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Toward Quality Texture Display: Vibrotactile Stimuli to Modify Material Roughness Sensations

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Abstract

For industrial purposes such as product design, texture displays should deliver a quality sense of touch to users. We have developed a vibrotactile texture display that uses real materials such as fabric, wood, and leather to enable the presentation of quality textures to users. By applying two types of vibrotactile stimuli to users' finger pads through the materials, their fine and macro roughness sensations can be selectively modified while maintaining their original perceptual characteristics. This approach is effective for different types of textures such as paper, wood, leather, and cloth unless they possess strong damping properties that may attenuate the vibratory stimuli applied through them.

keywords: Tactile texture display, Vibration stimulus, Augmented reality

1 Introduction

The tactile sensation of materials is an important factor in the design and marketing of various products. A good sensation imparts expensiveness to the product and increases its affinity to users. We have developed a tactile texture display to virtually present the tactile sensations of material surfaces such as cloth or wood, and potentially help product designers engineer virtual materials and achieve the desired tactile sensations. Most texture displays are designed to present either a broad range of textures typically for virtual reality applications rather than specific materials with greater precision, or to achieve mechanical simplicity of devices (cf. related study). Neither type of device aims at providing a tool for product design.

The purpose of our research is to investigate the tactile texture display technology to identify an approach for a device that can deliver the quality adequate for supporting product design. In this study, we propose a vibrotactile texture display approach that involves applying vibratory stimuli of a certain range to real materials to slightly modify the sensation of their roughness without producing

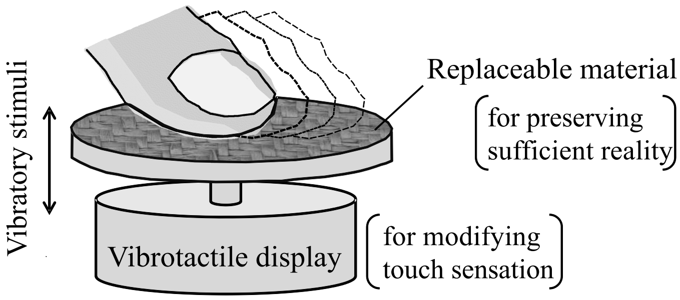


Figure 1: Vibrotactile texture display with real materials.

a strong sense of vibration. As shown in Fig. 1, in such a method, stimuli are applied to finger pads as they scan the material surface. The application of real materials in texture displays enables the presentation of more realistic material sensations than those done by previously reported techniques. Moreover, the proposed method can potentially be used with various types of textures by just replacing the materials. Nonetheless, because earlier vibrotactile texture displays used flat or smooth contactors, the effectiveness of this approach needs to be confirmed in a situation where the finger is exposed to two stimuli sources, namely, the asperities of material surfaces and vibratory stimuli. The idea of using real materials in texture displays was originally presented by the authors [1], wherein two types of vibrotactile stimuli could selectively influence the fine and coarse (or macro) roughness sensations of materials. Experiment 1 of the present study is based on our previous report and demonstrates that the roughness sensation of materials can be controlled by vibrotactile stimuli. Experiment 2 confirms that the tactile sensation of materials is modified slightly and not completely; i.e., their perceptual characteristics must be maintained upon the application of vibrotactile stimuli. Experiment 3 verifies whether the effect of vibrotactile stimuli depends on the type of material. From these experiments, we have constructed the foundation of the technology that combines vibrotactile stimuli with materials.

Figure 2 shows a possible application of texture displays in industrial design. It presents an imaginary scenario of two industrial designers discussing textures of cloths used to cover a certain product wherein one is holding and feeling the cloth material and attempting to deliver his preferences. Although aurally communicating the feeling in such scenario is difficult, modifying the texture offers potential benefit as both designers can share their tactile experiences of the texture using a vibrotactile texture display. Furthermore, although presenting a plethora of cloth samples with different textures is also a practical solution, the studied technology enables users to interpolate sample textures and makes sharing tactile experiences more effective when face-to-face or telephonic communication is unfeasible.

2 Related studies

Tactile texture displays are potentially classified based on the following desired features: (a) applicability to a broad range of textures and (b) simplicity. However, both categories of devices do not aim to present

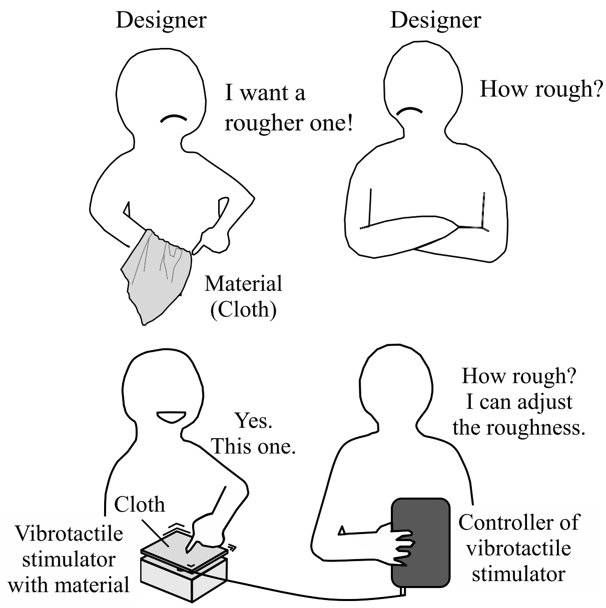


Figure 2: Application image for communicating tactile sensation of textures.

textures with the quality adequate to aid product design. The proposed approach is unique in that it focuses on neither feature but slightly modifies the tactile sensations of real materials while maintaining their perceptual characteristics.

The first major category of devices focused on broad applicability, aiming to present a variety of materials virtually using a single device rather than limited types of materials with high quality. For example, the tactile interface, incorporating a vibrator and thermal transducer, developed by Caldwell et al. presented the differences in the surface roughness, friction, and thermal conductivities of different materials [2]. A similar approach but with pin-array actuators was adopted by Bergamasco et al. [3]. Pin-matrix tactile texture displays controlled the height or pressure distributions of virtual surfaces to present a variety of surface patterns [4, 5, 6]. Yamamoto et al. [7], Winfield et al. [8], and Wiertlewski et al. [9] attempted to present a broad range of textures by producing either the tangential displacements of the finger pads or the frictional forces between them and the texture displays. Vibrotactile texture displays are representative approaches to create virtual material surfaces by applying vibratory stimulation to finger pads at dynamically variable frequencies and amplitudes [10, 11, 12, 13, 14]. Although these devices have superior applicability to a broad range of textures, they are not designed for presenting even limited types of textures with the quality adequate for aiding product design.

The second major category focused on using simple mechanical structures as devices for presenting complex texture stimuli. For example, the display developed by Konyo et al. employed vibrotactile approach for presenting the sense of friction [15] whereas more complex mechanical structures are required generally. Further, slippery or sticky surfaces can be presented by tangentially deforming the finger pads [16, 17, 18, 19] without modifying the actual frictional properties of the tactors. With the aim of presenting virtual softness simplistically, Bicchi and Scilingo et al. [20, 21], Fujita et al. [22], and Kimura et al. [23] proposed displays that controlled the contact area between the human finger pad and the tactor. Electric tactile displays also have the potential to function as simple texture displays without any mechanical structures [24, 25]. These devices focus more on device simplicity than the fidelity of the physical interactions between real materials and finger pads.

Finally, Hollins et al. investigated the perception of vibrating roughness gratings [26] and suggested that vibration increased their perceived roughness. However, they used constant vibrations irrelevant to finger motions unlike our methods because their interest was not to control roughness sensations but test roughness percepts under vibratory circumstances. Moreover, such constant vibrations imposed on the gratings do not always increase the roughness percepts but may mask and curtail roughness [27].

3 Vibrotactile stimuli to alter roughness sensations

In our study, we used two types of known vibrotactile methods to alter the fine and macro roughness sensations of materials. Fine roughness is experienced while touching surfaces with small, densely arranged nubs or bumps [28], the sizes of which range from less than hundreds of micrometers to 1 mm. Such roughness is observable typically in synthetic materials such as woven cloth or paper. In contrast, macro (or coarse) roughness is experienced while touching surfaces with sparsely arranged, sharp nubs or edges, a typical attribute of the surfaces of natural materials such as wood or stone [28]. These two types of roughness are perceived by a difference in the sensory mechanism (e.g., [26, 29]).

3.1 Method for altering fine roughness using virtual wavy surface

A related study [30, 11] proposed a method to present a virtual wavy surface using vibrotactile stimuli, presenting tactile sensations such as touching a cloth or sandpaper with fine roughness. Figure 3 shows the schematic representation of the stimuli using this method of modifying the perceived fine roughness of materials. The displacement applied to the human finger pad is expressed as

$$y_1(t) = A_1 \sin\left(2\pi \frac{x(t)}{\lambda}\right), \tag{1}$$

where A_1, $x(t)$, and λ are the amplitude, position of the human finger, and wavelength of the virtual wave, respectively. The typical value of λ is set to 0.8 mm. In earlier vibrotactile texture displays, the use of multiple surface wavelengths has effectively improved perceptual quality [11]. However, in this method, real materials are composed of a large set of wave components and such multiplicity of artificial waves is not required for improving perceptual quality. As vibratory stimuli are applied according to finger movements, their frequency is directly proportional to the velocity of the movement, determined as $|\dot{x}(t)| / \lambda$. The perceived fine roughness sensation increases with A_1, which is effective at approximately 0.5–2.0 μm.

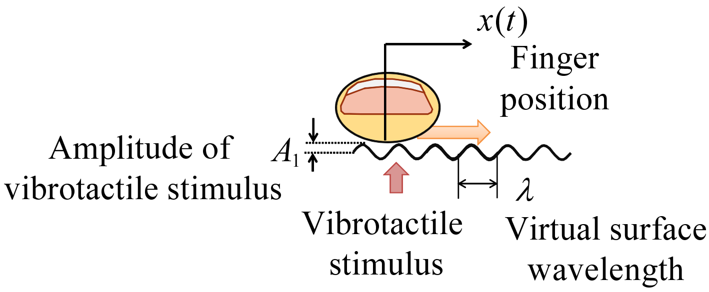


Figure 3: Vibrotactile stimulus to modify fine roughness sensations.

3.2 Method for altering macro roughness using impulsive vibrotactile stimuli

Okamura et al. proposed a method using impulsive tactile stimuli [31] for presenting virtual roughness similar to that perceived while scanning the surface of a material with sharp edges or coarse ridges on a plane. In this case, the perceived roughness is different from the fine roughness described in section 3.1. Figure 4 shows the schematic representation of this method, which used a decaying sinusoidal wave to apply impulsive stimuli. The displacement to the human finger pad is expressed as

$$y_2(t) = A_2 \exp(-at) \cdot \sin(2\pi f t), \tag{2}$$

where A_2, a, and f are the amplitude, damping ratio, and damped natural frequency of the finger pad, respectively. The value of f was fixed at 200 Hz based on a related study [32]. An increase in A_2 results in an increase in the magnitude of perceived roughness. As this method presumes relatively larger skin deformation, A_2 was assigned a value in the range approximately 0.5–2.0 mm, significantly greater than A_1. Furthermore, we set $a = 5.0\ \mathrm{s}^{-1}$ so that the sensations are perceptually similar to those of actual edges. However, in practice, such sensations do not strictly rely on f and a, and some deviations are acceptable. Unlike the fine roughness stimulus, this impulsive stimulus does not depend on the finger movement, as it is presented at the moment at which the finger passes over the virtual projection. For this study, we set the frequency of stimulation (optionally as the spatial density of the virtual edges) to 1 impulse/10 mm.

4 Vibrotactile texture display

4.1 Mechanical structure of vibrotactile display

The tactile texture display developed through our research presents vibrotactile stimuli using a voice coil motor (X-1740, Aoyama Special Steel Co. Ltd., Tokyo, Japan, Maximum force: 2.42 N) as the actuator. Figure 5 shows the schematic representation of its mechanical structure. The parts shown in dark gray color (acrylic plate and coil) and the replaceable real material were linked and actuated along the y-axis, with the moving range of the linked parts being 4 mm. The control value to the voice coil motor is

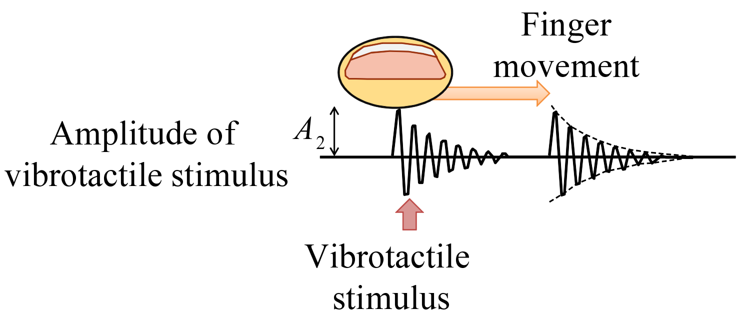


Figure 4: Vibrotactile stimulus to modify macro roughness sensations.

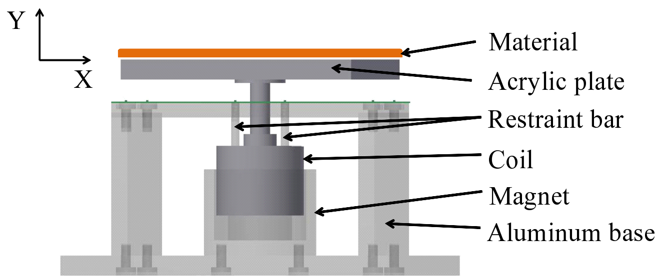


Figure 5: Schematic representation of vibrotactile display based on voice coil motor.

frequency-shaped so that regardless of the frequency band, the target displacement is outputted [1]. This displacement, set for a load of 1 N (in the range of the typical load applied when a finger traces the material) varied with the load because the latter was not fed back to the control system. For example, at 50 and 100 Hz, the displacements were, respectively, in the range of 0 to -0.6 dB and 0 to -0.5 dB for loads of 0.5–2.0 N, with that at 1 N being 0 dB. Although this variation with load might have led to individual differences in the results, the consistency of each participant's answers was not possibly corrupted given that he/she employed a consistent exploratory strategy during the experiment.

4.2 Control system

Figures 6 and 7 show the schematic representation of the experimental apparatus and block diagram of the display system, respectively. The position of index finger $x(t)$ of the participant who traces the material mounted on the top of the acrylic plate of the display was captured using a camera (PlayStation Eye, Sony Computer Entertainment, Tokyo, Japan, 320 $\times$ 240 pixel, 30 fps) that tracks the red marker attached to the finger to determine its position. Both the spatial (0.625 mm) and temporal resolutions of position measurement were not adequately precise with respect to the criteria of texture rendering [33]. Hence, the finger position used for generating the tactile stimulus was fully computed by integrating the finger speed at 5 kHz without any correction for slow sampling. In this method, the change in time series is consecutive, and hence, the vibrotactile stimuli given by (1) was smooth but did not yield accurate

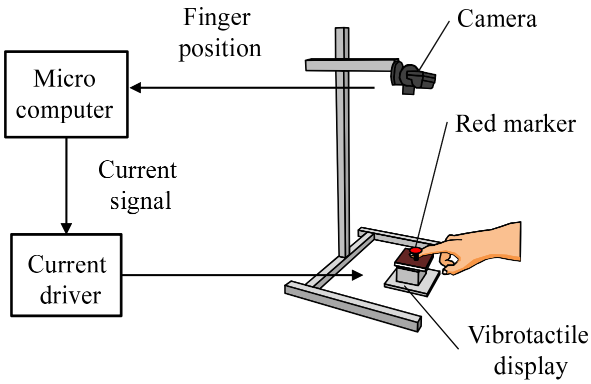


Figure 6: Schematic of experimental setup.

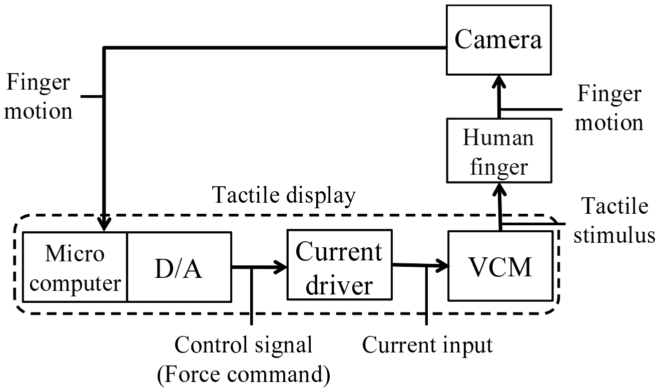


Figure 7: Block diagram of vibrotactile display.

position mapping of the real materials and virtual roughness stimuli. However, the present case did not strictly require a spatial match between real and virtual textures. The latency of feedback from the camera was high at 33 ms plus a small computational overhead that was sustainable for real-time operation. Therefore, the latency can be regarded as fairly smaller than its threshold for tactile texture feedback, i.e., 40–60 ms [34].

5 Experiments for altering roughness sensations of materials

We evaluated ways to modify the perceived roughness through three kinds of experiments. Through experiment 1, we validated that the fine and macro roughness sensations could be selectively modified. Through experiment 2, we confirmed that it is possible to slightly modify the tactile sensation of the material using vibrotactile stimuli while retaining its original perceptual characters. Through experiment 3, we checked whether the detection threshold of the vibrotactile stimuli depends on the material and tested their effects on different materials. The experiments, including the procedure, methods, and participants, obtained approval in the Nagoya University Department of Engineering Ethic Sectional Meeting.

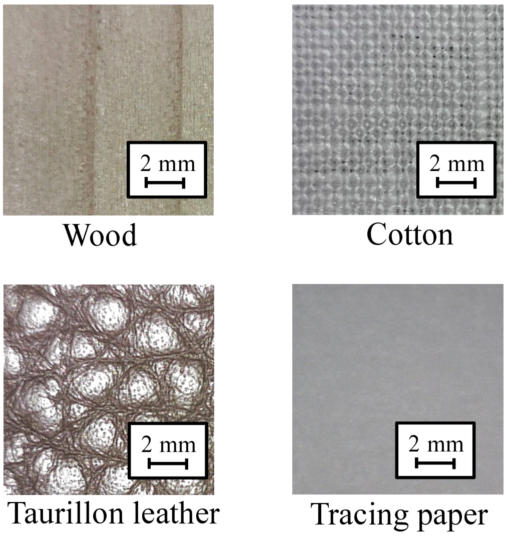


Figure 8: Optical microscopy images of materials to which vibratory stimuli were applied

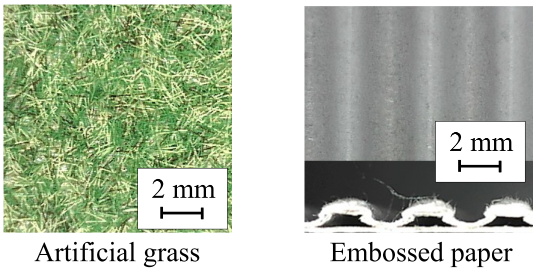


Figure 9: Reference materials. Left: reference for fine roughness. Right: reference for macro roughness. Top: top view. Bottom: cross-sectional view.

5.1 Materials and participants

Materials with different textures were tested to verify the effectiveness of our roughness presentation methods. As shown in Fig. 8, we used four types of material surfaces: cotton cloth (rough, moderately soft, and 1.03 mm thick), taurillon leather (uneven, soft, and 2.06 mm thick), wood (rough, hard, and 4.88 mm thick), and tracing paper (smooth and 0.196 mm thick). The participants (12 students of the Nagoya University chosen through a public advertisement) were blindfolded so that their perceptions of roughness were not biased by the appearances of the material surfaces. They also wore headphones and listened to pink noises for canceling out the sounds generated by the motor and mounted the red marker on their index finger for their finger position to be measured.

5.2 Experiment 1: Selective modification of fine and macro roughness sensations

5.2.1 Stimuli

We investigated four levels each for fine and macro roughness stimuli. For determining the two types of stimuli using (1) and (2), respectively, the values of A_1 and A_2 were set to 0.75, 1.0, 1.25, and 1.5 μm and 0.7, 1.0, 1.3, and 1.6 mm, respectively, across the levels. The participants tested the materials for each type of stimuli applied to each of the four types of materials, as well as in the absence of any vibratory stimuli. Thus, each material was tested for the application of nine different stimuli, and 36 stimuli (9 stimuli $\times$ 4 materials) were randomly presented to each participant (one set). Totally, 144 trials (four sets) were conducted across all individuals.

5.2.2 Tasks

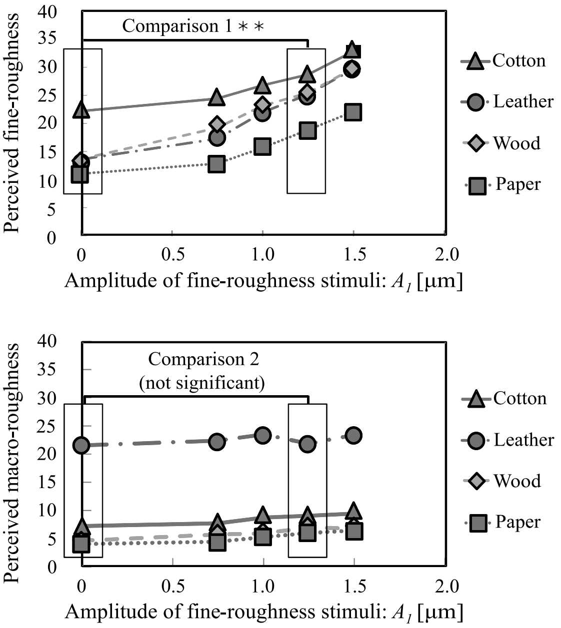
Triggered by a sound cue, the participants explored the surface of the material mounted on the tactile display. Their exploratory motions were not controlled but monitored during the experiment for any substantial irregularity. They reported their perceived fine and macro roughness for each stimulus using the magnitude estimation method, in which they adopted a number according to the perceived roughness that compared with a reference value. As shown in Fig. 9, we provided fine artificial lawn grass and embossed paper as the reference for fine and macro roughness, respectively. Both reference values were set at 50 and provided to the participants once in every 18 trials (half set).

5.2.3 Results

Figures 10 and 11 show the geometric averages of the roughness perceived by the participants upon application of fine and macro roughness stimuli, respectively. As seen in Fig. 10, an increase in the amplitude of fine roughness stimuli resulted in an increase in the perceived fine roughness (Fig. 10 top) but not in the perceived macro roughness (Fig. 10 bottom). The application of macro roughness stimuli also increased only the perception of macro roughness (Fig. 11). The differences between the perceived roughness values were tested using a two-way ANOVA, with the vibrotactile stimuli (or the lack of it) and the type of material as the factors for analysis.

First, we applied fine roughness stimuli with $A_1 = 1.25$ μm and compared the perceived fine roughness of materials with and without stimuli. We concluded that the application of stimuli significantly increased the perceived fine roughness ($F_0(1, 280) = 18.12$, $p = 2.8 \times 10^{-5}$, comparison 1) but the perceived macro roughness was not affected ($F_0\ (1, 280) = 1.01$, $p = 0.315$, comparison 2). Furthermore, we observed the same results for $A_1 = 1.5$ μm; i.e., the application of fine roughness stimuli only affected the perceived fine roughness.

Next, we applied macro roughness stimuli with $A_2 = 1.3$ mm and compared the perceived fine roughness of materials with and without stimuli. The result indicated that the perceived fine roughness



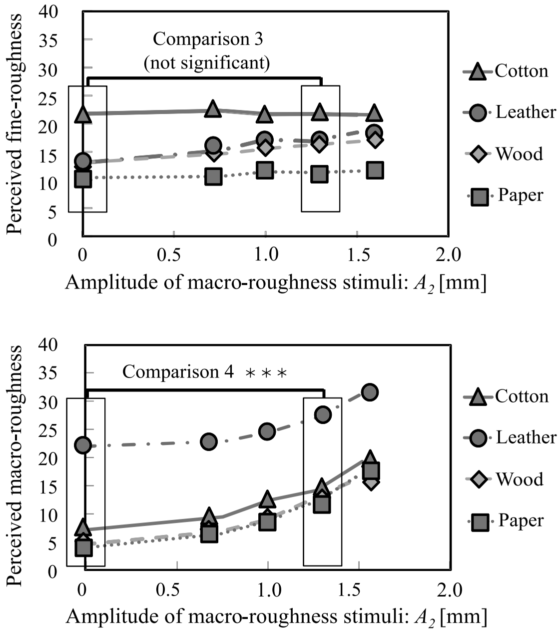


Figure 10: Perceived fine and macro roughness values upon application of fine roughness vibratory stimuli to real materials. ** indicates a significance level of 0.01.

Figure 11: Perceived fine and macro roughness values upon application of macro roughness vibratory stimuli to real materials. *** indicates a significance level of 0.001.

was not affected (F_0 $(1, 280) = 0.39$, $p = 0.53$, comparison 3) but the application of macro roughness stimuli increased the macro roughness sensation (F_0 $(1, 280) = 17.85$, $p = 3.2 \times 10^{-5}$, comparison 4). Again, the same observations were made with $A_2 = 1.6$ mm.

The above results indicate that both methods for the presentation of roughness stimuli could selectively modify the fine and macro roughness sensations, respectively.

The gradient of the curve for perceived roughness indicates the sensitivity of roughness perception with vibration. To understand whether the effects of vibrotactile stimuli depended on the type of material, we calculated the gradients of the perceived fine and macro roughness in the range of $A_1 =$ 0.75–1.5 μm and $A_2 = 0.7$–1.6 mm, respectively, for individual participants and investigated their differences across materials. The averages and standard deviations for cotton, leather, wood, and paper, respectively, were 9.9±3.8, 14.7±6.3, 13.8±7.5, and 13.2±5.7 μm^{-1} and 10.6±3.5, 8.8±2.6, 11.3±7.0, and 11.5 ± 5.0 mm^{-1} for the perceived fine and macro roughness, respectively, after removing the maximum and minimum values for each material. A one-way ANOVA revealed no differences among materials for both fine ($F_0(3, 36) = 1.22$, $p = 0.32$, $1 - \beta = 0.77$) and macro ($F_0(3, 36) = 0.66$, $p = 0.58$, $1 - \beta = 0.77$) roughness sensations, with possible differences equal to the variances within groups of 5.7 μm^{-1} and 4.8 mm^{-1}, respectively. These analyses suggested that the difference in the effects of vibrotactile stimuli on the different types of materials is nonsignificant for both fine and macro roughness sensations.

5.3 Experiment 2: Similarity analysis of textures modified by vibrotactile stimuli

As described before, the present approach aims to slightly modify the roughness sensations of real materials while sustaining their unique textures, and hence, we do not expect that the application of vibrotactile stimuli to totally change their textures and cause them to be perceived as different materials. To verify the slight modification of textures, this experiment investigated the degree of perceptual dissimilarity between textures, judged on the basis of comprehensive tactile percepts including roughness, friction, softness, and vibration sensations. Subsequently, we constructed a multi dimensional space where the textures were located based on their perceptual characteristics. This analysis enabled us to capture the human material percepts whereas only roughness percepts were discussed in experiment 1.

5.3.1 Stimuli

For the fine and macro roughness stimuli determined using (1) and (2), respectively, the values of A_1 and A_2 were set at 1.25 μm and 1.3 mm, respectively. In addition, there was one case of presenting the material without vibration stimulus. Each of these stimuli was applied to each of the four types of materials and hence, 12 stimuli were applied in experiment 2. We presented paired stimuli from these 12 conditions to participants at random.

5.3.2 Tasks

Similar to experiment 1, triggered by a sound cue, the participants explored the surface of materials mounted on the tactile display and reported their subjective non-similar degree of perception, that is also known as perceptual distance or dissimilarity, across the paired stimuli using a numerical value. We instructed the participants to report zero in the case of same tactile perceptions under paired stimuli conditions. However, there were no participants who perceived the same stimuli conditions. As in experiment 1, participants' exploration was not specifically controlled but monitored through an experimenter.

5.3.3 Results

The degrees of dissimilarity reported were normalized within each participant and then averaged across all participants. Thereafter, we arranged the 12 stimuli in a Euclidean plane using the Torgerson's multi dimensional scaling method of multivariate analysis to evaluate stimulation in multidimensional space using the degree of dissimilarity as the distance on the plane, in this case. The coordinates of stimulation were decided such as to preserve the distance relationship reported by participants. Figure 12 shows the result of experiment 2, in which the two-dimensional system describes the variance of data with the contribution ratio being 0.88. The images of the stimuli on the (a) material only (white image), (b) material with the application of fine roughness stimulation (gray image), and (c) material with the

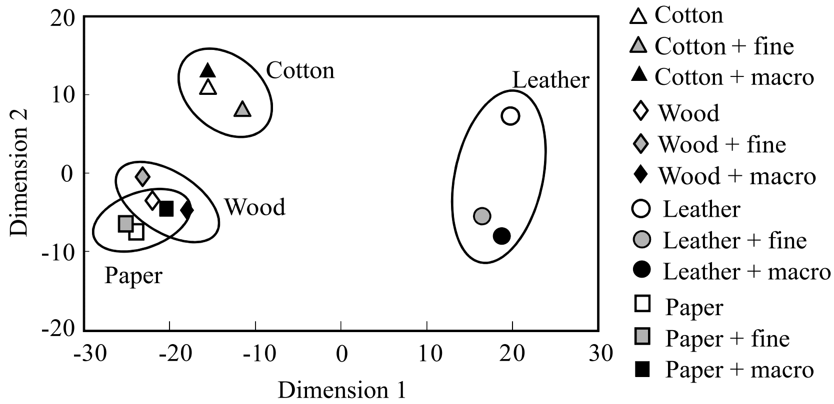


Figure 12: Perceptual locations of materials based on their dissimilarity.

application of macro roughness stimulation (black image) for each material are represented, with the images of the same material being closely located. The stimuli applied to each material being similar perceptually, we thus verified that the tactile sensation of the material was modified not totally but slightly using vibrotactile stimuli.

5.4 Experiment 3: Independence of roughness stimuli on materials

In experiment 1, the nonsignificant dependence of vibrotactile stimuli on the type of material was verified using the gradients of perceived roughness upon the application of the stimuli, which specified the perceptual characters of supra threshold stimuli. In contrast, from experiment 3, we verified whether the detection thresholds of vibrotactile stimuli (the minimum amplitude of stimulus required for influencing texture perception) depended on the type of material.

5.4.1 Stimuli

We used the method of limits that gradually raised or lowered the amplitude of stimulation to measure its threshold. The amplitude steps for the application of fine and macro stimulations were set at 0.15 μm and 0.15 mm, respectively. From the result of experiment 1, the least effect of fine roughness stimuli was found on cotton cloth material and the most was on taurillon leather, whereas the differences in the effects of macro roughness stimuli were minuscule. Thus, we compared the thresholds of vibrotactile stimuli for cotton cloth and taurillon leather by considering four trials (2 materials $\times$ 2 applications of roughness stimuli) as one set, and conducted the experiment with two sets per person.

5.4.2 Tasks

Participants were exposed to materials with paired stimulations (a pair of materials with and without vibrotactile roughness stimuli) and were asked to report whether they felt the same or different roughness sensations. The amplitude of application of roughness stimulus was raised or lowered when participants

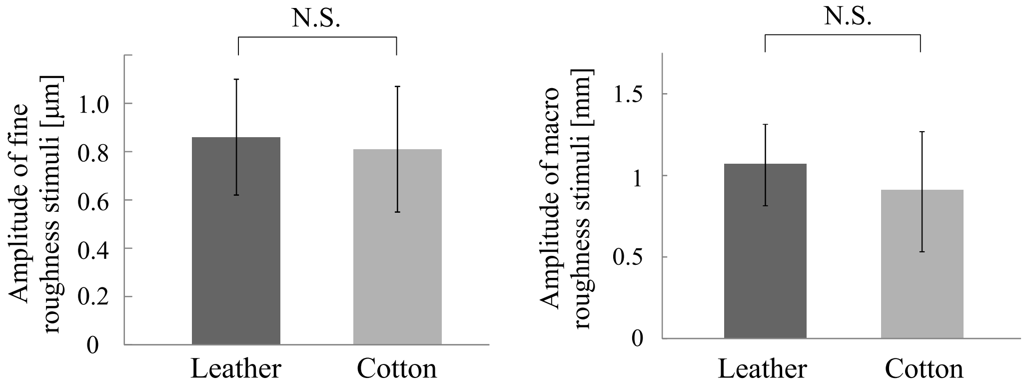


Figure 13: Perceptual thresholds of vibrotactile fine and macro roughness stimuli. Left: Fine roughness stimuli. Right: Macro roughness stimuli.

regarded similar or different sensations, respectively. For example, after the point when participants reported same roughness sensations (when the amplitudes of vibrotactile stimuli were adequately small), the amplitudes were continuously raised until they felt a difference in the perceived roughness, after which the direction of stimulation was changed from upwards to downwards (or vice versa). This point of change is called the transition point, and the trial was concluded with ten achievements of this point. Similar to the previous two experiments, participants' exploration was not specifically restricted.

5.4.3 Results

We calculated the perceptual thresholds of fine and macro roughness stimuli for cotton cloth and taurillon leather as the average of the amplitudes at the transition points obtained in the individual trials. We obtained 24 thresholds from 12 participants for each combination of material and modification of roughness sensations. We removed the two maximum and minimum values for each combination and applied the remaining thresholds to statistics. The thresholds of cotton cloth and taurillon leather were 0.86 ± 0.24 and 0.81 ± 0.26 μm, respectively, for fine roughness stimuli (Fig. 13 left) and 0.91 ± 0.25 and 1.07 ± 0.37 mm, respectively, for macro roughness stimuli (Fig. 13 right). From the result of the ANOVA, a meaningful difference was not recognized between the thresholds of the two materials upon application of fine ($F_0(1, 39) = 0.4$, $p = 0.53$, $1 - \beta = 0.56$) and macro ($F_0(1, 39) = 3.08$, $p = 0.087$, $1 - \beta = 0.56$) roughness stimuli, with possible differences equal to the standard deviations, of 0.25 μm and 0.31 mm, respectively. The results suggested that the effect of vibrotactile stimulation did not significantly depend on the material. The threshold may rise about the material that clearly damps vibration (e.g., sponge). However, we do not need to be particular about the effects of material types used in this study.

6 Discussion

In most previous studies, the contactors in vibrotactile texture displays had flat surfaces. In contrast, in the present study, the contactors were materials, and their surface asperities caused skin deformations including vibratory signals when being explored by finger pads. The results of experiment 1, in which the two types of vibrotactile stimuli successfully modified the roughness percepts of materials, encourage the use of vibrotactile display even under the condition of mixing both material- and vibrotactile-derived skin deformations, and offer scope for further research and development.

Despite functioning well in a series of experiments, the limitation of the proposed method is that the vibrations in the materials attached to the display are apparent when the amplitudes of the vibrotactile stimuli are significantly large. Hence, as described before, our approach is unsuitable for modifying the sensations of materials to a greater extent. Although the magnitude of the vibrotactile stimulus used in the experiments was small enough for users to feel the natural material textures, they could discern vibrations when the stimuli were even moderately increased, and this could have hindered the perceptual quality or realism of textural stimuli. The definition and measurement of naturalness are complex, and there seems to be no general method for specifying such a concept. For example, one of the most reliable and frequently used evaluations to measure the quality of tactile displays is classification, in which assessors classify randomly presented stimuli to the type of material that feels most similar to the simulated texture (e.g., [9, 11, 25]). The ratios of correct classifications become the criteria of their quality; i.e., the higher the better. However, because this is applicable for the comparison of real and simulated textures, it is not relevant for the present study. Among such difficulty, analysis using multidimensional perceptual spaces is regarded the most effective and fair approach among known test methods (e.g., [13, 35, 36]), offering the benefit of testing the similarity between textures from multiple perceptual aspects or comprehensive human percepts. Hence, it is difficult to supplement the test results by explicitly designating perceptual criteria such as roughness or hardness. Although experiment 2 may not fully advocate the quality of vibrotactile textures, it is regarded to be one of the best measures to verify the effectiveness of our approach.

The introspective reports of the experimental participants led to the suggestion that the perceived naturalness of the stimuli relies on the combination of material types and virtual wavelength of vibrotactile fine roughness stimuli, considering which we should be cognizant of the dependence of our method on the type of material, although experiments 1 and 3 revealed no differences in the effects of vibratory stimuli on the type of material.

Our methods modify the roughness of materials, which is only a part of the overall characteristics of tactile textures. In related studies, vibrotactile display methods for other characteristics such as hardness or softness [11, 30, 37, 38], and friction [15] are discussed. Although our method causes an increase in the perceived roughness of materials, it can be reduced as desired by using our method with ultrasonic wave vibration [8, 39]. The technical applicability of our proposed method can improve when it is successfully combined with these methods.

7 Conclusion

In summary, we have devised a tactile texture display using real materials to present quality tactile sensations. This approach enables us to modify the roughness sensations of material surfaces and experience realistic textures. We have confirmed that the perceived fine and macro roughness sensations of materials could be selectively modified (experiment 1) while maintaining their tactile characteristics using slight (experiment 2) instead of total modification. Furthermore, our approach, which combines vibrotactile stimuli and real materials, has been found effective regardless of the type of material (such as cotton cloth or taurillon leather (experiments 1 and 3)). Although these experiments have provided the base for vibrotactile texture displays using real materials for presenting quality textures, some topics remain to be studied in the future as the known experimental designs seem inadequate to assert that the textural quality of materials are sustainable upon the application of strong vibrotactile roughness stimuli. Moreover, the two types of vibrotactile stimuli used in this study may not be the best and may be improved or other effective vibratory profiles may be used. One potentially successful method to improve the naturalness of sensations is using good approximation of physics. For example, it is known that vibrotactile signals decay with increase in their frequencies [40] whereas in our fine roughness presentation, the amplitude of vibrotactile stimuli was maintained constant across the entire frequency range. Fortunately, because many researchers are actively working on the development of vibrotactile texture stimuli, the combination of real materials and vibrotactile texture stimuli has profound application potential in the future. Such display techniques are expected to facilitate the texture design of commercial products. Our method enables designers to engineer material surfaces using texture display by allowing them to adjust textures by carefully selecting the surface finishing processes or kinds of textile fibers based on their experience and sharing tactile feelings.

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