Virtual Alteration of Body Material by Periodic Vibrotactile Feedback

Yosuke Kurihara [1] Taku Hachisu [1,2] Michi Sato [1,2] Shogo Fukushima [1,2] Hiroyuki Kajimoto [1,3]

[1] The University of Electro-Communications, [2] JSPS Research Fellow, [3] Japan Science and Technology Agency

ABSTRACT

Characters with body materials that are different from that of humans, such as metal robots or rubber people, frequently appear in movies and comics. While the abilities of their synthetic bodies can be easily observed from their actions, their somatic sensations are more difficult to appreciate. Our aim in this work is to simulate the alteration of the material of the human body by means of vibrotactile feedback. The feedback represents the properties of the materials and is periodically applied to the elbow joint in synchrony with the elbow angle. This simulated sensation of having a different body material gives us the feeling of those characters. This technique can also be applied to improve maneuverability in the teleoperation of master-slave systems because it gives the operator a robot-like sensation.

Keywords: Body sense, material, vibrotactile feedback, virtual reality.

Index Terms: H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems — Artificial, augmented, and virtual realities. H.5.2 [Information Interfaces and Presentation]: User Interfaces — Haptic I/O.

1. INTRODUCTION

The human body comprises biological components such as muscles, tendons, and bones. We are seldom conscious of the materials of these body parts because they function very smoothly and the activities of the haptic receptors are not intense. Consequently, we have become accustomed to the relationship between motions of biological materials and the sensations they create.

However, in many movies, comics, and video games, we see characters created from different materials, such as metal robots and rubber people. Although these characters only exist in the realm of fantasy, many of us would be interested in becoming them. The question therefore naturally arises: how do these characters feel?

The aim of our work is to virtually alter the material of the human body. In this study, we used vibrotactile feedback that simulates the innate vibration of materials when they collide. We periodically applied this feedback to the elbow joint in synchrony with the elbow angle to induce the sense of the arm being made of rubber, wood, or metal (Figure 1).

We envision that this technique would be useful for full-body virtual reality (VR) games by offering the experience of being a fictional character with a synthetic body, such as a robotic hero.

{kurihara, hachisu, michi, shogo, kajimoto}@kaji-lab.jp

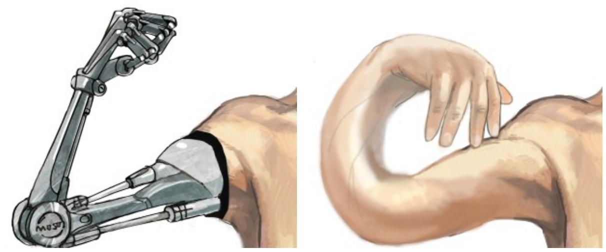

Figure 1: Metallic arm (left) and rubber arm (right).

2. RELATED WORK

There have been many works on the modulation of haptic perception, a process referred to as haptic augmented reality (AR). Haptic AR systems generally alter the feel of a real object, such as its stiffness [1] or boundaries [2], using a force feedback interface. The feel of the material can also be virtually altered by tactile feedback. Visell et al. [3] designed a vibrotactile floor display to stimulate the senses of walking on different ground materials (e.g., gravel or snow). Romano et al. [4] proposed a method of rendering a virtual texture when a tool is held by recording the vibration during real interactions. Hachisu et al. [5] developed a stick-type haptic AR system with a simple setup to alter the perceived stiffness of a real object by modulating the vibration generated by tapping. In a touch interface, the technique of programmable friction between the finger and the panel is used to recreate various textures on the smooth plate [6][7]. This allows us to touch a variety of objects outside our bodies.

The presentation of the sense of the human body has also been studied. One method of presenting bodily sense is called kinesthetic illusion. It involves the use of a vibration of about 100 Hz to activate muscle spindles, which creates an illusory arm motion [8][9][10]. This illusion can be extended to the elongation of parts of the human body, which is known as the Pinocchio illusion [11]. However, to the best of our knowledge, none of these studies have focused on the presentation of the material properties of the human body.

3. VIRTUAL ALTERATION OF ELBOW MATERIAL

3.1. Haptic Properties of Materials

While we do not know the real sensations of a synthetic body, we are very familiar with how materials around us feel. We can identify a material from its haptic property. While noting that subjective realism is more desirable than the true physical phenomenon, we can use known techniques of rendering material properties to express the material of the human body.

The vibration waveform that results from the collision of objects is one of the dominant cues used for discriminating material properties. Several works [5][12][13] have modeled the vibration with the exponentially decaying sinusoidal wave of Eq. (1), which is based on the observation of real collisions, and recreated the feelings of tapping on different materials.

$$Q(t) = A(v)e^{-Bt}\sin(2\pi f t), \qquad (1)$$

where Q is the acceleration of the vibration generated by the impact, t is the time elapsed since the impact, v is the impact velocity, A is the initial amplitude (a function of v), B is the decay rate, and f is the vibration frequency. The model can be used to express many types of materials by modifying A, B, and f. Using this model, Okamura et al. [13] and Hachisu et al. [5] simulated three materials (rubber, wood, and aluminum) by means of stylus-type haptic feedback systems.

We employ the same technique to express different materials. The transducer was directly attached to the skin at the elbow joint.

3.2. Periodic Vibrotactile Feedback

While the model simulates the vibration of a single impact, the movement of the human body is continuous. Thus, we propose the presentation of a periodic vibrotactile feedback synchronized with the angle of the elbow, as shown in Figure 2. A type of periodic haptic feedback, known as rotary switch feeling, has often been used for the perception of rotation [14]. We have also used the same periodic impact to emphasize the sense of body movement [15]. As an extension of these previous works, we presently focus on expressing the material property of the body by modulating the vibration.

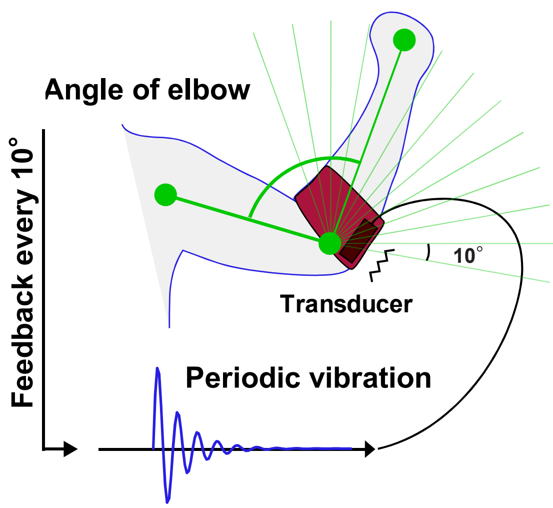

Figure 2: Periodic vibrotactile feedback.

4. SYSTEM

Figure 3 illustrates the configuration of our system. First, a Kinect camera (Microsoft Co. Ltd., [16]) captures the three-dimensional position of the user's right shoulder, elbow, and hand at a sampling rate of 30 Hz. Next, the PC calculates the user's right elbow angle from the three sets of position data and sends it to the microcontroller (mbed NXP LPC 1768, NXP Semiconductors). For every 10° change in the elbow angle, the microcontroller outputs a decaying sinusoidal wave through the D/A converter (LTC1660, Linear Technology, 10 bit), with a refresh rate of 10 kHz. This is amplified by the audio amplifier (RSDA202, Rasteme Systems Co., Ltd.) and the output is finally used to actuate the vibrotactile transducer (Haptuator Mark II, TactileLabs Inc.) mounted under a cotton band. The band is attached to the right forearm close to the elbow joint so that the transducer makes contact with the lateral side of the elbow joint. The width of the band is 80 mm and its weight (including the transducer) is 33 g.

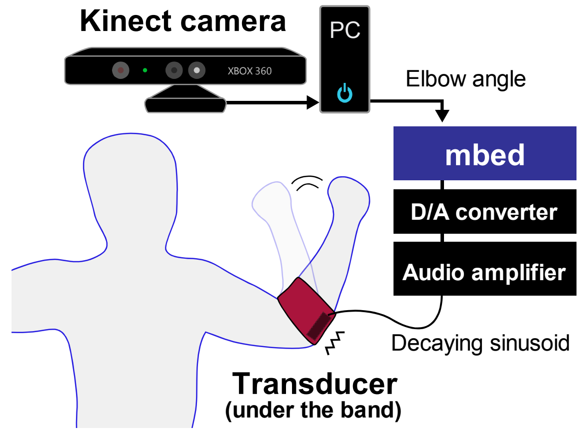

Figure 3: System configuration.

To express the materials, we used the values adopted by Okamura [13], which are listed in Table 1. The initial acceleration was made constant.

Table 1: Vibration parameters

Material	A [m/s^2]	B [s^{-1}]	f [Hz]
Rubber	15.1	60	30
Wood	10.5	80	100
Aluminum	19.6	90	300

4.1. Latency Evaluation

We measured the latency from the movement of the arm to the output of the stimulation signal, which was approximately 50 ms. Most of the latency was due to the camera. Assuming a 90° per second angular speed of the elbow joint, this delay was equivalent to 4.5°. Because the gap was less than half of the interval angle of the vibrotactile feedback (10°), we considered it to be sufficiently small. In our primary experiment described in Section 5, none of the participants noticed this latency.

5. EXPERIMENT

We performed an experiment to assess the effect of virtual material alteration using our system. Five males and three females (aged 22 - 27 years) participated in the experiment. All participants were right handed and were members of our laboratory who had never experienced the system. The authors did not participate in this experiment. While wearing the band, the participants stood facing the Kinect camera as shown in Figure 4. Three types of vibrotactile feedback (for rubber, wood, and aluminum) were presented in synchrony with the elbow movement of the participants. The participants were required to identify the elbow material as rubber, wood, or aluminum. We gave the participants options to choose from because they had no experience of how real elbow joints made of these materials felt and could not determine the materials without suggestions or a context. The participants were allowed to repeatedly alternate between the types of feedback by pressing the keyboard button. The number of alternations and the time taken were not restricted. There was no prior training and the correct answers were not given to the participants during the experiment. We repeated this matching task three times with each participant. This number of trials was sufficient considering that the participants tended to remember the three types of stimulations and fix their answers. The transducer produced not only vibrotactile stimuli but also small sounds. We did not mask the sound from the transducer because bone conduction could not be entirely blocked.

Figure 4: Overview of the experiment.

After the trials, the participants were asked to answer the following two yes/no questions:

(1) Did you feel the feedback from within or outside the elbow? A feeling from within the elbow indicated an alteration of the elbow material itself, and not a feeling of the external habiliments.

(2) Did you feel a reaction force when the feedback was presented? This question was asked considering that an imaginary elbow of a different material should have a certain amount of "resistance." If the participants could feel the reaction force while the vibration was being presented, it could be used to measure subjective realism.

6. Results

Table 2 shows the identification rates for the three types of vibrotactile feedback. The correct identification rates for all the three materials (highlighted cells) were higher than 80%, with the overall rate being 87.5%. The correct perception of the aluminum feedback by the participants was particularly high (91.7%). We performed a Chi square test to determine the differences among the materials and no significant difference was found ($\chi^2(2)$ = 0.762, p = 0.683, n.s). All three vibration models were therefore almost evenly discriminated.

Table 2: Identification rates for three types of feedback

Answer	Vibrotactile feedback Rubber	Wood	Aluminum
Rubber	83.3%	12.5%	4.2%
Wood	8.3%	87.5%	4.2%
Aluminum	8.3%	0.0%	91.7%

Figure 5 shows the frequencies of affirmative answers to the two questions the participants were asked. The overall frequency of an affirmative answer to Question 1 was 62.8%. That for rubber was the highest (87.5%), followed by that for wood (62.5%), and then that for aluminum (37.5%). A Chi square test did not show any significant difference ($\chi^2(2)$ = 4.267, p = 0.118, n.s), but a post-hoc comparison using Tukey's method indicated that the difference between the frequency for rubber and that for aluminum was marginally significant (MS = 2.921, p < 0.10).

The overall frequency of an affirmative answer to Question 2 was 70.8%. The frequency for rubber was the highest (87.5%), followed by that for wood (75.0%), and then that for aluminum (50.0%). A Chi square test showed no significant difference ($\chi^2(2)$ = 2.824, p = 0.244, n.s).

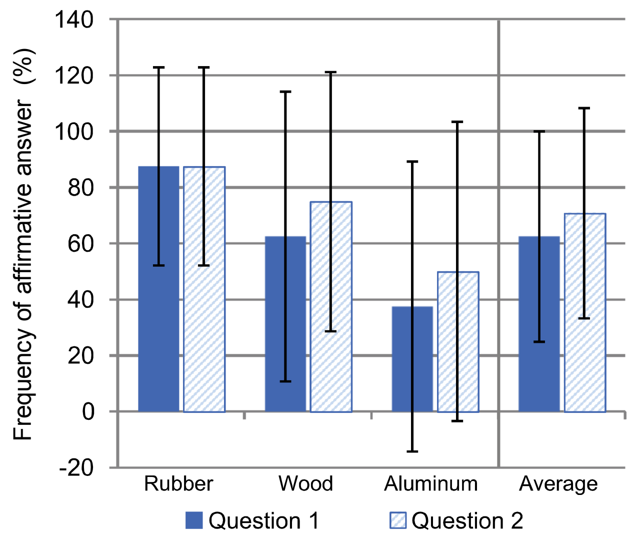

Figure 5: Answer frequencies for the two questions.

7. Discussion

The overall frequency of correct identification of the materials (87.5%) was higher than that of Okamura's experiment [13] for identification by tapping. Although there were no statistically significant differences in the rates of correct identification of the materials, there was the tendency to mistake rubber and wood, whereas aluminum was distinctly identified. This was similar to Okamura's observation. Nevertheless, the results showed that the vibration model feedback could render material properties to the elbow joint.

Concerning the subjective location of the vibration, the low frequency vibration models (rubber and wood) were mostly perceived as a sensation from within the elbow. The participants reported that their elbow joint material had been altered to rubber or wood, but they were not exactly sure of this because they had never experienced such a feeling. These observations were promising for our research because they suggested that simple skin stimulations could induce the feeling of the internal materials of our body. In contrast, the presentation of aluminum, which was expressed by a higher frequency vibration, was mostly perceived as a stimulus from an external body—like wearing an exoskeleton suit.

The illusory reaction force was mostly felt for the low frequency vibration models. Although there was no statistical significance of the frequency of the perception, the participants commented that the reaction force of the rubber- or wood-like feeling was stronger than that of the aluminum-like feeling. Some previous works observed that a fingertip vibration used to simulate friction was perceived as an external force [17]. While our findings might be partially explained by this misinterpretation, the moving body part and the location of the stimulation of our study were quite different. We speculate that this illusory reaction force is a reflection of the subjective realism of the body part alterations.

We must note that the experiment had two major limitations. First, because the participants were laboratory members with the knowledge that a higher vibration frequency indicated a stiffer object, we cannot exclude the possibility that they had judged the correct material from the vibration frequencies, rather than by intuition. Second, the unmasked small sound from the tactile device might have served as a cue. However, two participants commented that they felt a sticky force when the rubber-like vibration was presented. This suggested that they really felt that their elbow material had been altered. Nevertheless, we must clarify these issues by using naïve participants and masking the sound. We are also considering additional experiments involving the electro-tactile stimulation of the skin, to completely eliminate the effect of bone conduction.

8. CONCLUSION AND FUTURE WORK

In this paper, we proposed a technique for the virtual alteration of body material by means of periodic vibrotactile feedback, which can be used to render material properties in synchrony with body movements. We implemented a prototype system that focuses on the elbow joint and evaluated it by means of a material identification test using three different materials (rubber, wood, and aluminum). The vibrotactile feedback to the right elbow joint was identified with a high success rate. The low frequency vibration models (rubber and wood) successfully induced the sensation of the elbow joint being made of rubber or wood. The participants also perceived a reaction force for the low frequency models. In contrast, the sensation of the aluminum model was perceived as coming from outside the body, although the feedback was correctly identified as aluminum in the material identification test.

Several future works are envisaged to improve the realism of the body material. The first is to determine the optimal vibration parameters. In the current system, we used Okamura's parameters for a decaying sinusoidal waveform [13] modeled on object collisions. These parameters need to be modulated to correspond to the sensations of body materials. The discussion of the optimal stimulation should also include the modulation of the interval angle of the periodic feedback for each material and the location of the stimulus on various body parts. The system should also be made to allow free body movement. The final goal of this study is to create a new VR system that offers the experience of having special powers—like those of movie superheroes.

Another possible future application of this technique is in teleoperation systems. In a master-slave operation, the feeling of directly controlling the object would facilitate more efficient maneuvering. While many approaches to mechanically matching an impedance of the robot (slave) with that of the human (operator) have been proposed [18][19], matching a human more closely with a robot is an unexplored field. We consider that enabling an operator to experience a robot-like feeling is an alternative approach to improving maneuverability in master-slave systems, to which the virtual alteration of the material of the human body potentially contributes.

REFERENCES

[1] S. Jeon and A. Choi. Haptic augmented reality: taxonomy and an example of stiffness modulation. *Presence: Teleoperators and Virtual Environments*, 18(5):387-408, 2009.

[2] T. Nojima, D. Sekiguchi, M. Inami, and S. Tachi. The SmartTool: a system for augmented reality of haptics. *Proceedings of IEEE Virtual Reality Conference* (Orlando, FL, USA, March 24-28, 2002), pages 67-72.

[3] Y. Visell, A. Law, and J. R. Cooperstock. Touch is everywhere: floor surfaces as ambient haptic interfaces. *IEEE Transactions on Haptics*, 2(3):148-159, 2009.

[4] J. M. Romano and K. J. Kuchenbecker. Creating realistic virtual textures from contact acceleration data. *IEEE Transactions on Haptics*, 5(2):109-119, 2012.

[5] T. Hachisu, M. Sato, S. Fukushima, and H. Kajimoto. Augmentation of material property by modulating vibration resulting from tapping. *Haptics: Perception, Devices, Mobility, and Communication* (*Proceedings of EuroHaptics'12*, Tampere, Finland, June 13-15, 2012), 7282(1):173-180.

[6] L. Winfield, J. Glassmire, J. E. Colgate, and M. Peshkin. T-PaD: tactile pattern display through variable friction reduction. *Proceedings of World Haptics Conference* (Tsukuba, Japan, March 22-24, 2007).

[7] O. Bau, I. Poupyrev, A. Israr, and C. Harrison. TeslaTouch: electrovibration for touch surfaces. *Proceedings of ACM Symposium on User Interface Software Technology* (*UIST'10*, New York, NY, USA, October 8-11, 2010), pages 283-292.

[8] G. M. Goodwin, D. I. McCloskey, and P. B. C. Matthews. The contribution of muscle afferents to kinaesthesia shown by vibration induced illusions of movement and by the effects of paralysing joint afferents. *Brain*, 95(4):705-748, 1972.

[9] D. Burke, K. E. Hagbarth, L. Löfstedt, and G. Wallin. The responses of human muscle spindle endings to vibration of non-contracting muscles. *J. Physiol (Lond)*, 261(3):673-693, 1976.

[10] E. Naito. Sensing limb movements in the motor cortex: how humans sense limb movement. *Neuroscientist*, 10(1):73-82, 2004.

[11] J. R. Lackner. Some proprioceptive influences on the perceptual representation of body shape and orientation. *Brain*, 111(2):281-297, 1988.

[12] P. Wellman and R. D. Howe. Towards realistic vibrotactile display in virtual environments. *Proceedings of ASME Dynamic Systems and Control Division*, 57(2): 713-718, 1995.

[13] A. M. Okamura, M. R. Cutkosky, and J. T. Dennerlein. Reality-based models for vibration feedback in virtual environments. *IEEE/ASME Transactions on Mechatronics*, 6(3):245-252, 2001.

[14] M. Badescu, C. Wampler, and C. Mavroidis. Rotary haptic knob for vehicular instrument controls. *Proceedings of Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems* (*HAPTICS'02*, Orlando, FL, USA, March 24-25, 2002), pages 342-343.

[15] Y. Kurihara, Y. Kuniyasu, T. Hachisu, M. Sato, S. Fukushima, and H. Kajimoto. Augmentation of kinesthetic sensation by adding "Rotary Switch Feeling" feedback. *Proceedings of 3rd Augmented Human International Conference* (Megève, France, March 8-9, 2012).

[16] Microsoft. Kinect. 2010. http://www.xbox.com/en-US/kinect

[17] M. Konyo, H. Yamada, S. Okamoto, and S. Tadokoro. Alternative display of friction represented by tactile stimulation without tangential force. *Haptics: Perception, Devices and Scenarios* (*Proceedings of EuroHaptics'08,* June 10-13, 2008), 5024:619-629.

[18] C. L. Fernando, M. Furukawa, T. Kurogi, K. Hirota, S. Kamuro, K. Sato, K. Minamizawa, and S. Tachi. TELESAR V: TELExistence surrogate anthropomorphic robot. *Proceedings of ACM SIGGRAPH 2012 Emerging Technologies* (Los Angeles, CA, USA, March 5-9, 2012).

[19] Y. Yokokohji and T. Yoshikawa. Bilateral control of master-slave manipulators for ideal kinesthetic coupling-formulation and experiment. *IEEE Transactions on Robotics and Automation*, 10(5):605-620, 1994.