2012 IEEE RO-MAN: The 21st IEEE International Symposium on
Robot and Human Interactive Communication.
September 9-13, 2012. Paris, France.

Vibrotactile Display Approach that Modifies Roughness Sensations of Real Textures

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***Abstract*—In this study, we developed vibrotactile display methods that can assist designers in product design. In order to achieve realistic sensations required for such designing purposes, we used real materials such as cloth, paper, wood, and leather and applied vibrotactile stimuli to modify the roughness sensations of these materials. This approach allowed us to present textures of various virtual materials with a strong sense of reality. We verified that our proposed methods could selectively modify the fine and macro-roughness sensations of real materials. The methods are expected to aid product designers in deciding tactile sensations suitable for their products.**

***Index Terms*—Vibrotactile texture display, Surface roughness**

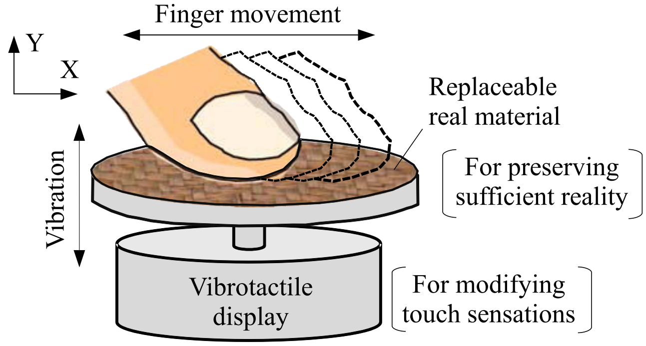

Fig. 1. Schematic of vibrotactile texture display using real materials

I. Introduction

Tactile sensation of materials is known as an important factor in the design of various products. Hence, we develop a tactile texture display that aids designers in product design. The tactile texture display is a device that virtually presents the tactile sensations of material surfaces, such as cloth or wood. Such devices potentially enable product designers to engineer virtual materials and achieve desired tactile sensations. However, as described in sec. II, currently, most texture displays employ either substitutional methods that produce complex tactile stimuli using simple devices, or those capable of producing a broad range of virtual textures using a single device. While the former leads to the mechanical simplicity of devices, the latter, typically used in virtual reality applications, is designed to cover a broad range of textures rather than present precise specified materials. However, since neither of these devices aims realistic stimuli, designers cannot use them for designing purposes.

Proposal (Vibrotactile texture display with real materials): We propose a vibrotactile texture approach with quality adequate to assist in product design. To this end, we apply vibratory stimuli to real materials to slightly modify the sensation of their roughness. As shown in Fig. 1, in these methods, such stimuli are applied to finger pads as they scan the material surface. The application of real materials in texture displays is a novel idea that can enable the methods to present more realistic material sensations than those presented through previously reported techniques. Moreover, the proposed methods can potentially be employed with various types of textures by replacing the materials.

Applications: This texture display enables product designers to experience and decide a tactile feel suitable for their products. For example, suppose that a designer considers using wood as the packing material for a certain product; then, using such texture displays that present a sensation of wood, the designer can experience various wood-based textures, which differ slightly in their roughness, after which s/he can make an appropriate selection.

Objectives: Thus far, the potential of including real materials in combination with vibrotactile stimuli has not been studied. Therefore, to the best of our knowledge, this is the first report establishing this potential. We evaluate the proposed approach by investigating whether or not conventional vibrotactile techniques can modify the roughness sensations of a variety of real materials, such as wood (rough and hard), cotton (rough), leather (soft and uneven), and paper (smooth and hard). These techniques may be unsuitable for some rough or soft materials, and their effectiveness depends significantly on the material type. Hence, we address this concern to establish the potential of using real materials in combination with vibrotactile stimuli.

II. Related studies

Tactile texture displays are classified on the basis of the following desired features: simplicity or the applicability of the device to a broad range of textures. However, devices under both these categories do not aim to present textures with quality sufficient to aid in product design. The proposed approach is unique in that it focuses on neither of these features. Instead, our approach slightly modifies the tactile sensations of real materials while maintaining their perceptual characteristics.

The first category of devices focused on broad applicability, where a single device aims to present a variety of materials virtually, rather than to present limited types of materials with high quality. For example, Caldwell et al. developed a tactile interface using a vibrator and a thermal transducer and demonstrated that the interface transferred the differences in the surface roughness, friction, and thermal conductivities of different materials [1]. Pin-matrix tactile texture displays represented by Ikei et al. [2] and Kyung et al. [3] were aimed at presenting a variety of surface patterns with limited spatial resolution. Yamamoto et al. [4], Winfield et al. [5], and Wiertlewski et al. [6] attempted to present a broad range of textures through either the tangential displacements of finger pads or the frictional forces generated by the interactions between finger pads and the material surfaces. Although, these single devices have superior applicability to a broad range of textures, they are not designed for presenting limited types of textures with quality sufficient for aiding in product designs.

The second category focused on simple mechanical structures that could be applied as devices for complex-texture stimuli. For example, Konyo et al. developed a friction display that used vibrotactile stimuli [7]. The display presented vibration stimuli to the finger pads that mimicked stick-slip phenomena observed while exploring frictional surfaces. With the aim of presenting virtual softness simplistically, Bicchi et al. [8] and Fujita et al. [9] proposed displays that controlled the contact area between the human finger pad and a tactor. Further, slippery surfaces could be presented even without modifying the actual frictional properties of the tactors, by tangentially deforming the finger pads [10], [11], [12]. Finally, electric tactile displays have also been reported to have the potential to function as simple texture displays without any mechanical structures [13]. These texture displays aimed to present textures with mechanically simple devices. They focused more on device simplicity than on the fidelity of physical interactions between real materials and finger pads.

III. Vibrotactile stimuli to alter roughness sensations

We use two types of conventional vibrotactile methods to alter the fine and macro-roughness sensations of materials. We define the fine-roughness sensation as the roughness experienced by touching surfaces with small nibs or bumps that are densely arranged. The sizes of these nibs/bumps range from less than hundreds of micrometers to 1 mm. The roughness of such a fine surface is mediated mainly by rapidly adapting mechanoreceptors [14], [15]. Fine roughness is observable typically in synthetic materials such as woven cloth or paper. In contrast, we define macro roughness as roughness resulting from sparsely arranged sharp nibs or edges; it is a typical attribute of surfaces of natural materials such as wood or stone.

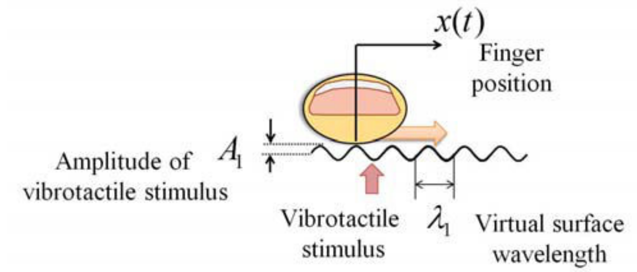

Fig. 2. Schematic representation of application of vibrotactile stimulus for modifying fine-roughness sensations

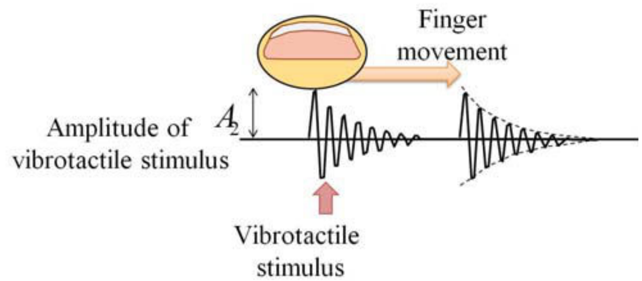

Fig. 3. Schematic representation of application of vibrotactile stimulus for modifying macro-roughness sensations

A. *Method for altering fine roughness using virtual wavy surface*

Konyo et al. proposed a method for presenting vibrotactile roughness using a single vibratory source [16], [17]. In this method, a virtual wavy surface with wavelength of λ was considered to present fine roughness. Fig. 2 shows a schematic representation of this method. The displacement applied by the tactile display 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, λ, and $x(t)$ are the amplitude and wavelength of the virtual wave, and the position of the human finger, respectively. We set $\lambda = 0.8$ mm for typical fine roughness.

In this method, vibratory stimuli are applied in response to finger movements. Therefore, the frequency of vibratory stimuli provided to the finger pads varies with the velocity of movement of the human finger. This frequency is determined as $|\dot{x}(t)|/\lambda$. As the velocity of the finger movement increases, the vibratory frequency of finger pad skin also increases. Furthermore, the virtual roughness perceived by humans increases with A_1. Larger A_1 produces stronger roughness sensations. We employ this method for altering fine roughness sensations.

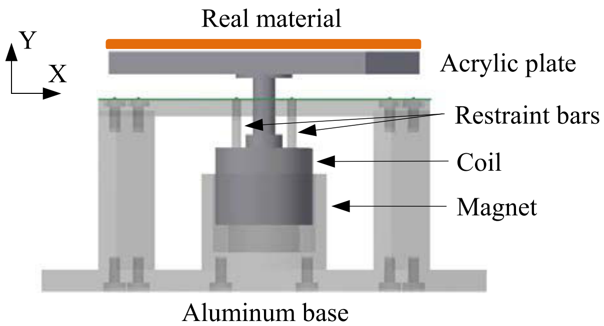

Fig. 4. Schematic representation of vibrotactile display based on voice coil motor

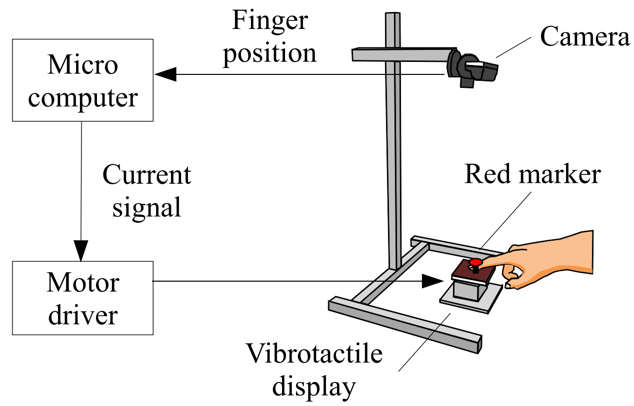

Fig. 5. Schematic of experimental setup for vibrotactile display

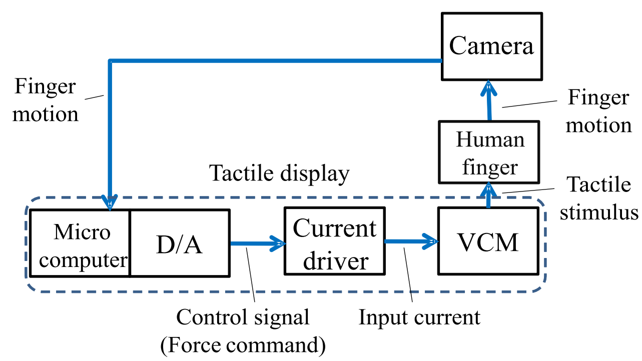

Fig. 6. Block diagram of experimental setup of vibrotactile display

B. Method for altering macro roughness using impulsive vibrotactile stimuli

Okamura et al. proposed a method for presenting virtual roughness using impulsive tactile stimuli [18]. The roughness presented by this method is similar to that by scanning the sharp edges on a plane. This roughness sensation is completely different from the fine roughness described above. Fig. 3 shows the schematic representation of this method. We model the impulse as a decaying sinusoidal wave. The cutaneous displacement applied by the tactile display 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 maximum amplitude of the impulse, damping ratio, and damped natural frequency of human finger pad. The value of f was set at 200 Hz on the basis a previous study [19]. An increase in A_2 results in an increase in the magnitude of perceived roughness. We set $a = 5.0$ s^{-1} so that the sensations become perceptually similar to those of the actual edges. We employ this method as the method for altering macro-roughness sensations.

According to this method, impulsive stimuli are provided to the finger pads when they come across a virtual edge. In this study, we set the spatial density of virtual edges as 1 impulse per 10 mm. This density can be set arbitrarily unless it becomes too dense. When the density is extremely high, the stimuli of individual impulses may overlap with each other and the sensations perceived by this method will no longer represent macro roughness.

IV. Vibrotactile Texture Display

A. Structure and usage

1) Mechanical structure of vibrotactile display: The vibrotactile texture display used in this study was based on a voice coil motor (X-1740, Aoyama Special Steel Co. Ltd., Tokyo, Japan). The maximum continuous-output force of the motor was 2.42 N with a current of 0.96 A. Fig. 4 shows the schematic of mechanical structure of our vibrotactile texture display. The parts shown in dark gray and the real material were rigidly linked and actuated along the y-axis. They include the real material, acrylic plate, and coil. The moving range of these parts was 4 mm. The real material could be replaced. The remaining parts (light gray), i.e., the magnet, base, and restraint bars, were earthed. The restraint bars allowed the coil to move along only the y-axis.

2) Control signal flow of system: Figs. 5 and 6 show the schematic of the experimental setup and the block diagram of the display system, respectively. The user senses the material mounted on the top panel of the tactile display. The position of the user's hand, $x(t)$, was captured using a camera (Playstation Eye, Sony Computer Entertainment, Tokyo, Japan). The camera tracked a red marker attached to the user's index finger to determine the finger position. In our system, the spatial resolution of position measurement was 0.625 mm. The refresh rate of the tracking system was set to 30 Hz. A microcomputer determined the target displacement given to the finger pad based on (1) and (2) and $x(t)$ and the corresponding current values for the voice coil motor. The motor was then driven by a current driver.

B. Compensation for frequency response characteristics of voice coil motor and finger pad

In order to ensure application of the set of target output displacements to the finger pads, we compensated for the frequency characteristics of human finger pad and the voice coil motor system. Using a FFT analyzer (CF-7200, Ono Sokki Co., Ltd., Yokohama, Japan), we measured the frequency response with the input and output being the applied electric voltage and the finger pad displacement, respectively. The finger pad was placed on the acrylic panel

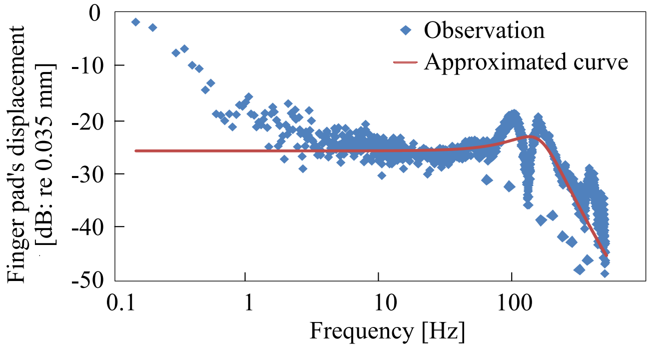

Fig. 7. Frequency response characteristic of vibrotactile display with output force of 0.425 N

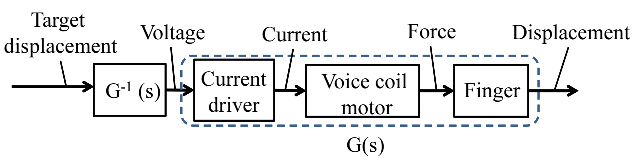

Fig. 8. Block diagram of vibrotactile display system compensating for nonlinear frequency responses of the finger pads and voice coil motor

linked to the voice coil. The finger displacements were measured using a laser displacement meter (CD5-30, OPTEX FA Co. Ltd., Kyoto, Japan), where the laser was directed toward the finger pad through a hole on the acrylic panel. During measurement, the contact force between the finger and the plate, determined using a scale, was maintained at approximately 100 g. This force is comparable to that with which humans typically explore material surfaces.

The measured frequency response characteristics are shown in Fig. 7. We used the following second-order transfer function that well approximated the characteristics of the high-frequency band (more than 5 Hz). The transfer function was

$$G(s) = \frac{6 \times 10^4}{s^2 + 800s + 10^6}. \quad (3)$$

As shown in the block diagram (Fig. 8), we applied the inverse of this function to compensate for the nonlinear frequency responses of the finger pad and the voice coil motor.

Fig. 9 shows the frequency characteristics before and after the compensation. The dotted line indicates the characteristics before the compensation in which the voice coil motor generated the constant force amplitude of 0.75 N whereas the solid one indicates those after the compensation. The observed characteristics were not nearly flat at less than 5 Hz because the transfer function for the approximation did not match well in the low-frequency band. However, this compensation is valid in our setup because it does not include stimuli in such a low-frequency band. We apply this compensation to the method for presenting the fine roughness, wherein the vibrotactile frequency varies according to the velocity of the human hand. We do not need to apply this compensation to the method for presenting

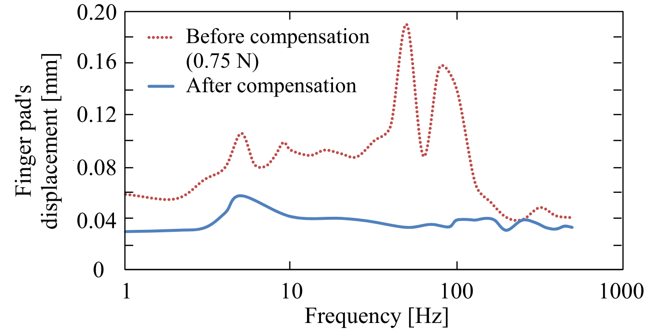

Fig. 9. Frequency response characteristics of tactile display and finger pad before and after application of compensation

the macro roughness, because the vibrotactile frequency remains constant in this case.

V. Experiment for Altering Roughness Sensations of Real Materials

We verified the effectiveness of our methods for presenting roughness sensation for real materials through experiments. We investigated whether the two methods for presenting vibrotactile stimuli could selectively present the fine and macro-roughness sensations.

A. Participants and materials

Real materials with different textures were tested to verify the effectiveness of our roughness presentation methods. As shown in Fig. 10, they were wood (rough and hard), cotton cloth (rough and moderately soft), taurillon leather (uneven and soft), and tracing paper (smooth and hard).

Owing to the preliminary nature of this study, we decided to invite four volunteers from the authors' laboratory. (Note that the authors did not participate in these experiments.) They were blindfolded, wore headphones, and listened to pink noises for shutting out the sounds generated by the voice coil motor.

B. Stimuli

We investigated four levels for each of the fine and macro-roughness stimuli. For the fine roughness stimuli, determined using (1), the amplitudes of vibrotactile stimuli (A_1) were set at 1.0, 1.3, 1.5, and 2.0 μm. For the macro-roughness stimuli, determined using (2), the amplitudes (A_2) were set at 0.5, 1.0, 1.5, and 1.8 mm. Each of these stimuli was applied to each of the four types of materials. Furthermore, the participants also tested the materials in the absence of any vibratory stimuli. Hence, each material was tested following the application of nine different stimuli. Thus, 36 stimuli (nine stimuli $\times$ four materials) were randomly presented to each participant (one section). In all, 144 trials (four sections) were conducted for individuals.

a) Tasks: Triggered by a sound cue, the participants explored the real materials mounted on the tactile display. They reported their perceived fine and macro-roughness for each stimulus using the magnitude estimation method, where the magnitude of perceived roughness, reported as

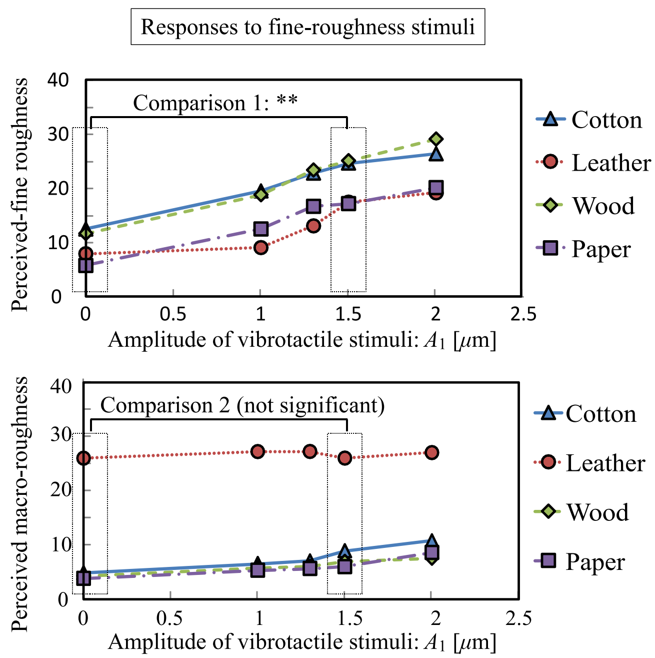

Fig. 12. Perceived fine and macro-roughness values upon application of fine-roughness vibratory stimuli to real materials

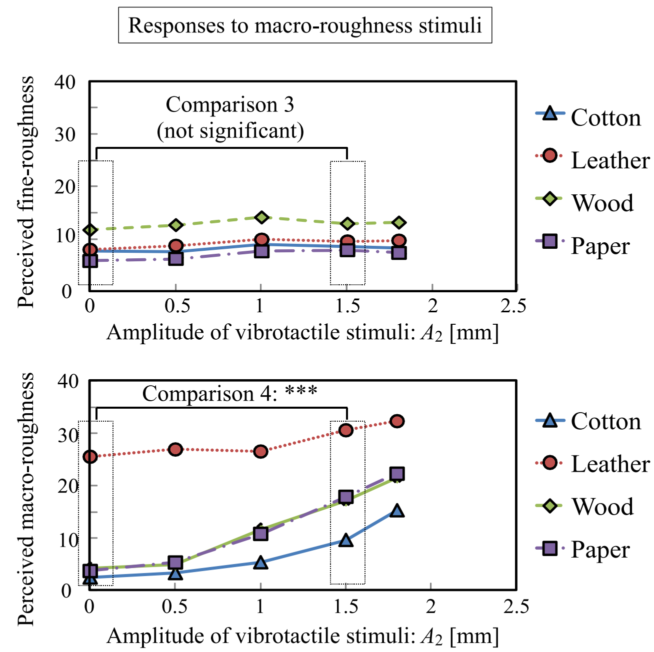

Fig. 13. Perceived fine and macro-roughness values upon application of macro-roughness vibratory stimuli to real materials

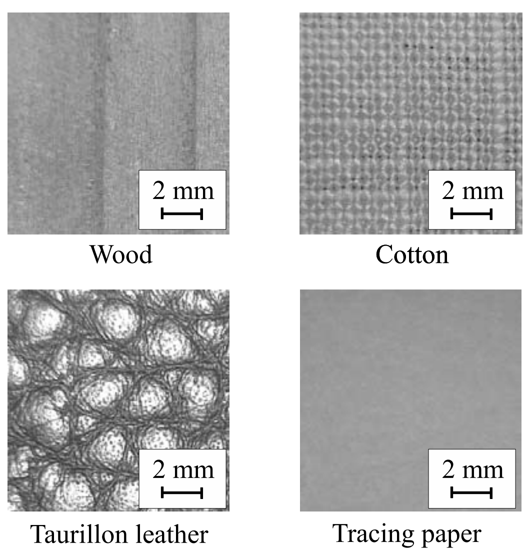

Fig. 10. Optical microscopy images of real materials to which vibratory stimuli were applied in experiments

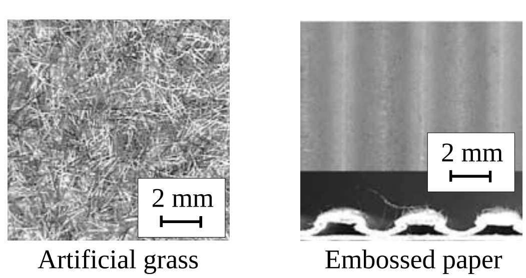

Fig. 11. Reference materials. Left: reference for fine roughness. Right: reference for macro roughness. Up: top view. Bottom: cross-sectional view.

a number, was compared with a reference value. For fine roughness, the reference material was fine artificial lawn grass, as shown in Fig. 11, that is typically used for dioramas or miniatures. This reference value was set at 50. Similarly, the roughness of an embossed paper that is also shown in Fig. 11 was used as a reference macro-roughness. This value was also set at 50. These references were provided to participants after every 18 trials (half section).

C. Results

Figs. 12 and 13 show the geometric averages of the roughness perceived by the participants upon application of fine and macro-roughness stimuli, respectively. As shown in Fig. 12, an increase in the amplitudes of the fine-roughness vibratory stimuli increased the perception of fine roughness. However, such an increase was not observed in the perceived macro-roughness. In contrast, an increase in the amplitudes of macro-roughness stimuli increased the perception of only the macro-roughness (Fig. 13).

The statistical relevance of the differences between the perceived roughness values was tested using two-way ANOVA. The vibrotactile stimuli or the lack of it and the type of material were used as factors for the analysis.

First, we tested the effects of application of fine-roughness vibrotactile stimuli. We compared the perceived fine roughness of the materials in absence of the vibrotactile stimuli and that perceived upon application of stimuli with $A_1 = 1.5$ μm (Comparison 1). From the analysis, we concluded that the application of fine-roughness stimuli significantly increased the perceived fine roughness ($F_0(1, 88) = 10.23$, $p = 1.92 \times 10^{-3}$). In contrast, the perceived macro roughness was not affected ($F_0(1, 88) = 1.69$, $p = 0.20$, Comparison 2). Furthermore, we observed similar results for $A_1 = 2.0\ \mu$m (data not included).

Next, we tested the effects of the application of macro-roughness vibrotactile stimuli. We compared the perceived fine-roughness (Comparison 3) and macro-roughness (Comparison 4) measured upon the application of the macro-roughness vibrotactile stimuli with amplitude of $A_2 = 1.5$ mm with that in the absence of the stimuli. While the macro-roughness vibrotactile stimuli did not significantly affect the perceived fine-roughness ($F_0(1, 88) = 0.78$, $p = 0.38$, Comparison 3), it did significantly affect the perceived macro-roughness ($F_0(1, 88) = 20.38$, $p = 1.96 \times 10^{-5}$, Comparison 4). Again, similar observations were made with $A_2 = 1.8$ mm.

The above analysis results indicate that the two methods for the presentation of roughness stimuli could selectively modify the perception of fine roughness and macro roughness.

VI. Conclusion

To the end of realizing tactile texture displays with sufficient quality, we devised a novel tactile display that uses real materials. We applied vibrotactile stimuli to real materials such as wood, cloth, leather, and paper, and modified their roughness sensations. To the best of our knowledge, this is the first attempt of using real materials in combination with vibrotactile texture stimuli. Hence, we testified the applicability of conventional roughness presentation methods to real materials through experiments. As a result, we confirmed that the perceived fine and macro-roughness could be selectively modified. Various vibrotactile texture methods, other than those described in the present study, should also be verified in the future for establishing techniques that assist product designers in selecting tactile sensations for their products.

Finally, one may concern the visuo-tactile cross-modal effects on our approach. For example, the users can feel a sheet of paper very rough with the vibratory stimuli applied whereas it looks as smooth as the ordinal paper. Such discrepancy between visual and tactile sensations may poorly reflect on the achievement of our approach. We suppose that small discrepancy between two modes is acceptable, however the limitation of the approach remains to be clarified.

Acknowledgment

We thank Prof. Susumu Hara, Nagoya University, for providing valuable advices. This study was supported in part by MEXT KAKENHI (23135514).

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