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Vibrotactile Stimulation to Increase and Decrease Texture Roughness

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***Abstract*—We have developed a texture display system that modifies the perceived roughness of textured surfaces via a voice coil actuator worn on the finger. To increase the roughness sensations, the vibrotactile stimuli from the actuator simulate the skin deformations that are activated when a wavy surface is scanned. Conversely, to decrease the roughness sensations of the textured surface, a high-frequency vibrotactile stimulus offsets the activity levels of tactile mechanoreceptors. This offset suppresses the perceived roughness of the surfaces being touched, with increase in the offset correlating with increase in the feeling of smoothness of the surfaces. We conducted an experiment in which we tested the effects of these two types of vibrotactile stimulation on grating roughness specimens, with subjective responses acquired from eight participants via the magnitude estimation method. The results obtained indicate that our method selectively increases and decreases the roughness felt. The intention is for the technique to be used to develop an augmented reality device for textures.**

***Index Terms*—Augmented reality, haptic device, mechanoreceptors, roughness, texture, vibrotactile stimulation.**

I. Introduction

Tactile interfaces could include capabilities to vary the perceived mechanical properties of the objects including perceived texture. Vibrotactile stimuli, which are generated by stimulators worn on the finger or installed on the surfaces to be touched by the finger pad, enhance the roughness percepts of material surfaces [1]–[3]. Such stimuli should be synchronized with hand motions to present sensations that match those experienced during natural active touch. Electrostatic forces that arise between the human body and the surface of an object have been used to modify surface texture [4]. Furthermore, noisy sounds associated with touch motions can effectively influence the roughness percepts of materials [5], [6].

Prior methods exert additional sounds or mechanical energy on humans in order to increase the roughness percepts of touched surfaces. However, decreasing the roughness percepts is more challenging. Although Guest *et al.* [2] demonstrated that the attenuation of the sounds caused by touch suppresses the perceived roughness, methods to control the reduction of the roughness percepts are limited. In addition, because the squeeze effect caused by ultrasonic vibrations can reduce the surface friction of elastic bodies [7]–[11], such an effect may lead to a reduction in the sense of surface roughness. However, this approach is used for surfaces whose frequency response characters are carefully designed and are not suited to changing textures such as thick cloth and wood.

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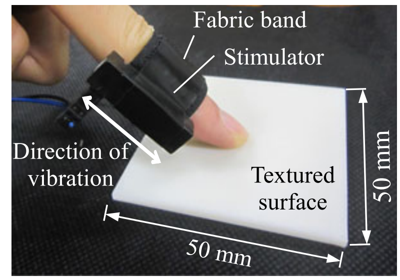

Fig. 1. Index finger mounted with vibrotactile stimulator.

In this paper, we discuss the development of a wearable texture display technique that can alter the perceived roughness of surfaces when they are touched by the wearer. Since the device is installed on the human body, the technique does not require any modification of the materials or objects being touched. The study presented here builds on [12], in which we verified the ability of vibrotactile stimulus to decrease the roughness percept. Here, we also use a vibrotactile stimulus to increase the roughness percepts and include two types of textured samples with different roughness levels. These conditions curtailed any risks of artifact or conditioning by experimenters' instructions. Consequently, our results show that vibrotactile stimuli can increase and decrease the roughness texture of materials in a single experimental paradigm. The long-term goal is for the technique to be used in a new type of vibrotactile texture display.

II. Experiment

The Ethical Committee of the Engineering School at Nagoya University approved this study.

A. Apparatus

The apparatus included a recoil-type voice coil motor (Haptuator Mark II, Mr. Amir Berrezag, UPMC, France) driven by a current amplifier (ACJ-090-03, Copley Controls, MA, USA) through a fabric band placed between the DIP and PIP joints of the index finger of the participant's writing hand, as shown in Fig. 1. The motor was affixed to the band using double-sided tape and generated accelerations along the longitudinal direction of the finger with a refresh rate of 5 kHz.

Fig. 2 shows the experimental setup, in which a camera (PlayStation Eye, Sony Computer Entertainment, 30 ft/s, 320 × 240 px) measured the position of the marker on each participant's finger. The measured position was used for the vibrotactile stimulation method to increase the roughness percepts. The spatial (0.625 mm) and temporal resolutions of the camera were not appropriate for texture display; therefore, we calculated the finger position by integrating the finger velocity at

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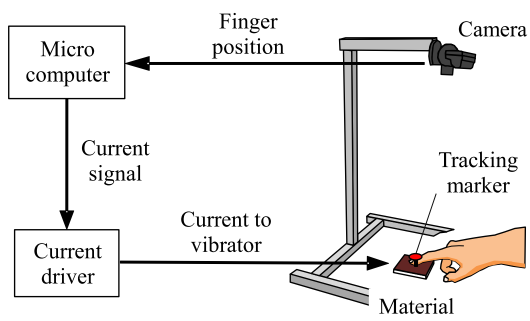

Fig. 2. Signal flow in the experimental setup.

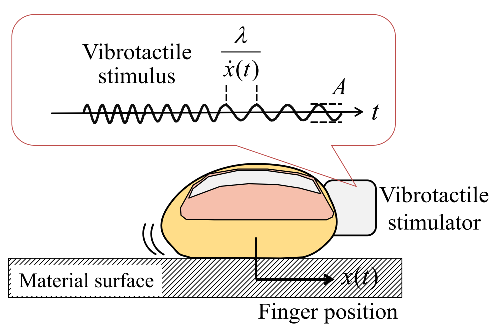

Fig. 3. Presentation of fine roughness using sinusoidal vibrotactile stimuli to finger pad.

5 kHz to generate its smooth displacement without directly referring to the position measured by the camera. In this case, the position measurement accumulated absolute errors. The velocity was calculated using a Savitzky–Golay filter of length five [13].

B. Vibrotactile Stimuli to Increase and Decrease Perceived Roughness of Textured Surfaces

1) Virtual Wavy Stimulus Synchronized With Hand Motions to Increase Roughness Percept: To increase the roughness percepts of textured surfaces, we used the virtual wavy surface method that was originally introduced for the presentation of virtual roughness [14], [15], and later applied to real surfaces [4]. In this method, a mechanical displacement is applied to the finger pad to simulate or mimic the displacements experienced when scanning a wavy profile. This method allows the support of percepts related to fine roughness as that possessed by some cloths and abrasive papers.

Fig. 3 shows the scheme utilized in this roughness presentation method. The sinusoidal vibratory stimuli are generated by the voice coil actuator attached to the finger according to the finger position estimated using a camera. The voltage instruction to the voice coil motor was determined by

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

where A, $x(t)$, and λ are the voltage amplitude, planar displacement of the finger on the textured surface, and the surface wavelength of the virtual wavy profile, respectively. λ was fixed to 1.0 mm in the latter experiment. The instantaneous vibratory frequency is equal to $\dot{x}(t)/\lambda$. As a result of the dynamics of the recoil-type voice coil motor, the acceleration values became virtually flat above 200 Hz, but decayed beneath several tens of Hertz with the resonance at approximately 100 Hz. We used several values of A to test some acceleration levels. The larger accelerations evoked the larger roughness percepts.

2) High-Frequency Vibrotactile Stimuli to Reduce Roughness Percepts: While no researchers reduced the perceived roughness using vibrotactile stimuli related study follows.

Gescheider *et al.* [16] demonstrated that when the cutaneous receptors are adapted after exposure to a strong vibration for a sustained period, the roughness experienced from dotted textures decreases. Further, this adaptation restricts the discrimination of finely textured surfaces [17]. These studies suggest that cutaneous receptors temporarily incapacitated by strong vibrations disturb roughness percepts. However, our objective is to control the decrease in roughness percepts without such prior stimuli for adaptation. The smoothness percept caused by the adapted mechanoreceptors is not our research objective.

Vibrotactile stimuli have a masking effect that gradually degrades the detectability of vibrotactile signals under noisy background vibration [18]. The greater the background noise, the greater the impedance to perception of the vibratory signal.

Uncertainty exists as to whether these two types of phenomena, adaptation and masking effect, are based on the same neurophysiological principle; however, from these early studies, we formulated our hypothesis. The roughness percept can be regulated by adjusting the strength of the vibrotactile stimuli presented to a person's finger while she/he is exploring the material. We used a high-frequency background vibration (250 Hz) that has a prominent effect on fast adaptive receptors. In this case, our method would influence the percept of fine roughness that the fast adaptive receptors are primarily in charge of, whereas the percept of coarse roughness would not be affected.

C. Stimuli: Textured Surfaces and Accelerations of Vibrotactile Stimuli

We used two types of rectangular grating scales made of ABS plastic. The ratio of their ridge and groove widths was 1.0, and the widths were 145 and 290 μm for the two types of scales. The heights of the ridges were 200 and 600 μm for the former and latter scales, respectively. The latter scales are perceived as rougher when scanned by a finger.

We also used two types of vibrotactile stimuli to realize the increase and decrease in roughness percepts. To adjust the effects of the vibrotactile stimuli, we prepared three levels for each type of stimulus. The three levels for the roughness increase corresponded to $\pm$ 3.7, 4.9, and 6.2 m/s^2 acceleration at 250 Hz. Those for roughness decrease corresponded to $\pm$ 27.0, 31.6, and 36.2 m/s^2 acceleration at 250 Hz. These values were the outputs of the voice coil motor, which delivered the vibratory stimuli to each participant's finger through a fabric band. In addition to these six vibratory conditions (three levels and two types of vibrotactile stimuli), a condition with no vibratory stimuli was also tested. Hence, in total, seven types of conditions were prepared.

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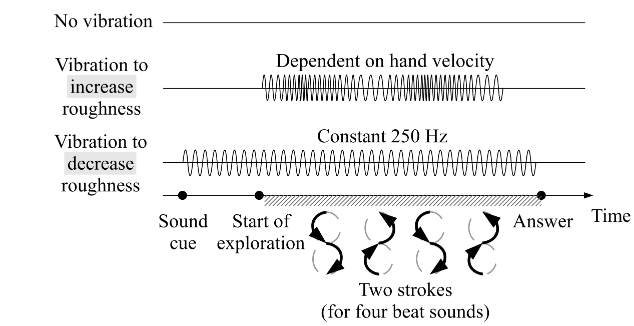

Fig. 4. Procedures used for tactile exploration in the experiment.

D. Procedure

The experiment was conducted using the magnitude estimation method, in which each blindfolded and sound-masked participant scanned the textured surface, and stated the magnitude of the perceived roughness using arbitrary positive numbers. They did not use any references (moduli) to judge the roughness.

To ensure that the finger moved smoothly on the surface, the participants were instructed to scan the surface by tracing a figure eight. This figure-eight scanning made it easier to control the finger scanning speeds than the linearly reciprocating scan that includes pausing phases to change the direction of finger movement. Furthermore, in order to prevent extraordinary deviation of exploratory hand movements between participants and trials, the participants synchronized their hand motions with the sounds of a metronome set to oscillate at 0.86 Hz. This sound was played through headphones along with pink noise. They scanned half a figure eight for one beep sound, and completed the figure after the second beep, as illustrated in Fig. 4.

During the experiments, to avoid significant tactile adaptation, the participants observed the following procedures. In a single trial, the participants started their exploration immediately following a sound cue, with the vibrotactile stimuli used to decrease roughness sensations beginning at the same time. Each trial was restricted to two reciprocating motions. Thus, in total, their fingers were exposed to the vibration for approximately 4–5 s in each trial. Between trials, a break of approximately 10 s in length was taken.

E. Participants

The participants were eight volunteer students from Nagoya University, who were unaware of the objectives of the study. They ranged in age from 19 to 23 years. Each read and signed a written informed consent form before participating in the experiment.

F. Experimental Design and Data Analysis

By combining the seven vibratory conditions and the two types of textured materials, we tested 14 stimuli. With these 14 stimuli as one block, each participant performed four blocks. In each block, the stimuli were presented in a randomized order.

The perceived roughness values for each stimulus condition were geometrically averaged for individual participants. To facilitate easier comparison, individual values were then normalized by dividing them by the magnitude of the roughness the subject perceived for the rougher grating scale (290-μm ridges and grooves) without vibratory stimuli. We tested the Spearman's rank correlation between the perceived roughness (dependent variable) and the stimulus levels (independent variables) using two-tailed t-tests for each combination of the two roughness specimens and two types of vibrotactile stimuli with Bonferroni correction of four (two specimens $\times$ two vibrotactile stimuli). For each test, 32 values (four averaged answers per individual $\times$ eight participants) were used.

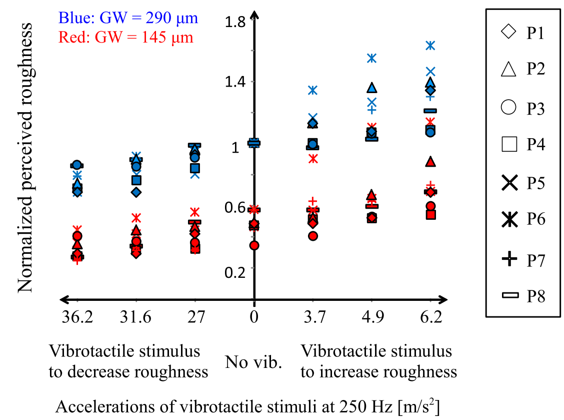

Fig. 5. Individual perceived roughness values for the two types of vibratory stimuli: GW signifies groove width.

III. Results

Fig. 5 shows the geometric averages of individual answers. The horizontal axis indicates the types of vibrotactile stimuli and their levels. On the right and left sides of the figure, the answers for the scales with vibrotactile stimuli to increase and decrease perceived roughness are shown, respectively, with the answers for the scales without vibration being at the center of the axis. For both types of vibrotactile stimuli, their stimulus levels increase the farther away from the center of the axis they are located. The red and blue symbols correspond to the answers for the grating scales of GW $= 145$ and 290 μm, respectively. Similarly, Fig. 6 shows the numerical averages of all the participants.

First, in the absence of vibrotactile stimuli, the grating scale with the larger ridge and groove widths felt rougher than that with the smaller widths. Such natural responses toward grating scales support the idea that the roughness percepts of participants were intact during the experiment.

Second, the perceived roughness of all the participants was positively correlated with the intended roughness of the rendering. The vibrotactile stimuli that were designed to increase roughness percepts increased the perceived roughness as their stimulus level rose. For the vibrotactile stimuli that increase roughness, the effects were statistically significant for the scale of 290 μm ($\rho = 0.73$, $p < 0.01$, (1) in Fig. 6) and that of 145 μm ($\rho = 0.70$, $p < 0.01$, (2) in Fig. 6). Similarly, the vibrotactile stimuli that were designed to decrease roughness percepts decreased the perceived roughness. The effects of vibrotactile

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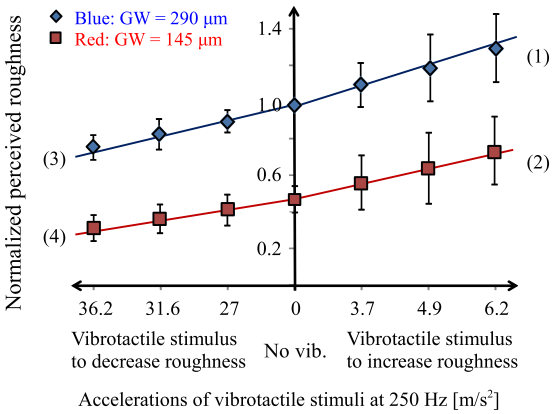

Fig. 6. Average perceived roughness values and standard deviations among participants.

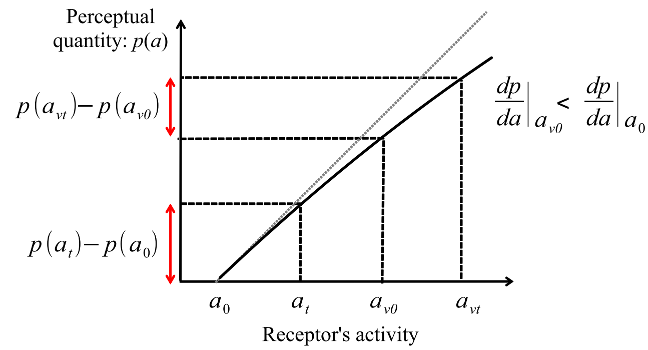

Fig. 7. Perceived roughness versus impulsive rate of FA I unit (computed from [23]).

stimuli that decrease roughness percepts were statistically significant for the scale of 290 μm ($\rho = 0.87$, $p < 0.01$, (3) in Fig. 6) and that of 145 μm ($\rho = 0.63$, $p < 0.01$, (4) in Fig. 6). On the basis of these results and analyses, we concluded that the two types of vibrotactile stimuli could increase and decrease the roughness percepts of grating scales. These results agree with those when we decreased the roughness stimuli in our prior study [12].

IV. Discussion

The experimental results were predominantly in line with our expectations that the constant vibrotactile stimuli applied to the finger would decrease the roughness percepts of the grating scales. Let us now look at a potential mechanism for this effect. One idea is that when the mechanoreceptors' activities are adapted or saturated because of exposure to strong vibrotactile stimuli over a sustained period, they are unable to correctly code the roughness sensations of the scales. This blockage of roughness percepts by adaptation may well be consistent with the results of earlier studies [16], [17]. However, this explanation does not necessarily hold for our experiment in which the receptors were not fully adapted. Other studies on masking effects address, for example, how the detection of short-term tactile stimulus is influenced by another relatively strong or long stimulus when they are initiated simultaneously or with a slight temporal gap (see, e.g., [19]–[22]). When the duration of the stimuli is relatively long, such masking effects due to temporally close stimuli are not necessarily observed [19]. Hence, those studies do not directly link to the roughness reduction by vibrotactile stimuli investigated in this study. We surmise that another mechanism, with which the offset of the receptors' activities are caused by vibration, reduced the roughness perceptions.

Yoshioka *et al.* [23] investigated the relationships between cutaneous stimuli caused by asperities of roughness specimen, roughness sensations, and the receptors' firing rates from the neurophysiological and psychophysical aspects. They compared the human roughness percepts with the receptors' activities of a monkey through the same roughness specimen. Fig. 7 shows a conceptual relationship between the firing rate of FA I units and the roughness percepts. The curve was plotted based on the equations reported in [23]. The point being made is that the perceptual quantity of roughness increases nonlinearly with the receptors' activities. The rate of roughness percepts to receptors' activities, which is defined by the gradient of the curve, declines as the receptors' activities rise. Hence

$$\left.\frac{dp}{da}\right|_{a_0} > \left.\frac{dp}{da}\right|_{a_{v0}}, \quad \text{if} \quad a_{v0} > a_0 \tag{2}$$

holds as shown in Fig. 7. a_0, a_t, a_{v0}, and a_{vt} are the receptors' activity levels in the absence of any stimuli, while exploring the surface, in the presence of vibrotactile stimuli, and while exploring the surface with vibrotactile stimuli being applied to the finger, respectively. The suffixes 0 and t indicate nontouch and touch, respectively. Further, v indicates the vibrotactile stimuli being applied. $p(\bullet)$ associates the receptors' activity with perceptual roughness quantity. On the basis of such connections between roughness sensations and receptors' activities, vibrotactile stimuli are likely to reduce the roughness experienced in exploring textured surfaces.

We simplify the relationship and define the magnitude of perceived roughness by the difference in perceptual quantities before and after touching the surface. The roughness sensation caused by touching the surface is described as

$$p(a_t) - p(a_0). \tag{3}$$

Given that the vibrotactile stimuli are applied to the fingertip through a vibrator worn on the finger, the receptors' activity level is a_{v0}. The finger then scans the textured surface, and the receptor's activity level rises to a_{vt}. The roughness experienced in this scenario is described by

$$p(a_{vt}) - p(a_{v0}). \tag{4}$$

As shown in Fig. 7, (3) and (4) follow

$$p(a_t) - p(a_0) > p(a_{vt}) - p(a_v) \tag{5}$$

when $a_t - a_0 \geq a_{vt} - a_{v0}$. Hence, when a constant vibration that is independent of active hand movements is applied to the fingertip, humans perceive textured surfaces as being less rough than they do without the vibration. In order to take advantage of this roughness coding curve, we need intense vibrotactile stimuli that lead to a large bias in the curve because it is a monotonically increasing function with a marginally declining slope, as shown in Fig. 7. The strengths of the stimuli to decrease perceived roughness were five to ten times as large as those to increase perceived roughness. We ignored the variations of receptors' activities during active exploration to simplify the discussion. Nevertheless, similar principles are likely to dynamically hold, and the vibrotactile stimuli reduce the roughness percepts of textures during active exploration of the textured surface.

In our experiment, limited types of specimen were tested. The vibrotactile stimuli increased the perceived roughness of wood, paper, cotton, and artificial leather, when the vibratory source was installed on these materials [4]. Hence, the stimuli by the actuator worn on a finger are also expected to influence these types of materials in a similar fashion. Conversely, the effect of vibrotactile stimuli to decrease perceived roughness on general materials is unknown, and further experimental studies are required before any conclusions can be drawn. Its effect is expected to be the same for materials (e.g., abrasive paper) similar to the specimen used in this study. However, in terms of other natural materials that include both fine and macroscopic surface roughness, the effect of our strong vibrotactile stimuli to decrease perceived roughness still remains to be studied, especially because the strong vibrotactile stimuli in a high-frequency range also influence the cutaneous receptors, which are primarily sensitive to low-frequency vibration [18]. Furthermore, human perception of material softness or friction may be altered by these vibrotactile stimuli because the activities of cutaneous receptors also mediate these percepts (see, e.g., [24], [25]).

V. Conclusion

In this paper, we discussed the development of a wearable-type vibrotactile display that increases and decreases the roughness percepts of surfaces touched by the wearer. Earlier studies have shown that such wearable displays can increase textural roughness. We were able to also increase the roughness experienced by scanning grating scales using vibrotactile stimuli representing virtual wavy textures. However, in general, there is no known method to decrease roughness percepts by applying additional physical energy to the skin of the finger. We discovered that the vibrotactile offset of mechanoreceptors' activities decreases the perceived roughness of touched surfaces with increases in the offset correlating with increases in the feeling of smoothness of the surfaces. This approach reduced the perceived roughness of the grating scales for all eight participants in our experiment. Thus, this study is a first report on a single experiment that demonstrates that the vibrotactile stimuli can selectively increase and decrease roughness percepts.

Some of the users of these techniques may feel uncomfortable with the vibration, especially the intense vibration that decreases perceived roughness. This is similar to the problem of imperfect perceptual fusion of real and artificial stimuli, which is common in augmented reality systems. At present, there appears to be no effective method to eliminate the sense of vibration and achieve natural fusion. Nevertheless, the methods presented in this paper can provide users with a wearable system that does not require additional devices in the environment. These positive and negative points should be properly weighed for individual purposes.

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