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A Method for Altering Vibrotactile Textures Based on Specified Materials

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Abstract— **A vibrotactile texture display produces virtual textures by applying vibratory stimuli to finger pads. In this study, we developed a technique to alter such textures based on certain specified materials. For example, the technique allows us to alter vibrotactile textures using terms such as "wood-," "cotton-," or "paper-like" which are familiar to end users of displays. The altered textures feel more similar to these specified materials. We realized this technique by constructing a material space, in which the materials are located based on the features of their vibrotactile spectra. The vibrotactile textures were then modified in this space. Our experimental results show that the technique can be used to alter a virtual wood texture to feel like cloth.**

I. INTRODUCTION

A tactile display is a device used for presenting cutaneous stimuli. In this article, we address a specific type of tactile display, a vibrotactile texture display. Such displays produce the tactile sensations of virtual material surfaces such as cloth and wood by applying vibratory stimuli to finger pads. Such texture displays are expected to be used for Internet shopping, virtual museums, or software programs with haptic feedback for mobile devices.

The purpose of this study is to provide a new method for altering vibrotactile textures based on specified materials. This method modifies a virtual material such that it becomes perceptually similar to other materials such as cloth, wood, or leather. One advantage of such modification is that the users of vibrotactile displays can design virtual textures by using the names of familiar materials without special knowledge regarding mechanical receptors, or the physical interactions between finger pads and materials. For example, with our technique, museum curators can create virtual textures of untouchable exhibits by using the names of specified materials. They can indicate a texture such as the mixture of cloth and wood. Then, through the use of texture displays, they can provide visitors with touch sensations of the exhibits.

Differences from related studies in terms of virtual texture designs at the end-user side

Tactile texture displays have not always been suitable for helping end users design virtual textures on their own. A typical tactile texture display is a pin matrix. Using this device, end users touch pins imitating the surface profiles of the intended materials or the pressure distributions within the contact area between the finger pads and the materials [1] [2] [3]. With this technique, end users need to specify the distribution of pin heights when designing virtual textures. Therefore, such devices are generally not easy for end users to use when designing virtual textures although Ikei et al. proposed a method for creating virtual textures for pin matrices based on photos of the materials [2]. Some tactile texture displays duplicate the shear force or friction that occurs between the materials and the finger pads during tactile exploration [4] [5] [6] [7] [8] [9]. To design textures using these texture displays, the end users need to know or be able to measure the frictional interactions. Ideally, however, such knowledge or procedure should not be required. Furthermore, some methods synthesize virtual textures by selectively stimulating the mechanical receptor classes [10] [11]. However, these methods are not for end users as they require specific knowledge of receptors.

One of the easiest methods for end users when designing textures is the synthesis of physical or psychophysical primitives. For example, Caldwell et al. developed a tactile texture display that can selectively control the heat, pressure, surface roughness, and slippage stimuli [12]. The authors then presented virtual materials by combining these physical primitives. Yamauchi et al. also proposed a method for synthesizing three types of psychophysical primitives, i.e., perceived roughness, softness, and friction, for vibrotactile texture displays [13]. Using these methods, the end users can potentially create and modify virtual textures by adjusting these familiar primitives. Our technology clearly differs from the methods in [12] and [13], which are based on specified physical and psychophysical properties, whereas our method is based on specified materials. Providing these methods together will be more helpful for end users when designing virtual textures.

II. ALTERING VIBROTACTILE TEXTURES BASED ON TEXTURE SPECTRA

Here, we describe our technique for altering vibrotactile textures based on specified materials. First, we configure a feature quantity space of cloth, wood, and leather. The feature quantities are generated based on the power spectra of vibrations that occur when a probe scans the material surfaces. The measurement of vibrations is described in sec. II-A. The methods used to compute the feature quantities and space are described in sec. II-B. The method used to alter the virtual textures is described in sec. II-C.

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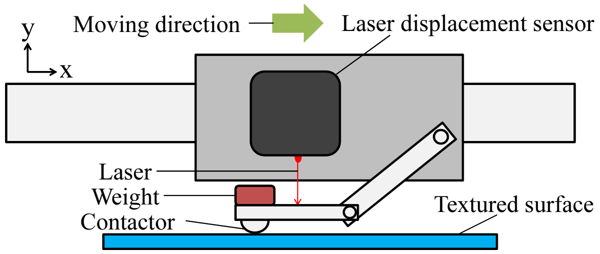


Fig. 1. Schematic diagram of the apparatus used for measuring the surface profile of a texture with sustained pressure

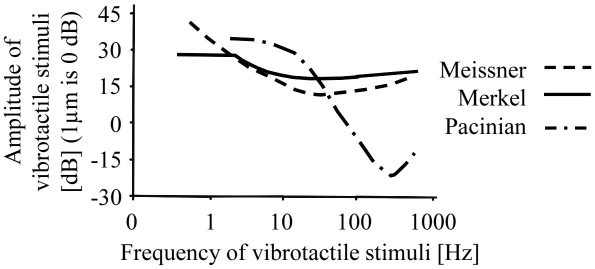


Fig. 3. Frequency characteristics of mechanical receptors: detection threshold (redrawn from [17])

A. Texture characteristics hidden in the spectrum of vibrotactile signals

Some studies have indicated a close relationship between the tactile sensations of material surfaces and the spectra of finger pad vibrations or deformations. For example, Bensmaïa and Hollins suggested that tactile differences between finely rough surfaces correlate with the differences between the power spectra of the high-frequency bands of the skin vibrations caused when stroking such surfaces [14]. Okamoto et al. showed that perceived differences in vibrotactile textures are represented by an index based on their spectra, including not only high-frequency bands but also bands of around a few tens of hertz [15]. Furthermore, Wiertlewski et al. showed that virtual materials can be presented even in the absence of a relative displacement between the finger pad and tactile display by maintaining the spectra of friction forces between them [9]. Based on these studies, we hypothesize that feature quantities related to the perceived characteristics of materials are extracted from the spectra of vibrotactile signals.

B. Feature quantities of vibrotactile textures

1) Measuring the vibration of a contactor with sustained pressure: Finger pad deformations depend on the surface profiles of the material during a tactile exploration. Some researchers have attempted the indirect measurements [14] [16]; however, the direct measurement of such finger pad deformations remains difficult to achieve. Hence, instead of real finger pad deformations, we measured the vibrations of a metal contactor using a load equal to a typical human force during a tactile exploration of 120 g. The contactor has a rigid hemisphere with a radius R of 4 mm, and was moved horizontally using a linear robotic arm (Fig. 1). Each material was measured for a randomly selected distance of 100 mm with a scanning speed of 20 mm/s. The displacements of the contactor were measured using a laser displacement sensor (CD5-30, OPTEX FA Co., Kyoto, Japan), the resolution of which was set to 0.02 μm. For the materials, we measured poplar wood, walnut wood, four types of clothes, and taurillon and vegetable-tanned leathers, as shown in Fig. 2. Each material was sampled thrice.

2) Feature quantity vector related to textures:

Role of mechanical receptors and frequency characteristics: Three types of mechanical receptors contribute to the detection of deformations in nonhairy parts of the skin. Fig. 3 shows the frequency threshold characteristics of these mechanical receptors for Meissner's, Merkel's, and Pacinian corpuscles. Meissner's and Merkel's corpuscles are relatively sensitive in a band of up to a few tens of hertz. The sensitivity of Pacinian corpuscles is considerably high in a band higher than approximately 100 Hz. We chose the feature quantities of the vibrotactile textures by considering their frequency characteristics, as described in the following section.

Method for extracting a feature quantity vector related to textures: We assume that the tactile sensations of material surfaces are influenced by the vibrotactile spectra unique to a material. We computed the amplitude spectra of the vibrations obtained in sec. II-B.1. We divided the frequency band of 0–500 Hz into ten subbands, and calculated the sum of the amplitude spectra for each subband. The sum of the amplitudes in the ith subband for material A was determined by

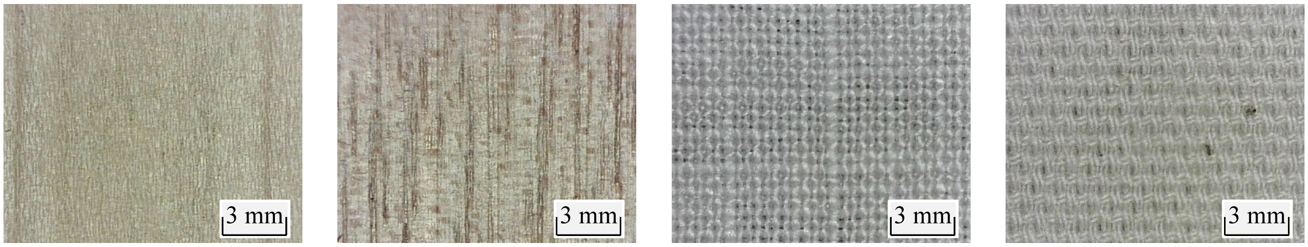
$$s_{Ai} = \int_{f_{i-1}}^{f_i} a(f)df \qquad (i = 1, \cdots, 10), \tag{1}$$

where f and $a(f)$ are the frequency and amplitude spectra, respectively. These sums were considered as the feature quantities related to the perceived characteristics of the materials. The intervals of integration are

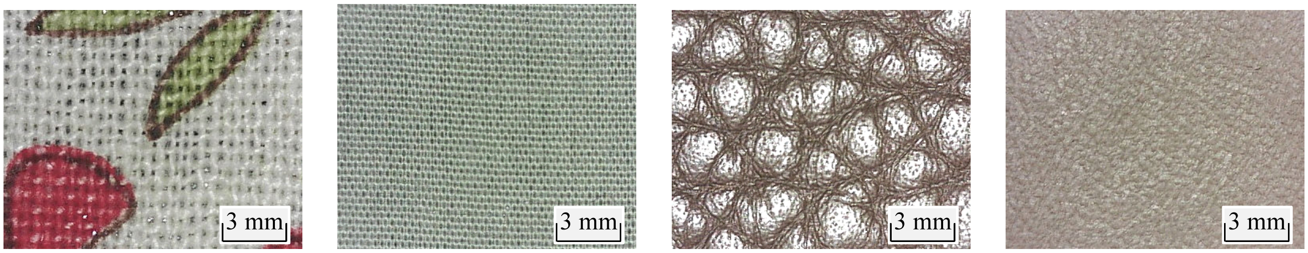
$$\begin{aligned}&\{f_0, f_1, \cdots, f_{10}\}\\ &\quad = \{0, 5, 10, 30, 50, 70, 100, 150, 250, 350, 500\}.\end{aligned} \tag{2}$$

We used narrow intervals for integration at lower frequencies, as the sensitivities of Meissner's and Merkel's corpuscles at the low-frequency bands are high, while the bands in which these receptors are more sensitive than the others are narrow. We used wide intervals for integration at high-frequency bands of more than 100 Hz since, in this wide band, the sensitivity of Pacinian corpuscles is markedly higher than the sensitivities of the other two types of corpuscles. The feature quantity vector related to the perceived characteristics of material A is expressed as

$$\boldsymbol{s}_A = (s_{A1}, s_{A2}, \cdots, s_{A10})^T. \tag{3}$$



(a) Wood (poplar) (b) Wood (walnut) (c) cloth A (cotton) (d) cloth B (linen)



(e) cloth C (roughly woven) (f) cloth D (finely woven) (g) Taurillon leather (h) Vegetable-tanned leather

Fig. 2. Measured materials

C. Space of texture features: Factor analysis of feature quantity vectors

We applied the factor analysis to feature quantity vectors of the materials to construct a factorial space of virtual materials. A factor analysis is a method used to present a variety of multivariates with fewer factors. As a result of the analysis, three factors were extracted. The implication of each factor can be known from its factor loadings. The factor loadings indicate the strength of the relationship between a factor and its multivariates.

For the first factor, its factor loadings for low-frequency bands were small, while those for high-frequency bands were high. Hence, a material whose first factor is large has high-frequency components. For the second factor, its factor loadings for high-frequency bands were small, and those of low-frequency bands were large. The second factor represents the magnitudes of low-frequency components. For the third factor, its factor loadings for the middle bands (30–70 Hz) were larger than those for the other bands. Hence, this factor features components of the middle-frequency bands.

The distributions of the materials in the factorial space are shown in Fig. 4. In the first and second dimensional planes (Fig. 4(a)), wood is located at the bottom. Coarse cloth (cloth A, B, and C) and leather are located in the upper part. Fine cloth (cloth D) is located at the center. In the second and third dimensional planes (Fig. 4(b)), wood is located in the left part. Coarse cloth (cloth A, B, and C) and leather are located in the right part. Fine cloth (cloth D) is located at the bottom. The same types of materials were located near each other in space, and thus, the feature quantities extracted from the vibrotactile spectra represent the characteristics of the materials well.

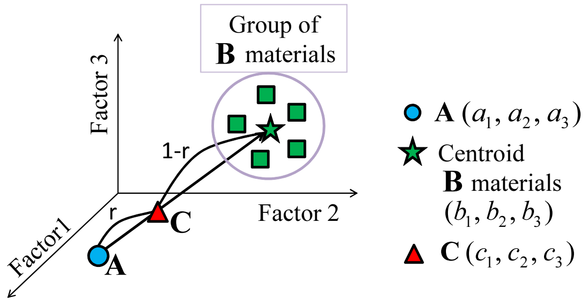


Fig. 5. Method for making texture A perceptually close to texture B

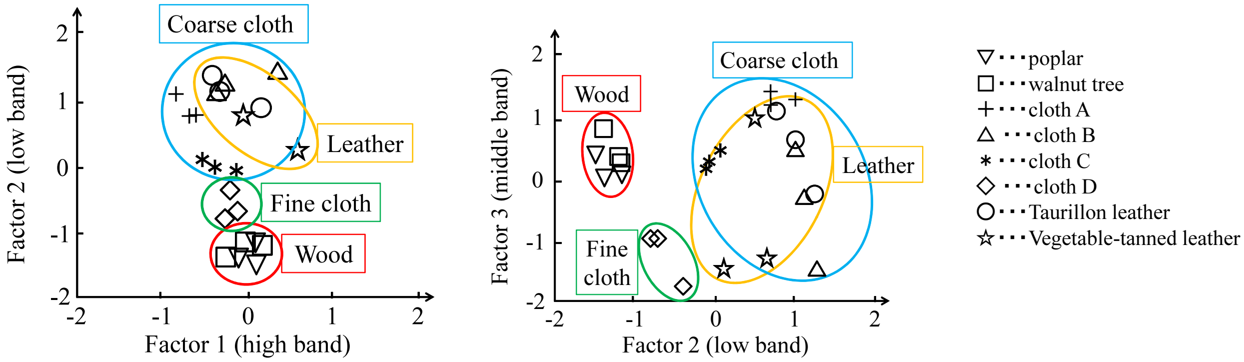
D. Method for altering vibrotactile textures based on specified materials

Here, we describe how to alter the vibrotactile texture of material A, such that it feels similar to that of material B. To achieve this, we generate material C on a line passing through material A and the center of the group of B materials, as shown in Fig. 5. The squares and the star represent the group of B materials and their centroid, respectively. The feature quantities of material C are very similar to those of material A, as material C is closely located to material A. However, the features of material C somewhat include those of material B. Hence, we consider material C to feel like a combination of materials A and B.

Let a_i and $\boldsymbol{a} = (a_1, a_2, a_3)^T$ be the ith factor score and coordinate of material A in the factorial space, respectively. In addition, r is a mixing ratio, which indicates how closely we make material A feel like material B. The position vector of material C in the factorial space is determined by

$$\boldsymbol{c} = r\boldsymbol{b} + (1 - r)\boldsymbol{a}. \tag{4}$$

In (4), $\boldsymbol{b}$ is the position vector of the center of the B materials. Given that the ith factor loading vector obtained by the factor analysis is $\boldsymbol{l}_i$, the feature quantity vector of material C is



(a) First and second factorial planes

(b) Second and third factorial planes

Fig. 4. Distribution of materials in factorial space

obtained by

$$\boldsymbol{s}_C \sim (\boldsymbol{l}_1,\boldsymbol{l}_2,\boldsymbol{l}_3)\begin{pmatrix}c_1\\c_2\\c_2\end{pmatrix}=\begin{pmatrix}s_{C1}\\s_{C2}\\\vdots\\s_{C10}\end{pmatrix}. \tag{5}$$

The amplitude spectra of material A are

$$\begin{aligned}\boldsymbol{a}_A &= (a_A(f), f=1,2,\cdots,500)\\ &= (\boldsymbol{a}_{A1-5},\boldsymbol{a}_{A6-10},\cdots,\boldsymbol{a}_{351-500})\end{aligned} \tag{6}$$

where f and $\boldsymbol{a}_{Al-m}$ are the frequency and the subvector consisting of the amplitudes for the frequencies of l to m, respectively. $\boldsymbol{a}_{Al-m}$ is determined by

$$\boldsymbol{a}_{Al-m} = (a_A(l), a_A(l+1),\cdots,a_A(m))\,. \tag{7}$$

The amplitude spectrum of material C is determined by

$$\begin{aligned}\boldsymbol{a}_C &= \left(\frac{s_{C1}}{s_{A1}}\boldsymbol{a}_{A1-5},\cdots,\frac{s_{C10}}{s_{A10}}\boldsymbol{a}_{A351-500}\right)\\ &= (a_C(1),a_C(2),\cdots,a_C(500))\,.\end{aligned} \tag{8}$$

Given that the phase spectrum of material C is identical to that of material A, the surface profile of material C is determined by

$$y(x)=\sum_{f=1}^{N}\left[a_C(f)\cdot\cos\left(\frac{2\pi f x}{N}+\angle C_A(f)\right)\right], \tag{9}$$

where x and $C_A(f)$ are a position on the material surface, and the complex number of the spectrum of material A, respectively. $y(x)$ is the surface profile of virtual material C, and is presented to the user of the texture display as vibrotactile stimuli.

III. EXPERIMENTAL APPARATUS

A. Vibrotactile texture display

The vibrotactile texture display used in this study is shown in Fig. 6. The dark gray parts were driven along the Y-axis, whereas the light toned parts were grounded. The users explored an acrylic plate along the X-axis of the display with their finger, and experienced Y-axial vibrotactile stimuli applied by the display. The display can present vibratory stimuli of more than 500 Hz, which covers the activation bands of the three types of mechanical receptors: Meissner ’ s, Merkel ’ s, and Pacinian corpuscles. We used a cylindrical-type voice coil motor (X-1740, Aoyama Special Steel Co., Tokyo, Japan) as the actuator. Its maximum thrust force was 2.42 N with a current of 0.96 A. The movement of the coil was restricted along the Y-axis, producing a sufficient amount of thrust.

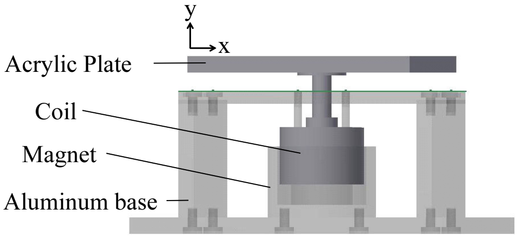


Fig. 6. Schematic illustration of the tactile display

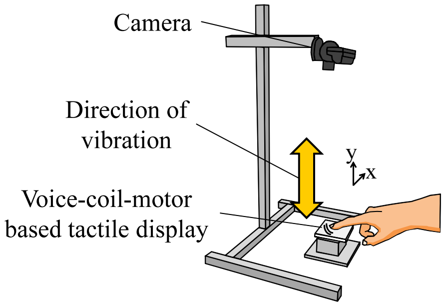


Fig. 7. Schematic illustration of the experimental apparatus

B. Experimental system

The experimental apparatus is shown in Fig. 7. This apparatus measures finger motion using a camera (PlayStation Eye, Sony Computer Entertainment Co., Tokyo, Japan), and presents vibration stimuli to the finger pad in response to the measured motions. The spatial resolution of the camera was 0.625 mm/pix. The control flow of the system is shown in Fig. 8. The participants in the experiment scanned the acrylic

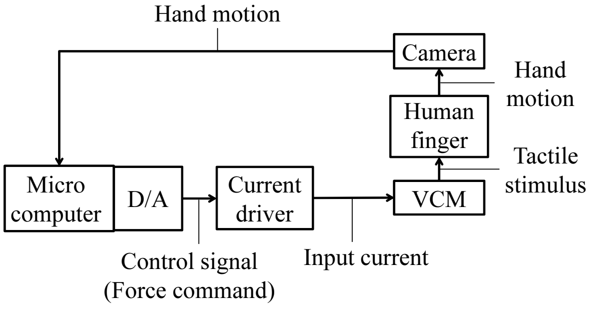


Fig. 8. Block diagram of the experimental apparatus

plate of the vibrotactile display with their index finger, which was attached to a red marker. The camera above the display calculated the position of the center of the marker. The positional information was sent to a microcomputer, which determined the displacements applied to the finger pad. Given that the finger position was $x(t)$, $y(x(t))$ determined by using (10) was presented to the participant's finger pad as vibrotactile stimuli.

IV. EXPERIMENTS ON ALTERING VIBROTACTILE TEXTURE

A. *Objective of the experiments*

In experiment 1, we tested four types of materials to select those most suitable for a vibrotactile display. In experiment 2, we investigated whether our method can alter vibrotactile textures based on the specified materials. For this, we used the materials chosen through experiment 1.

B. *Experiment 1: Materials suitable for a vibrotactile display*

1) Stimuli: The virtual materials used were made up of vibratory stimuli from four types of materials, poplar wood, cloth A (cotton), cloth B (linen), and taurillon leather. We expected that the participants would identify these four types of virtual materials successfully since they were able to correctly identify their real counterparts. The participants were informed in advance that these four types of virtual materials would be presented. However, they did not know the correspondence between the real and virtual materials. Each material was presented 20 times in random order. Hence, a total of 80 trials were conducted per participant.

2) Procedures: The participants touched the virtual materials one by one before identifying them. The participants were also allowed to touch the real materials freely during the experiment. They wore headphones, which played a pink noise to insulate the participants from the sounds generated by the voice coil motor. They were not blindfolded. Because the experiment was preliminary, the participants were three volunteers from our laboratory, none of whom are an author of this article.

3) Results of experiment 1: The average answer rates of experiment 1 are listed in tabel I. The participants were able to identify the vibrotactile stimuli of wood and linen, as their correct answer rates were higher than chance (0.25). In contrast, the correct answer rates of cotton and taurillon leather were not significantly higher than chance. These two materials were often confused, which is reasonable since they are closely located in the factorial space (Fig. 4). However, the tactile sensations of their real counterparts are not very similar and are easily identifiable. According to the introspective reports of the participants, the softness of taurillon leather was not presented well by the vibrotactile display. Softness is not represented by the vibrations. Hence, we have deemed taurillon leather unsuitable for our vibrotactile display. In experiment 2, we used wood, cotton, and linen. Cotton was expected to be recognizable among these three materials.

C. *Experiment 2: Verification of the method for altering vibrotactile textures based on the specified material*

The participants identified the virtual materials including cotton, linen, wood, and the one altered using the proposed method, which was a mixture of wood and cotton.

1) Stimuli: Four types of virtual materials were presented to the participants: cotton (cloth A), linen (cloth B), wood (poplar), and material X. Material X was a mixture of poplar and cotton, with poplar as the base material. Using the proposed method, we modified material X to feel similar to cotton, with $r = 0.2$. The participants were informed that the four virtual materials would be presented. As in experiment 1, they did not know the correspondence between the real and virtual materials. Each material was presented 20 times in random order. Hence, a total of 80 trials were conducted per participant.

2) Procedures: The participants touched the virtual materials, and identified whether they were cotton, linen, or wood. They were allowed to freely touch the real counterparts of these three virtual materials during the experiment. They wore headphones, and were not blindfolded. The participants were the same three volunteers from experiment 1.

3) Result of experiment 2: The average answer rates of experiment 2 are listed in tabel II. The correct answer rates of wood, cotton, and linen were 0.95, 0.52, and 0.95,

TABLE I

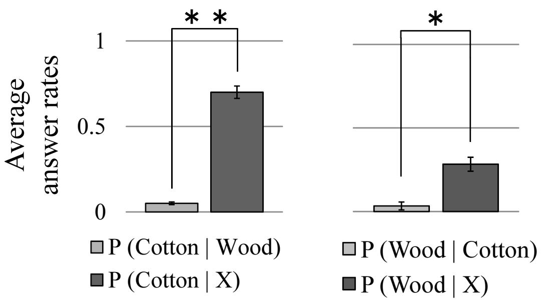
RESULTS OF EXPERIMENT 1: AVERAGE ANSWER RATES

		Perceived/Identified material			
		Poplar	Cotton	Linen	Leather
Presented virtual material	Poplar	0.77	0.18	0.02	0.05
	Cotton	0.02	0.27	0.42	0.30
	Linen	0.00	0.05	0.52	0.43
	Leather	0.15	0.60	0.12	0.13

TABLE II

RESULT OF EXPERIMENT 2: AVERAGE ANSWER RATIOS

		Perceived/Identified material		
		Poplar	Cotton	Linen
Presented virtual material	Poplar	0.95	0.05	0
	Cotton	0.03	0.52	0.45
	Linen	0	0.05	0.95
	X	0.28	0.70	0.02



(a) $P(\text{Cotton}|\text{Wood}) < P(\text{Cotton}|\text{X})$ (b) $P(\text{Wood}|\text{Cotton}) < P(\text{Wood}|\text{X})$

Fig. 9. (a) The rates at which wood and material X were answered as cotton, and (b) the rates at which cotton and material X were answered as wood. Material X was a mixture of poplar and cotton, and its base material was poplar. Using the proposed method, we modified material X to feel similar to cotton.

respectively. These rates were higher than chance (0.33). Hence, the participants were sufficiently able to identify the vibrotactile textures of these materials.

Material X was determined to be wood and cotton at rates of 0.28 and 0.7, respectively. We tested whether material X felt similar to cotton by comparing the answer rates. The results of the t-test are shown in Fig. 9. Let $P(\text{Cotton} \mid \text{Wood})$ be the probability of the participants answering cotton for the wood material. $P(\text{Cotton} \mid \text{X})$ is the probability of the participants answering cotton material for the material X. We determined that $P(\text{Cotton} \mid \text{Wood}) < \mathrm{P}(\text{Cotton} \mid \text{X})(\mathrm{t_0}(4) = 7.12, \mathrm{p} < 0.01$, two-tailed), and $P(\text{Wood} \mid \text{Cotton}) < \mathrm{P}(\text{Wood} \mid \text{X})(\mathrm{t_0}(4) = 2.79, \mathrm{p} < 0.05$, two-tailed). Hence, material X is more similar to cotton than to the original wood. These results indicate that material X feels like a mixture of wood and cotton. Therefore, our technique was successful in altering the vibrotactile texture of wood based on cotton, and made the wood feel somewhat similar to cotton. This result should be tested for a sufficient number of paticipants and variety of materials in the future.

V. CONCLUSIONS

We developed a technique for altering vibrotactile textures based on specified materials. The technique enables the end users of a texture display to modify the textures using terms such as "wood-," "cloth-," or "paper-like," which does not require knowledge regarding the mechanical interactions between human finger pads and material surfaces or mechanical receptors. Our method utilizes the feature quantity spaces of materials, which were displaced based on the features of vibrotactile spectra. The spectra were observed by probing the materials. The textures were modified in this space such that their feature quantities approached those of the specified materials. We conducted two types of experiments using a vibrotactile texture display with a voice coil motor to verify the effectiveness of our technique, and verified the effectiveness of our method through material identification. Using our method, we altered a wood texture to feel similar to cotton. The participants of our experiments identified this altered texture more frequently as cotton than as the original wood texture. As a following study, we will apply the technique to various types of materials to further establish its effectiveness.

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