Toward augmented reality of textures: Vibrotactile high-frequency stimuli mask texture perception to be rougher or smoother?

Shuhei Asano, Shogo Okamoto, and Yoji Yamada
Department of Mechanical Science and Engineering,
Graduate School of Engineering, Nagoya University, Nagoya, Japan.

***Abstract*—Augmented reality technology realizes variable sensory feedback while maintaining a high perceptual quality by superposing real and virtual stimuli. In this research, we experimentally verified whether the masking effects of high-frequency vibrotactile stimulation on fingers is applicable to augmented reality of the tactile texture of materials. A vibrotactile stimulator was worn on a finger (ring-vibrating condition) or mounted on materials (material-vibrating condition). We investigated the effect of vibratory stimuli on perception of sand-paper roughness under these two conditions. Under both conditions, participants' performances to discriminate the roughness diminished because of the masking effects of the high-frequency vibratory stimuli (experiment 1). Subsequently, we specified how the masking effects influenced the perceived roughness using Scheffe's paired comparison. For the ring-vibrating condition, as accelerations of the vibrotactile stimuli increased, all participants reported a decrease in the perceived roughness of the sand-paper. For the material-vibrating condition, the roughness percepts increased or decreased depending on the individual (experiment 2). Although both implementation methods affect roughness perception, the ring-vibrating condition is recommended for augmented reality of tactile textures because it can steadily control the decrease in perceived roughness of touched materials.**

***Index Terms*—Tactile display, Vibration stimulus, Haptics**

I. Introduction

Augmented or mixed reality is a concept that was originally developed and has been actively studied for auditory and visual sensations, however, techniques for haptic sensations have also been developed, recently. For example, some research groups demonstrated that force feedback change the percepts of viscoelasticity of a soft material when touched using haptic displays [1], [2]. The manipulation of perceived shapes of touched objects has also been attempted [3]. Robotic surgery is potentially one of the promising areas where augmented or mixed reality of haptic sensations could be advantageous [4], [5], [6], [7]. A clear benefit of the introduction of augmented reality to haptics is the improvement of stimulus quality. Unlike audio and visual displays, the quality of haptic feedback represented by haptic stimulators remains unsatisfactory for commercial use. However, augmented reality allows us to combine complicated haptic experiences due to real physics and variable force feedback by haptic displays. The haptic properties of objects can be partly controllable while maintaining quality feedback from real objects.

Augmented reality can also be applied to percepts of tactile textures. For example, the perceived roughness of material surfaces is increased by noisy sound cues that synchronize hand exploratory motions [8]. Increase in the perceived roughness of materials can also be achieved by applying vibrotactile stimuli to materials [9]. A vibrotactile display mounted on nails [10] can be potentially used for similar purposes. These studies have outlined the augmented reality techniques for increasing roughness percepts of material surfaces. However, techniques to reduce the perceived roughness have yet to be reported. Once such techniques are realized, augmented reality techniques will be able to both increase and decrease the tactile roughness of textures. To aid in the development of the underlying technology for augmented reality of texture perception, this study investigates the effects of vibrotactile stimuli on the reduction of perceived roughness of material surfaces.

Because aurally communicating how a texture feels is difficult, a system that allows us to experience tactile textures will potentially enhance the process of designing the textures of products. Fig. 1 shows one possible application of this technology in the field of industrial design. We imagine that two industrial designers discuss the textures of cloths that are used to cover a certain product. They each are holding a sample of the cloth, and one of them is attempting to deliver his desires. However, aurally communicating these desires is difficult. Augmented reality technology for textures will be of potential benefit in these situations. The two designers can adjust and share tactile experiences of the textures using the augmented reality tool. Preparing a plethora of cloth samples is also a practical solution; however, the augmented reality technology enables users to interpolate those samples. Such sharing of tactile experiences is more effective when the two parties are unable to meet in person or talk by phone.

a) Objectives: As shown in Figs. 2 and 3, the implimentation of augmented reality is classified into two types according to whether the sensory display is installed on the body or in the environment. In the present research, in one case, users wear a vibrotactile display on their finger, and in the other case, the material being touched is mounted on a vibrotactile display. Based on the principles described later, these two types of approaches potentially have different capa-

978-1-4799-0652-9/13 $31.00 © 2013 IEEE
DOI 10.1109/SMC.2013.93

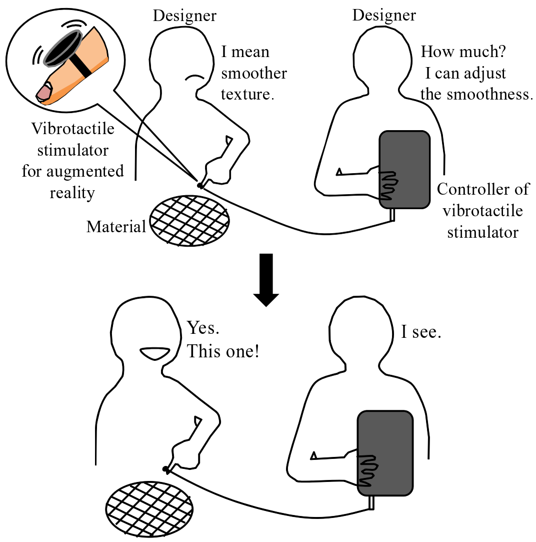

Fig. 1. Application image of augmented reality technology for tactile textures

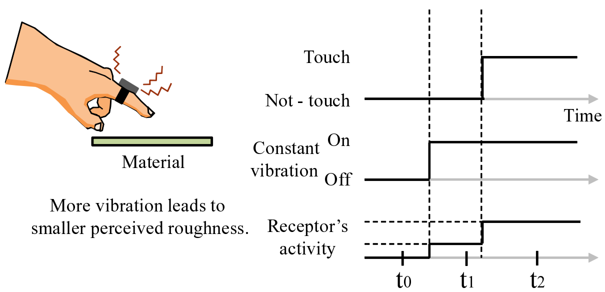

Fig. 2. Ring-vibrating case

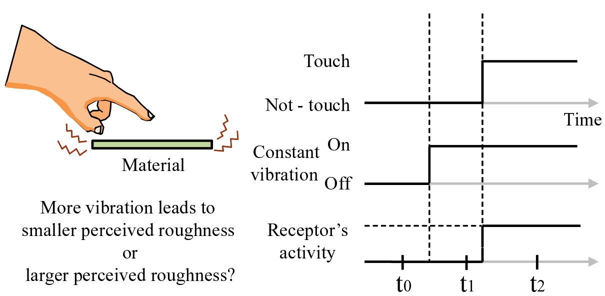

Fig. 3. Material-vibrating case

bilities, hence, this study experimentally investigates whether one or both can effectively decrease the roughness percepts of material surfaces. We then recommend one approach as a suitable augmented reality technique for tactile textures.

b) Principles: When a human finger contacts an object's surfaces, the finger pad deforms. Along with this deformation, cutaneous receptors are activated, and resultant nervous signals reach the central nervous system and yield a sense of the material's surface. These receptors are masked or adapted by vibrotactile stimuli. In particular, receptor units known as FAII readily adapt to the stimuli, and humans feel materials as being less rough or smooth while the adaptation remains in effect [11]. This situation is similar to what we experience when our hands are chilled and less sensitive to textures in the winter. FAII units are specifically masked by the frequency around 250 Hz. These units are selectively influenced when the vibrotactile masking stimuli are small, however, as the stimuli becomes larger, other receptor units are also adapted [12]. Because of masking effects, the capability to detect vibrotactile signals is significantly diminished [12]. These facts suggest that using a masking effect caused by vibrotactile stimuli, will diminish the material roughness perceived by humans.

$p(t)$ and $a(t)$ denote the magnitude of roughness perceived by humans and the activity level of cutaneous receptors at time t, respectively. $a(t)$ is a monotonically increasing function of the mechanical deformation or stimuli applied to a finger pad. The activity of the receptors increase with external stimuli. This model is sound as long as there is no significant adaptation due to long-term exposure to stimuli. In the later experiments, in order to prevent such long-term exposure, the participants' exploratory behaviors toward materials are controlled. It is speculated that human roughness perception is characterized by the distinction in receptor's activity levels between before and after touching materials. Hence, roughness experienced by touching a material at t is described as

$$p(t) = f(a(t) - a(t_0)) \tag{1}$$

where t_0 is the moment before the material is touched. Function $f(\cdot)$ links the receptor activities and roughness perception, and the following discussion is not restricted as long as it is a monotonically increasing function.

c) Hypothesis 1: Ring vibrotactile stimulator reduces the perceived roughness of materials: Here, we consider the case in which a vibrotactile stimulator is worn on a finger, as shown in Fig. 2. At t_0, there is neither vibratory stimuli nor contact between the finger and material. At t_1, the ring-type vibrotactile stimulator produces constant vibratory stimuli. During this period, $a(t_1) > a(t_0)$ because receptor's activity is increased by the stimuli. At t_2, the finger contacts and begins exploring the material. The receptor activity then further increases, and $a(t_2) > a(t_1)$. The perceived roughness is expressed by

$$p(t_2) = f(a(t_2) - a(t_1)). \tag{2}$$

The receptors have a maximum activity level: $a(t) < a_{\max}$. Therefore, when $a(t_1)$ or $a(t_2)$ reaches or is close to this level, the roughness is barely perceived when touching rough materials. For example, with stimuli large enough to saturate the activity level, $a(t_1) = a_{\max}$, and $a(t_2) = a(t_1)$. Perceived roughness then becomes zero as $p(t_2) = f(0|a(t_1), a(t_2) = a_{\max})$. This speculation is consistent with the masking effect previously described. Based on these ideas, the first hypothesis is that when the masking effect from the ring-type vibrotactile stimulator prevails, human perception of the material's roughness is diminished.

d) Hypothesis 2-1: Vibration applied to materials increases the perceived roughness of materials: Here, we consider the case in which material is mounted on a vibrotactile stimulator, as shown in Fig. 3. At t_0, the finger does not contact the material. At t_2, the finger contacts and begins exploring the vibrating material. The perceived roughness is expressed by

$$p(t_2) = f(a(t_2) - a(t_0)). \tag{3}$$

Suppose that $a'(t_2)$ denotes the receptors' activity caused by touching the material without vibratory stimuli, $a(t_2)$ is larger than $a'(t_2)$ because of the effects of vibratory stimuli. Accordingly, $p(t_2)$ is larger than $p'(t_2)$, which is the roughness percept of material without vibration. Thus, we hypothesized that the vibrotactile stimuli applied to the material increase the perceived roughness of the material when touched.

e) Hypothesis 2-2: Vibration applied to materials reduces the perceived roughness of the materials: It is possible that vibrating the material decreases the perceived roughness of the material. The material-vibrating condition may affect the percepts the way the ring-vibrating condition does. Hence, based on the same interpretation as hypothesis 1, the material-vibrating condition may affect perceived roughness.

As described above, this study experimentally tests these partly contradicting hypotheses. It should be noted that we value the experimental evidence to establish the augmented reality techniques as much as or more than the underlying perceptual mechanisms.

As a third hypothesis, the vibrotactile stimuli may not affect the roughness perception of materials, mainly because the vibratory stimuli are provided independently from the material properties and human hand motions. However, as shown in experiment 1 later, this idea does not hold.

II. Experimental Setup

We used two types of vibrotactile stimulators. The first one vibrated the textured surfaces attached on it. The second one was worn on the human finger and vibrated the finger itself.

A. Vibrotactile stimuli imposed to materials

The first one presented a tactile stimulus vibration to material by driving a voice coil motor (X-1740, Aoyama Special Steel Co. Ltd., maximum force: 2.42 N) as an actuator. Fig. 4 shows a schematic representation of this vibrotactile apparatus. The material, acrylic plate, and coil were combined. These three parts of the display are colored, and base-restraining bar, magnet and aluminum are displayed transparent. The vibrating direction was perpendicular (Z axis) to the plane of the tracing movement (X-Y plane). The textured surfaces were replaceable. The motor was driven using a current driver (Copley Controls, ACJ-090-03, MA) and function generator.

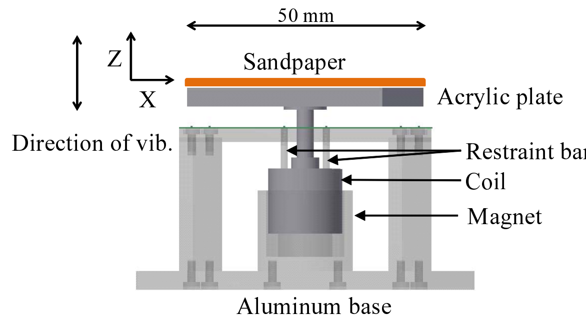

Fig. 4. Schematic representation of material-type vibrotactile display based on voice coil motor

B. Ring-type vibrotactile stimulator

The second device was a ring-type vibrotactile stimulator. Participants were fitted with a small recoil-type actuator (Haptuator mark II, A. Berrezag at UPMC, France) on the back of the index finger between the DIP and PIP joints using adhesive bands as shown in Fig. 5. A tactile stimulus was presented by vibrating the actuator in the longitudinal direction of the finger. A current driver (Copley Controls, ACJ-090-03, MA) and function generator were also used to control the vibrations of the actuator.

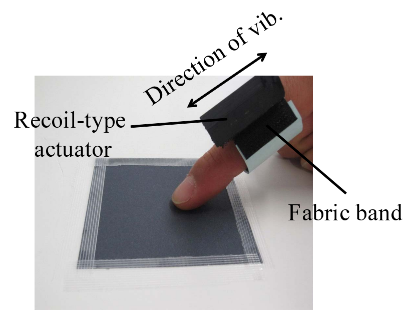

Fig. 5. Picture of index finger mounted with a ring-type vibrotactile stimulator

III. Experiment 1: Masking effects of high-frequency vibrotactile stimuli on roughness discrimination

A. Objective

As described previously, in order to reject the third hypothesis before testing hypotheses 1 and 2, we confirm the effects of vibrotactile stimuli on roughness perception under both material- and ring-vibrating conditions. For this purpose, experiment 1 tests the masking effects of vibrotactile stimuli using roughness discrimination tasks.

B. Tasks and participants

We invited five male volunteers from the authors' laboratory to participate in the study. The authors did not participate in any of the experiments. The participants were blindfolded, wore headphones, and listened to pink noise to mask the sounds generated by the voice coil motors. The participants compared two types of sand-paper and selected the rougher one in the following two tasks.

f) Task 1: Material-vibrating condition: Participants compared two types of sand-paper to which vibratory stimuli were applied. We restricted the participants' exploratory hand movements to two reciprocations for each type of sand-paper to prevent adaptation. As a result, it took as long as 2–3 s to scan one sheet of sand-paper. As a control condition, the participants also compared the two types of sand-papers without vibrating stimuli. In total, twenty trials were conducted for each participant, with ten trials for each condition. There was a 10 s rest between trials. The two conditions were randomly switched.

g) Task 2: Ring-vibrating condition: Participants wore the ring-type vibrotactile stimulator on their index finger and compared two sheets of sand-paper. To prevent adaptation to the vibrotactile stimuli, they were instructed to commence the exploration as soon as the vibration started. Similarly to task 1, the number of reciprocatory hand motions was limited to two. Therefore, the time required for one trial or comparison was at most 5 s. The participants also compared two sheets of sand-paper with no vibrotactile stimuli as a control condition. Twenty trials, ten for each condition, were conducted for each participant in a random order.

C. Stimuli

We used two types of sand-paper (50 × 50 mm) of #1500 and #2000 roughness. The frequency of vibrations was set to 250 Hz for both the material- and ring-vibrating conditions. For the material-vibrating condition, the peak-to-peak acceleration of the vibrotactile stimulus was ± 3.44 m/s^2, which corresponded to an amplitude of ± 0.697 μm. The peak-to-peak acceleration was measured by an accelerometer (Analog Devices Corp. ADXL335, MA) attached to the acrylic plate shown in Fig. 4. During the measurement, the finger was kept on the plate with the approximate load of 1.5 N. This load is comparable with the one observed during the exploratory tasks. For the ring-vibrating condition, the peak-to-peak acceleration of the vibrotactile stimulus was ± 39.3 m/s^2, which corresponded to an amplitude of ± 15.93 μm. The accelerometer was glued to the ring-type vibrotactile stimulator and measured these values. Similar to the material-vibrating condition, the finger was in contact with the material during the measurement.

D. Results

Fig. 6 shows the results of experiment 1. The percentages of correct answers illustrated on the vertical axis are means and standard deviations for five participants. The two graphs on the left are the results for the material-vibrating condition. The percentage of the correct answers was 82% ± 9.8% when comparing the sand-paper without vibration. The percentage of correct answers was 38% ± 16% when using the material-vibrating condition. The statistical relevance of the differences between the percentage of correct answers was tested using one-way analysis of variance. The presence of vibrotactile stimuli or the lack of it was used as a factor for the analysis.

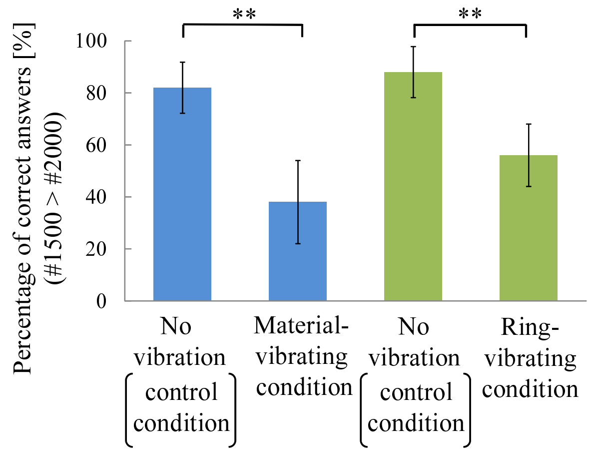

Fig. 6. Answer ratios at which participants selected #1500 as rougher than #2000, with and without vibrotactile stimuli. ∗∗ indicates a significance level of 1%.

From the analysis, we concluded that the application of high-frequency stimuli significantly decreased the percentage of correct answers ($F_0(1, 8) = 22.0$, $p = 1.561 \times 10^{-3}$).

The two graphs on the right in Fig. 6 are the results for the ring-vibrating condition. The percentage of correct answers was 88% ± 9.8% when comparing the sand-paper without vibration. While the percentage of the correct answers was 56% ± 12% when using the ring-vibrating condition. From the analysis, we concluded that the application of high-frequency stimuli significantly decreased the percentage of correct answers ($F_0(1, 8) = 17.07$, $p = 3.29 \times 10^{-3}$).

In each of the results, the correct answer rate for conditions with vibration was lower than that for the control conditions. Furthermore, these answer ratios were near chance level, which indicates that the participants could not discriminate the two types of sand-paper when vibrations were applied to fingers. Hence, the masking effects on roughness perception were confirmed for both the material- and ring-vibrating conditions.

IV. Experiment 2: Subjective Ratings of Sand-Paper Masked by Vibrotactile Stimuli

A. Objective

Using roughness rating tasks, experiment 2 investigates whether vibrotactile stimuli decrease (hypotheses 1 and 2-2) or increase (hypotheses 2-1) the material roughness perceived by participants.

B. Tasks and participants

The experiment was performed by the method of Scheffe's paired comparison. The participants compared the surface roughness of paired stimuli that were a sheet of sand-paper with constant vibrations of different amplitude levels applied to it or their finger. Sand-paper without applied vibrations was also included in the stimuli set. Participants responded with one of four answers: much rougher, rougher, slightly rougher, and the same. To prevent adaptation, the movement of the index finger was limited to two reciprocations for each stimulus. The five participants from experiment 1 participated in experiment 2. They performed comparisons under the material and ring vibrating conditions. Two of the five participants tested the material-vibrating conditions first, followed by the ring-vibrating conditions. The other participants tested the conditions in the opposite order. Similarly to experiment 1, aural and visual stimuli were masked during the tasks.

C. Material

The material was a sheet of sand-paper (#500). Basically, the participants compared this sand-paper under different vibration levels, and our main interest was in the effects of vibrations on ratings of perceived roughness. However, we also used #600 with no vibrations such that the participants would not easily guess that a single type of sand-paper was used for all stimuli, and only the vibration levels varied. According to introspective reports after the experiments, all the participants were unaware that most of the stimuli were based on sand-paper of a single roughness grade.

D. Vibration

Material-vibrating condition: Three levels of vibrations at 250 Hz were prepared. They were 1.68, 1.72, and 2.17 m/s^2 in peak-to-peak acceleration. These values corresponded to peak-to-peak amplitudes of 0.68, 0.70, and 0.88 μm, respectively. In total, five types of stimuli were compared. They were #500 and #600 with no vibration and #500 with three vibration levels. Ten pairs formed from the five stimuli were tested with two repetitions for each pair. For the second trial of each pair, the order of presentation of paired stimuli was inverted. Hence, twenty trials were conducted for each participants.

Ring-vibrating condition: The peak-to-peak accelerations of three vibration levels were 30.11, 39.32, and 48.53 m/s^2. These values corresponded to the peak-to-peak amplitudes of 12.16, 15.94, and 19.67 μm, respectively. As for the material-vibrating condition, five types of stimuli were used. They included #500 and #600 without vibration and #500 with the above three levels of vibrations. Twenty trials were performed similarly to those for the material-vibrating conditions.

E. Results

We assigned scores ranging from 3 to 0 to the four answers, with 3 being "much rougher" and 0 being "the same." The scores from each stimulus were then summed. Tables I and II show the averaged scores for each stimulus. By definition, the larger scores represent larger perceived roughness. The smaller or negative scores represent smoother percepts.

For both conditions, #500 with no vibration was perceived rougher than #600 with no vibration, which indicates the consistency of the experiments. In the material-vibrating condition (Table I), three participants responded the perceived roughness increased (Group 1), and the others responded that perceived roughness decreased (Group 2) as the magnitudes of vibration increased. In other words, the effect on the perceived roughness was dependent on the individual.

TABLE I
PERCEIVED ROUGHNESS VALUES UNDER MATERIAL-VIBRATING CONDITION. LARGER SCORES INDICATE ROUGHER PERCEPTS.

		Stimuli				
		#500 no vib.	#500 weak vib.	#500 middle vib.	#500 strong vib.	#600 no vib.
G 1	P 1	-12	-2	2	-2	-14
	P 2	-3	6	7	12	-9
	P 3	3	6	3	4	-6
	Ave.	-4	3.3	4	4.6	-9.6
G 2	P 4	3	-10	-9	-12	-2
	P 5	15	-2	0	1	5
	Ave.	9	-6	-4.5	-5.5	1.5

TABLE II
PERCEIVED ROUGHNESS VALUES UNDER RING-VIBRATING CONDITION. LARGER SCORES INDICATE ROUGHER PERCEPTS.

	Stimuli				
	#500 no vib.	#500 weak vib.	#500 middle vib.	#500 strong vib.	#600 no vib.
P 1	13	-7	-6	-8	14
P 2	21	-1	-2	-7	10
P 3	6	-4	-10	-8	7
P 4	12	0	-4	-8	6
P 5	10	-1	-6	-7	10
Ave.	12.4	-2.6	-5.6	-7.6	9.4

As shown in Fig. 7 and Table II, in the ring-vibrating condition, the most participants agreed that the perceived roughness monotonically decreased in accordance with the acceleration of the vibrotactile stimuli.

V. DISCUSSION AND CONCLUSION

To aid in the development of augmented reality technology for tactile texture perception, we examined the effect of decreasing the perceived roughness of the material surface using constant high-frequency vibrotactile stimuli (250 Hz). We prepared two methods for presenting vibrotactile stimuli to participants: ring- and material-vibrating conditions. Under the ring-vibrating condition, a vibrotactile stimulator worn on the

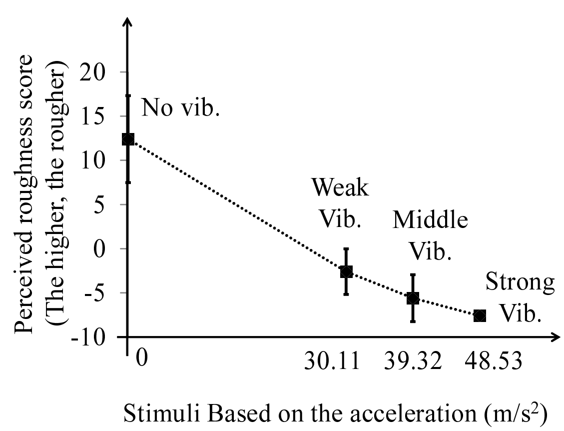

Fig. 7. The effects of vibrotactile stimuli on perceived roughness of sand-paper (#500) under ring-vibrating condition.

index finger vibrated the finger. Under the material-vibrating condition, material mounted on voice coil motor was vibrated. These two conditions are considered typical configurations for augmented reality.

In experiment 1, we presented a high-frequency vibrotactile stimulus to the participants. It was difficult for them to discriminate the perceived roughness of sand-paper, nevertheless, they could do so under the non-vibrating condition. Hence, in either vibrating condition, the tactile vibration stimulus affected the perceived roughness. These results did not support the third hypothesis that presenting constant vibrotactile stimuli to the finger does not affect the perceived roughness of a material.

In experiment 2, we investigated whether the perceived roughness of sand-paper increases or decreases under the two types of vibrating conditions using roughness rating tasks to verify the hypotheses 1 and 2. For the ring-vibrating condition, as the acceleration of the vibration increased, the perceived roughness of sand-paper decreased for all participants. For hypothesis 1, the perceived roughness of the materials was diminished by the masking effect of the ring-vibrating condition.

For the material-vibrating condition, as the acceleration of the vibration increased, three of the five participants reported an increase in the perceived roughness (consistent with hypothesis 2-1), and the others reported a decrease in the perceived roughness (consistent with hypothesis 2-2). Thus, individual differences in the effect on the perceived roughness were observed under the material-vibrating condition.

One of the reasons that individual differences occurred may be the difference in the speed at which participants traced the sand-paper. Normally, the tracing speed leads to differences in vibratory frequency occurring at the skin, and it contributes to the perceived roughness of fine textures. As the tracing speed increases, the frequency of the skin vibration increases. However, the stimulator presents a constant stimulus at 250 Hz, and it does not depend on the speed at which the sand-paper is traced. In this case, the participant whose tracing speed is relatively slow feels a higher spatial frequency of the sand-paper surface. As the spatial frequency increases or the spatial wavelength of the sample surface decreases, the perceived roughness decreases [13], [14]. Consequently, the difference in tracing speed might lead to these reported individual differences. Unfortunately, because we were unable to record the tracing movements of the participants, we cannot compare the results between tracing speeds and reported roughness.

Another possibility is that differences in the way to trace the sand-paper led to individual differences. It is likely to establish the interpretation of the hypothesis 2-1, when tracing smoothly the sand-paper. On the other hand, in the case of the hand movement is not smooth and intermitted, participants felt the vibrotactile stimuli in the material-vibrating condition despite their hand hardly moving. Because this is closer to the ring-vibrating condition, the interpretation of the hypothesis 2-2 will be established. Consequently, there may be individual differences in the material-vibrating condition because of differences in the way to trace the sand-paper of participants.

Whether either reason above is correct, a constrained tracing method is necessary to decrease the perceived roughness for the material-vibrating condition. It is not preferable for user to demand such a limitation in augmented reality technique. In addition, individual differences observed under the material-vibrating condition were not confirmed under the ring-vibrating condition. Thus, the ring-vibrating condition is recommended as an augmented reality technique to decrease the perceived roughness of materials.

Acknowledgment

We thank Mr. Amir Berrezag at ISIR in UPMC for discussing the research. This study was supported in part supported by Shitsukan (23135514 and 25135717).

References

[1] S. Jeon, S. Choi, and M. Harders, “Rendering virtual tumors in real tissue mock-ups using haptic augmented reality,” *IEEE Transactions on Haptics*, vol. 5, no. 1, pp. 77–84, 2012.

[2] Y. Kurita, A. Ikeda, K. Nagata, and T. Ogasawara, “Haptic augmentation utilizing the reaction force of a base object,” *Journal of Robotics and Mechatronics*, vol. 20, no. 1, pp. 72–79, 2013.

[3] Y. Ban, T. Narumi, T. Tanikawa, and M. Hirose, “Modifying an identified size of objects handled with two fingers using pseudo-haptic effects,” *Proceeding of the Joint Virtual Reality Conference of ICAT - EGVE - EuroVR EG Symposium*, pp. 1–8, 2012.

[4] G. Brandt, A. Zimolong, L. Carrat, P. Merloz, H.-W. Staudte, S. Lavallee, K. Radermacher, and G. Rau, “Crigos: a compact robot for image-guided orthopedic surgery,” *IEEE Transactions on Information Technology in Biomedicine*, vol. 3, pp. 252–260, 1999.

[5] M. Jakopec, S. J. Harris, F. R. y Baena, P. Gomes, J. Cobb, and B. L. Davies, “The first clinical application of a “hands-on” robotic knee surgery system,” *Computer Aided Surgery*, vol. 6, no. 6, pp. 329–339, 2001.

[6] L. Moody, A. Waterworth, A. D. McCarthy, P. J. Harley, and R. H. Smallwood, “The feasibility of a mixed reality surgical training environment,” *Virtual Reality*, vol. 12, pp. 77–86, 2008.

[7] V. Francoise, A. Sahbani, and G. Morel, “A comanipulation device for orthopedic surgery that generates geometrical constraints with real-time registration on moving bones,” *Proceedings of the IEEE International Conference on Robotics and Biomimetics*, pp. 38–43, 2011.

[8] Y. Suzuki and Y. Kawachi, “Modulation of tactile motion by intra- and inter-modal manipulation,” *Proceedings of the IEEE World Haptics Conference*, pp. 49–52, 2011.

[9] S. Asano, S. Okamoto, Y. Matsuura, H. Nagano, and Y. Yamada, “Vibrotactile display approach that modifies roughness sensations of real textures,” *Proceedings of the 2012 IEEE International Symposium on Robot and Human Interactive Communication*, pp. 1001–1006, 2012.

[10] M. Niwa, T. Nozaki, T. Maeda, and H. Ando, “Fingernail-mounted display of attraction force and texture,” *Proceeding of the EuroHaptics*, pp. 3–8, 2010.

[11] G. A. Gescheider, S. J. Bolanowski, T. G. Greenfield, and K. E. Brunette, “Perception of the tactile texture of raised-dot patterns: A multidimensional analysis,” *Somatosensory and Motor Research*, vol. 22, no. 3, pp. 127–140, 2005.

[12] G. A. Gescheider, R. T. Verrillo, and C. L. van Doren, “Prediction of vibrotactile masking ffunctions,” *Journal of Acoustical Society of America*, vol. 72, pp. 1421–1426, 1982.

[13] C. E. Connor, S. S. Hsiao, J. R. Phillips, and K. O. Johnson, “Tactile roughness: Neural codes that account fo psychophysical magnitude estimates,” *Journal of Neuroscience*, vol. 10, pp. 3823–3836, 1990.

[14] E. M. Meftah, L. Belingard, and C. E. Chapman, “Relative effects of the spatial and temporal characteristics of scanned surfaces on human perception of tactile roughness using passive touch,” *Experimental Brain Research*, vol. 132, pp. 351–369, 2000.