Roughness Modulation of Real Materials Using Electrotactile Augmentation

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Abstract. In this paper, we present a roughness modulation technique that employs electrotactile augmentation to alter material texture perception, which is conducted through mechanically unconstrained touch. A novel electrotactile augmented reality system that superimposes modulating nerve activity onto afferent nerves at the middle phalanx of a finger is described. We conducted a user study in which participants were requested to rate the roughness of real materials that were explored using the system. The results indicated that participants could perceive the modulated fine- and macro-roughness via the electrotactile augmentation.

Keywords: Haptic AR · Roughness modulation · Electrotactile display

1 Introduction

Presenting realistic kinesthetic/tactile sensation is one of the greatest challenges in haptics. While there have been tremendous advances in sensing, rendering and displaying, only a limited sense of touch can be conveyed. Haptic augmented reality (AR), particularly the modulation of real haptic perception has the potential to provide realistic sensation by perceptually fusing inadequate virtual haptic sensation with rich real haptic sensation. Specifically, haptic modulation technology is expected to encourage broad use of haptic technology in medical, industrial and educational fields. However, implementing haptic modulation is difficult because it requires making the coexistence of real and virtual haptic sensation without disturbing real sensation and without constraining touching action.

Several researchers have dealt with the haptic modulation. Jeon et al. described a technique for modulating the stiffness of soft materials by augmenting additional force based on tool object interaction [1]. Hachisu et al. proposed a method of modulating material perception using vibratory subtraction and addition [2]. Changing material stiffness using artificial stimuli (e.g., jamming control [3]) is another possible method of haptic modulation. Asano et al. succeeded in altering the fine- and macro-roughness of real materials by applying

M. Auvray and C. Duriez (Eds.): EuroHaptics 2014, Part I, LNCS 8618, pp. 10–17, 2014.
DOI: 10.1007/978-3-662-44193-0_2

vibrations to them [4]. The previous studies using artificial mechanical stimuli have reported excellent results in terms of user perception. However, it is difficult to eliminate mechanical constraints of materials and a finger because of size, location and actuation of the stimulator.

Various tactile displays have been developed for haptic AR [5–7]. Isolation between stimulated and perceived area is one of the possible approaches to eliminate the mechanical constraint, but has not yet been achieved with the tactile displays. To this end, we focused that electrotactile sensation evoked by transcutanecous electrical stimulus [8–10] is perceived at the site of the mechanorecptors rather than that of the stimulated area of the nerves [11]. Inspired by the characteristic, we have developed a new electrotactile display that allows users to augment virtual tactile sensation to real tactile sensation at their fingertip by stimulating at the base of the finger instead of at the fingertip [12].

We aim to develop a texture (i.e., roughness) modulation technique that enables users to feel the altered roughness of real materials via electrotactile augmentation. The main challenge is to reduce any unpleasant sensations induced by the electrical stimulus, to produce a realistic sensation of roughness. In this paper, we describe an electrotactile display capable of providing roughness modulation by controlling pulse amplitude and density of current according to real touch actions. Then, we investigate its effect on roughness perception during real texture exploration. The contribution of this study is to reveal how to fuse two different modal tactile stimuli (e.g., natural mechanical stimulus from real materials and artificial electrical stimulus from the proposed display) and its effect on the roughness perception.

2 Roughness Modulation Using Electrical Stimulus

This section details our method for roughness modulation using electrotactile augmentation. First, we discuss a roughness modulation scheme based on the spatio-temporal consistency of tactile stimuli. Then, we present an electrotactile display that enables users to perceive virtual touch at their fingertips without interfering with touch actions. Finally, we describe how the stimulus will be controlled to modulate roughness.

2.1 Modulation Scheme

To modulate tactile sensation, we have to maintain a spatio-temporal consistency between natural mechanical and artificial electrical stimuli. First, the location of the virtual tactile sensation from the electrical stimulus should correspond to that of the real sensation from the mechanical stimulus. We introduce electrotactile augmentation technology that can superimpose the virtual tactile sensation onto the real tactile sensation at the fingertip. Although the perceived area can be controlled by using the proposed display, we assume that the user touches a material with the fingertip only for the simplification. Note that spatial distribution of stimuli within the fingertip will not be dealt with in this paper because temporal information is considered to be of greater importance [13]. Second, the stimulus should be presented at an appropriate time relative to the natural mechanical stimulus. Our method renders vibrotactile sensation of various frequency by controlling the pulse density upon detecting exploration of a real material. If the spatio-temporal consistency is carefully designed, the user should perceive frequency synthesis between natural and artificial stimuli. Specifically, the user perceives the altered roughness sensation because roughness is considered to be related to the frequency of the vibrotactile stimuli [4]. The proposed system architecture is shown in Fig. 1.

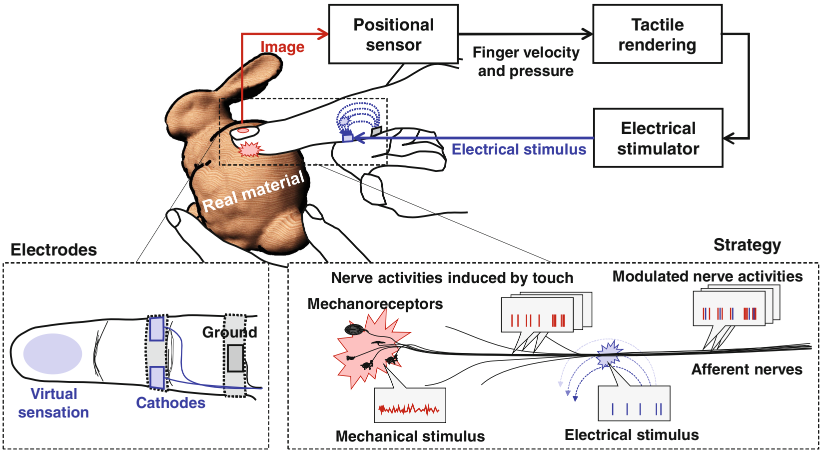


Fig. 1. The system architecture: Modulating nerve activity is superimposed onto the afferent nerves at the middle phalanx of a finger by using anodic pulse stimuli.

2.2 Electrotactile Display

Electrotactile sensation evoked by transcutanecous electrical stimulus is perceived at the site of the mechanorecptors rather than that of the stimulated area of the nerves [11]. As shown in Fig. 1, we investigated the optimal location of electrodes to achieve adequate separation between stimulation and perception [12]. The locations of the electrodes and the stimulus were carefully selected based on a theoretical understandings of the electrical stimulus and the anatomical structure of the digital afferent nerves. Specifically, we found both sides of the middle phalanx of a finger to be optimal sites for electrotactile augmentation.

With a width of 200 µs and amplitude of up to 3 mA, tactile display provides an electrical pulse stimuli density ranging from 1 to 100 pulses per second (pps). Since the threshold of sensitivity varies between individuals, the pulse amplitude at each electrode has to be adjusted accordingly. The tactile display enables users to perceive vibrotactile sensation of various intensity and frequency, though the activated receptor types cannot be selected [14]. Further discussions of electrotactile perception can be found in the literatures [8–10].

2.3 Stimulus Rendering

The electrical stimulus can be controlled according to the velocity and pressure of the finger. Specifically, we control the frequency of the vibrotactile sensation according to finger velocity. Rather than controlling the frequency of the sinusoidal stimulus in the same way as [4], we instead control the pulse density of the electrical stimulus for vibrotactile rendering. With the absolute values of velocity and modulation gain being v_f and m_g respectively, the pulse density f_p is calculated by

$$f_p = m_g \frac{v_f}{v_m} \quad (v_f > 0), \tag{1}$$

where v_m is experimentally determined as 200 mm/sec. We also control the pulse amplitude A_m according to finger pressure P_f to equalize virtual and real sensation intensities. Additionally, we introduce offset β and scale α to keep the amplitude within the appropriate range. Then the amplitude can be written as

$$A_m = A_{th}(\alpha P_f + \beta), \tag{2}$$

where A_{th} is the current value for sensory threshold. In practically, the finger pressure will be estimated by measuring the distance between the material surface and back of the finger. The resulting stimulus patterns with the periodical finger movement from side to side at a constant pressure for several modulation gains are drawn in Fig. 2. In this result, one can see that the pulse density increases according to the modulation gain and to the finger velocity. The stimulus patterns are similar to the activities of rapidly adapting (RA) and Pacinian (PC) receptors upon inputing sinusoidal mechanical stimulus as reported in the literature [15]. Finally, the same stimulus pattern is presented at each cathode.

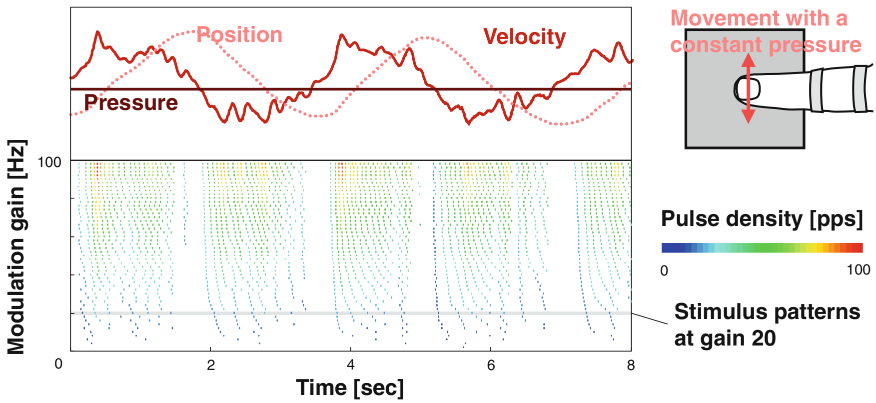


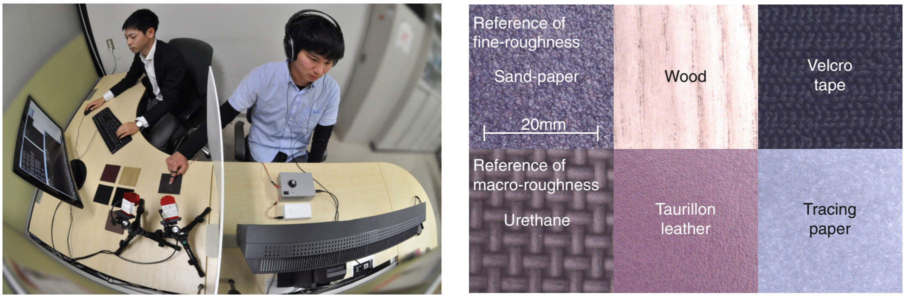
Fig. 2. Raster plot of electrical stimulus with finger position, velocity and pressure: The stimulus pattern at an arbitrary gain is presented with the electrotactile display.

3 Experiment to Evaluate Roughness Perception

To evaluate the proposed method, we investigated the effect of changing the modulation gain upon perception. Specifically, we were interested in the impact on roughness perception and real-virtual sensory fusion.

3.1 Experimental Setup

Our experimental setup is shown in Fig. 3. For finger tracking and contact detection, we used a positional sensing system comprising of two infrared cameras (FLEX V100R2, OptiTrack) with lenses of focal length 3.5 mm. The camera resolution was 640 × 480, and the sampling rate was 100 Hz. The tracking system was calibrated beforehand and its accuracy found to be about 0.1 mm.



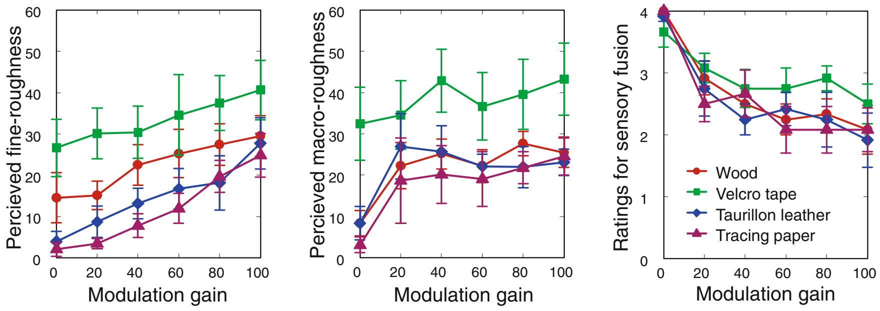
(a) (b)

Fig. 3. The experimental setup: (a) The participant explores (b) the material.

As shown in Fig. 3(b), two references and four test materials, i.e., sand-paper of number P40 (fine and hard), urethane (hubbly and soft), wood (rough and hard), velcro tape (rough and moderately soft), taurillon leather (uneven and soft), and tracing paper (smooth and hard), were selected for the evaluation. The modulation gains were set at 20, 40, 60, 80 and 100 Hz in addition to no stimulus, i.e., 0. These stimuli were randomly applied to each of the four test materials. In all, 72 trials (three sections including one familiarization section) were conducted with each participant. All participants were asked to wear electrodes on their right index finger, and to affix a retro-reflective marker to their nail for sensing. The participants sat at a desk and wore a set of headphones that played pink noise to mask ambient sounds. For each trial, the participant explored the materials and rated perceived fine- and macro-roughness (0–100) by comparing them with references. We define the fine-roughness sensation as the roughness resulting from densely arranged small bumps, while we define macro-roughness as roughness resulting from sparsely arranged edges [4]. The reference values for fine- and macro-roughness, which were defined as the sensation caused by exploring the sand-paper and the urethane, respectively, were set at 50. These reference materials were presented to the participant after every six trials. Additionally, the degree of sensory fusion was reported in five levels (0: not at all, 1: a little fused, 2: fused, 3: naturally fused, and 4: completely fused) to investigate whether the electrical stimulus is well fused into the mechanical stimulus or not. The participants were asked to use similar motions and finger pressure on each material. In this experiment, the finger pressure for the stimulus rendering was fixed at constant for the simplification. Note that pulse amplitude was individually adjusted to cause the same intensity as real sensation whilst exploring the sand-paper.

3.2 Result and Discussion

One hundred and thirty-six answers for each rating were recorded during the experiment (six participants, four materials, and six parameters). The average ratings for each material are shown in Fig. 4. A three-way ANOVA was performed to investigate the effects on electrotactile augmentation upon perception. The modulation gain was found to have a significant effect upon the three ratings, i.e., fine-roughness [$F(5,130) = 16.5$, $p < 0.001$], macro-roughness [$F(5,130) = 5.74$, $p < 0.001$], and sensory fusion [$F(5,130) = 32.5$, $p < 0.001$]. Furthermore, there were significant differences between materials for fine-roughness ratings [$F(3,130) = 46.0$, $p < 0.001$] and macro-roughness ratings [$F(3,130) = 19.9$, $p < 0.001$]. These results suggest that both the real and virtual stimuli contributed to the participant's perception. As expected, the fine-roughness rating increased in accordance with the modulation gain. Conversely, the change in macro-roughness rating between modulation gains was slight. The results indicate that electrical stimulus with a modulation gain greater than 20 gives various fine-roughness and bias of the macro-roughness perception. Figure 4(c) shows that electrotactile sensation can be effectively fused with real sensation. In particular, some participants reported remarkable fusion when exploring the velcro tape. Since the exploration on the velcro tape causes strong stimulus on the skin compared to the other materials, strong mechanical stimulus from real material appears to help with sensory fusion. Conversely, higher modulation gain degrades sensation. A possible explanation is that, with high pulse densities, the participants perceived pressure sensation rather than vibrotactile sensation. Since the proposed electrotactile display stimulates nerve fibers irrespective of receptor types, both pressure and vibrotactile sensation will be caused at the same time. With low pulse densities, the user would perceive vibrotactile sensation in synchronization with pulse rather than static pressure sensation. Furthermore, the presented stimulus patterns were similar to the activities of RA and PC that are related to vibrotactile perception. Thus the participants reported roughness in the same manner as the mechanical stimulus [4]. With high pulse densities, the user could not discriminate two electrical stimulus pulse because of sensory adaptation [9]. Thus the participants reported the static pressure sensation from slowly adaptive (SA) receptors rather than the vibrotactile sensation. The effect seems to be reduced by equalizing the intensities of the pressure sensation.



(a) (b) (b)

Fig. 4. Experimental results: (a) fine-roughness rating, (b) macro-roughness rating, and (c) sensory fusion ratings. (The vertical bars represent the standard errors.)

Surprisingly, some participants reported existence of electrical stimulus when they explored the velcro tape with no stimulus. This result suggests that user could not distinguish artificial electrical stimulus and natural mechanical stimulus at the lower modulation gain. This result supports that electrotactile augmentation has a potential to present realistic tactile sensation. Investigating the limitations of roughness modulation and its effects on other modalities, such as smoothness, is planned as future work.

4 Conclusion

We have presented a method of roughness modulation using electrotactile augmentation to address the following question: Is it possible to alter the texture sensation of a real material explored with mechanically unconstrained touch? We developed an electrotactile display that superimposes modulating nerve activity onto afferent nerves, and also conducted a user study. The results indicated that electrotactile augmentation contributes to fine- and macro-roughness modulation. Therefore, we conclude that roughness modulation without mechanical constraint has been achieved. Moreover, the proposed system is compact, low cost, and durable compared to the previous haptic AR using artificial mechanical stimulus. The proposed technology is expected to be implemented in industrial texture design and surgical skill training, in addition to computer entertainment.

Acknowledgements. This work was supported by JSPS KAKENHI Grant Numbers 22135003 and 25870394 in Japan. The study here presented has been approved by Ethical Committee of Graduate School of Engineering Science (25-3), Osaka University in Japan.

References

1. Jeon, S., Choi, S.: Haptic augmented reality: taxonomy and an example of stiffness modulation. Presence: Teleoperators and Virtual Environ. **18**(5), 387–408 (2009)
2. Hachisu, T., Sato, M., Fukushima, S., Kajimoto, H.: Augmentation of material property by modulating vibration resulting from tapping. In: Isokoski, P., Springare, J. (eds.) EuroHaptics 2012, Part I. LNCS, vol. 7282, pp. 173–180. Springer, Heidelberg (2012)
3. Follmer, S., Leithinger, D., Olwal, A., Cheng, N., Ishii, H.: Jamming user interfaces: programmable particle stiffness and sensing for malleable and shape-changing devices. In: Proceedings of UIST, pp. 519–528 (2012)
4. Asano, S., Okamoto, S., Matsuura, Y., Nagano, H., Yamada, Y.: Vibrotactile display approach that modifies roughness sensations of real textures. In: Proceedings of IEEE RO-MAN, pp. 1001–1006 (2012)
5. Kajimoto, H., Kawakami, N., Tachi, S., Inami, M.: Smarttouch: electric skin to touch the untouchable. IEEE Comput. Graphics Appl. **24**(1), 36–43 (2004)
6. Ando, H., Kusachi, E., Watanabe, J.: Nail-mounted tactile display for boundary/texture augmentation. In: Proceedings of ACE, pp. 292–293 (2007)
7. Bau, O., Poupyrev, I.: Revel: tactile feedback technology for augmented reality. ACM Trans. Graphics **31**(4), 1–11 (2012). Article no. 89
8. Kim, E., Sugg, K., Langhals, N., Lightbody, S., Baltrusaitis, M., Urbanchek, M., Cederna, P., Gerling, G.: An engineered tactile afferent modulation platform to elicit compound sensory nerve action potentials in response to force magnitude. In: Proceedings of WHC, pp. 241–246 (2013)
9. Kaczmarek, K.: Electrotactile adaptation on the abdomen:preliminary results. IEEE Trans. Rehabil. Eng. **8**(4), 499–505 (2000)
10. Antoni, H., Chilbert, A., Sweeney, D.: Applied Bioelectricity : From Electrical Stimulation to Electrophathology. Springer, New York (1998)
11. Micera, S., Keller, T., Lawrence, M., Morari, M., Popovic, D.: Wearable neural prostheses. restoration of sensory-motor function by transcutaneous electrical stimulation. IEEE Eng. Med. Biol. Mag. **29**(3), 64–69 (2010)
12. Yoshimoto, S., Kuroda, Y., Imura, M., Oshiro, O.: Development of a spatially transparent electrotactile display and its performance in grip force control. In: Proceedings of IEEE EMBC, pp. 3463–3466 (2011)
13. Lederman, S., Klatzky, R.: Sensing and displaying spatially distributed fingertip forces in haptic interfaces for teleoperator and virtual environment systems. Presence: Teleoperators and Virtual Environ. **8**(1), 86–103 (1999)
14. Yoshimoto, S., Kuroda, Y., Kagiyama, Y., Kuroda, T., Oshiro, O.: Tactile mapping approach using electrical stimulus pattern. In: Proceedings of IEEE RO-MAN, pp. 460–465 (2009)
15. Muniak, M., Ray, S., Hsiao, S., Dammann, J., Bensmaia, S.: The neural coding of stimulus intensity: linking the population response of mechanoreceptive afferents with psychophysical behavior. J. Neurosci. **27**(43), 11687–11699 (2007)

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http://www.springer.com/978-3-662-44192-3

Haptics: Neuroscience, Devices, Modeling, and Applications
9th International Conference, EuroHaptics 2014, Versailles, France, June 24-26, 2014, Proceedings, Part I

Auvray, M.; Duriez, C. (Eds.)

2014, XXVI, 563 p. 289 illus., Softcover
ISBN: 978-3-662-44192-3