision crystal force sensors and encoders. From the collected data, we extracted five continuous segments of 300 ms each (600 data points per segment at 2 kHz) in which the finger moved at a velocity of 75–125 mm/s [10]. In total, 3000 data points were used as the contact force data for stimulus presentation.

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### B. Apparatus

The tactile display used in this experiment is shown in Fig. 2. The system consisted of an ITO panel (SCT3260, 3M Touch Systems, Inc., MA, USA), an encoder (A30, Fritz Kübler GmbH, Germany), and vibration speakers (TAFU001, TafuOn, Inc., Japan).

Electrostatic friction stimuli were presented by controlling the voltage applied between the user's finger and the insulated surface of the ITO panel. Vibrotactile stimuli were delivered by two vibration speakers mounted at the central edge on the back of the panel, causing it to vibrate vertically. Finger movement along left-right direction (x-direction) during exploration was recorded by having participants wear a ring attached to a string connected to the encoder.

### C. Stimuli

The tangential friction force generated during exploration with the surface tactile display was modeled as follows:

$$F_e(x) = \mu\{W + kV^2(x)\}, \tag{1}$$

$$V(x) = \pm\alpha\sqrt{f_s(x)}, \tag{2}$$

where $\mu$ is the coefficient of friction, $W$ is the finger load, and $k$ is the electrostatic force constant. The parameter $\alpha$ represents the voltage gain, which was individually adjusted for each participant, and $f_s(x)$ denotes the pre-recorded tangential resistance at position $x$ for each material.

To generate normal-direction vibrations during exploration, the voltage input $F_v$ to the vibration speaker was determined by:

$$F_v(x) = \beta f_v(x), \tag{3}$$

where $\beta$ is the amplitude gain individually adjusted for each participant, and $f_v(x)$ is the pre-recorded normal contact force at position $x$ for each material.

For the combined stimulation condition, both stimuli defined above were presented simultaneously. In this case, the voltage amplitudes of both stimuli were reduced to 80% of their individually adjusted values to ensure that the overall intensity was comparable to the single-stimulus conditions.

### D. Procedures

Participants compared the realism of virtual textures under three stimulation conditions by ranking them alongside the corresponding real natural texture. Realism has frequently been used as a metric for evaluating the quality of virtual textures [11]–[13]. The ranking task was forced-choice: participants were required to assign a unique rank to each stimulus from first to third place, with no duplicated ranks allowed. During each trial, participants were permitted to freely explore both the virtual stimuli and the natural texture as many times as they wanted.

Throughout the experiment, participants wore headphones playing pink noise to mask auditory cues. The exploration speed was restricted to 75–125 mm/s; if the finger moved outside this range, the stimulus was not presented. For each material, the ranking task was repeated twice, resulting in a total of eight trials (four texture types × two repetitions).

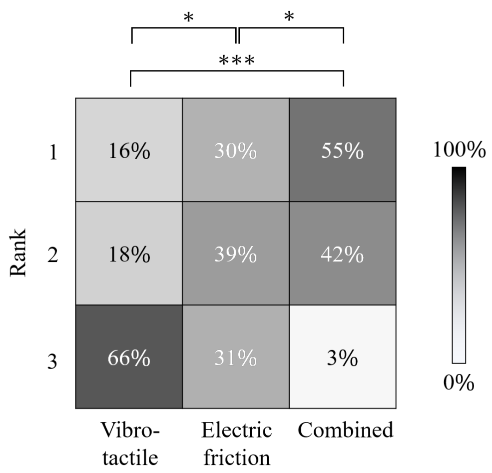


Fig. 3. Proportions of the ranks of the three types of stimuli (vibrotactile, electrostatic, and combined stimuli) across all natural materials. * and *** indicates $p < 0.05$ and $p < 0.001$, respectively.

### E. Participants

Ten university students (two females and 8 males aged 22–25 years old) participated in the study after providing a written informed consent.

### F. Data Analysis

For each material, one of the two responses from each participant was randomly selected for analysis. If the three stimulation conditions were ranked randomly, the probability that any one condition would be ranked higher than another by chance would be 0.5—that is, the chance level. Therefore, we tested whether the proportion of trials in which one condition was preferred over another exceeded 0.5 using tests of proportion.

## III. Results

Fig. 3 shows the distribution of realism rankings for each stimulus condition across all materials. The proportion of trials in which the combined stimulation was ranked as more realistic than the vibrotactile stimulation was 0.84, which was significantly greater than chance (0.5) ($z$-test, $z = 4.21$, $p < 0.001$). Similarly, the combined stimulation was ranked higher than the electrostatic friction stimulation in 68% of trials, also significantly above chance ($z$-test, $z = 2.27$, $p < 0.05$). Additionally, the electrostatic friction stimulation was ranked higher than the vibrotactile stimulation in 63% of trials, which was significantly greater than chance ($z$-test, $z = 2.52$, $p < 0.05$).

## IV. Discussion

The results indicate that among the three stimulation methods, the combined presentation of electrostatic friction and vibrotactile stimuli was rated as the most realistic, which is in agreement with previous studies using gratings [5], [6]. This suggests that presenting both types of stimuli together provides a richer array of texture information than either stimulus alone.

The effectiveness of combined stimuli may depend on the material properties. Both friction and vibrotactile stimuli are particularly effective for presenting textures characterized by fine roughness [14], [15]. Therefore, for such textures, there may be limited potential for the combined stimulation to further enhance realism. In contrast, the presentation of macroscopic shapes such as bumps is a characteristic feature of friction-variable displays [4], [16]–[19]. Hence, using the two types of stimuli for separate purposes may be an effective approach. In addition, there is currently no established method for conveying softness using surface tactile displays [20], [21]. Accurately presenting the realistic feel of soft materials remains challenging, and the impact of combined stimulation on these materials remains to be studied. Future research should more closely examine which types of textures can benefit most from combined stimulation in terms of perceived realism.

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