Large-Area Tactile Display Using Vibration Transmission of Jammed Particles

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ABSTRACT

Tactile displays to enrich audiovisual experience often employ vibration feedback from a chair or jacket. Providing vibration to lager area of the human body is a promising approach to make the experience more immersive. However, the system requires many vibrotactile transducers to be applied to the whole body, and contact between the transducers and the user's body surface is sometimes insufficient. We propose a novel vibrotactile display that covers a large area of the body surface and fits various shapes, based on vibration transmission through jammed particles. Styrofoam particles around the body are jammed by evacuating the air. Vibrations from speakers are delivered to the user's body though the jammed particles. We envision our vibrotactile transmission technique being applied to whole-body tactile displays.

Keywords: Tactile Display, Body Sense, Particle Jamming, Vibration Transmission, Deformable Material.

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

1. INTRODUCTION

Many vibrotactile displays have been developed to enrich audiovisual entertainment such as listening to music, playing video games, and watching movies. For example, Lemmens et al. [1] proposed a jacket-type vibrotactile display with 64 vibration motors to add tactile feedback to the audiovisual content. Chair-type vibrotactile displays [2][3] provide tactile "buzzes" from the backrest to enrich music and video game experiences.

A natural evolution of existing vibrotactile displays would be to increase the number of vibrotactile transducers in order to cover a larger area of the body, or even the whole-body, which would facilitate the effect of vibration feedback. However, large-area tactile displays require many transducers to cover a large area of the body surface, which leads to a complex and costly system [4]. Furthermore, fitting the display to the user's body shape is difficult, and the contact condition of each transducer becomes non-uniform [5]. We can realize stable contact by placing a deformable layer (e.g., urethane foam) between the transducer and skin, but this dampens (i.e., low-pass filters) the vibration. In summary, "fitting" is actually a significant problem for large-area tactile displays.

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This paper presents a novel vibrotactile display that uses vibration transmission of polystyrene particles to cover a large area of the body surface, as show in Figure 1. Deformable particles in a vacuum bag can cover the user's body without a contactless surface. When pressure inside the vacuum bag is reduced, the particles are jammed and become rigid. By presenting vibration from outside the vacuum bag, the jammed particles transmit the vibration to a large area of the body surface contiguous with the particles.

The main contribution of this paper is to present a new vibrotactile feedback technique that covers a large area and fits various shapes of the body surface with small number of actuators. The ultimate goal of this project is to develop the whole-body vibrotactile display in order to feel audiovisual contents with the whole body (i.e., from the neck to feet).

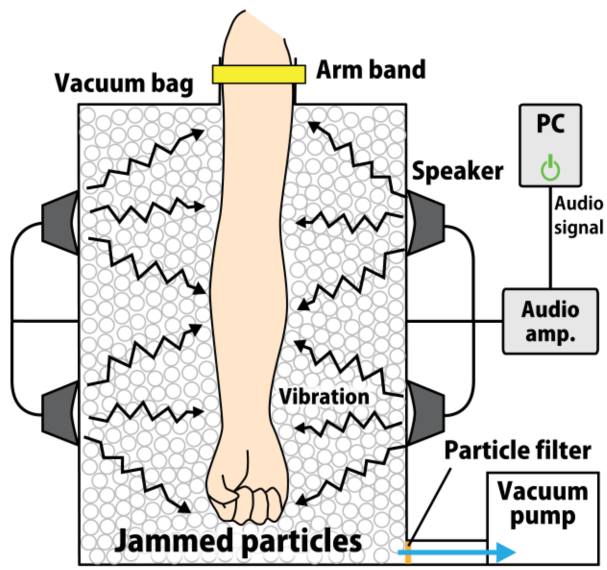

Figure 1: Vibration transmission system by particle jamming. This system is described in Section 6.1.

2. RELATED WORK

Many studies have examined using pneumatic control such as deformable cells for haptic displays [6][7]. Sato et al. [8] developed a deformable three-dimensional surface with dynamic softness control using pneumatic control of polystyrene particles. Follmer et al. [9] designed malleable and flexible user interfaces (e.g., stiffness-tunable tabletop surface, shape-changing mobile phone) by controlling material properties using jamming granular material. Mitsuda et al. [10] proposed a wearable force-feedback system that controls the stiffness of a vinyl tube with embedded Styrofoam particles. The fundamental concepts underlying these haptic displays are as follows: (1) when the pressure inside the object is atmospheric level, the display becomes soft, and the users can easily change the shape; (2) when the particles inside the display are jammed because the pressure is reduced to close to vacuum level, the surface becomes stiff and keeps the current shape. In other words, the programmable stiffness and shape itself directly work as the haptic display.

We use the same physical phenomenon. However, unlike the previous studies, we propose using jammed particles as a mediator of vibration for a vibrotactile display. By using the jammed particles, fitting the shape of the body becomes easy. As the particles are lightweight and hard, vibration is transduced with a smaller loss of energy.

3. EXPERIMENT

To verify whether the jammed particles sufficiently transmit vibration to wide area of the user's body, we conducted an experiment with a whole-arm vibrotactile display.

3.1. Experimental setup

The experimental setup was similar with Figure 1, but we used a vibration motor instead of speakers to simplify the system for the experiment. A vacuum bag (approximately 40 cm width × 50 cm length) is filled with polystyrene particles having a 5 mm diameter. When the user puts his or her arm into the bag, the whole surface of the user's upper arm is covered with the particles. After testing some materials and particles with different diameters, we chose the 5 mm diameter polystyrene for two reasons: the particles transmit vibration well owing to their light weight and they behave like sand and completely cover the body surface owing to their low friction characteristics with less static electricity. The top of the vacuum bag is sealed with an armband.

The bottom of the vacuum bag is connected to the vacuum pump (VP0625, Nitto Kohki Co. Ltd., -33.3 kPa attainable vacuum, 40 L/min displacement) through a particle filter. By reducing the pressure inside the bag to close to a vacuum, the particles become compressed, jammed, and hardened, as shown in Figure 2. A pressure sensor (20 INCH-D2-P4V-MINI, All sensors Corp.) was attached on the bottom of the vacuum bag to monitor the degree of vacuum. Coin-type vibration motors (FM34F, TPC Co.) is attached on the one side of the vacuum bag to deliver vibrotactile stimuli with approximately 200 Hz. When the vibration motor is actuated, the jammed particles transmit vibration to the user's body.

Because the pressure inside the vacuum bag is evenly reduced, the force pressing the user's arm is also even over the entire surface. Thus, ideally, vibrotactile stimuli are provided uniformly to all areas.

Figure 2: Particle jamming by evacuating the air.

3.2. Experimental condition

We recruited four participants (males, aged 21-23, right-handed) for the experiment. Figure 3 shows overview of the experiment. We stimulated the participants' right arms with the following two conditions.

Direct condition: The experimenter directly attached a vibration motor on the palmar side of right forearm and provided vibrotactile stimulus. Therefore, the vibration would be felt just around the vibration motor.

Via-particles condition: In this condition, the participants put their right arm into the vacuum bag so that the elbow joint were completely covered with the particles. The vibration motor was attached on the bag just above the palmar side of right forearm. Then the experimenter sealed the bag with an armband and reduced the pressure inside the vacuum bag to compress particles. The pressure was manually kept at approximately 96.1 kPa. Due to the jammed particle, the vibration would be felt around the whole arm.

We attached six vibration motors on the participants' left arm as references. The six positions were palmer side hand, forearm, elbow, and dorsal side hand, forearm, elbow. Both referential vibrations to the left arm and experimental vibrations to the right arm were simultaneously provided for ten seconds with the same amplitude and frequency. We asked the participants to evaluate the strength of vibration of six points; right arm palmer side hand, forearm, elbow, and dorsal side hand, forearm, elbow, by referring to the left side real stimulation. A visual-analog scale (0: no sensation, 100: the same with left arm) was used for the comparison.

Figure 3: Direct condition (right) and via-particles condition (left). The participants evaluate the intensity of the vibration felt in the evaluation points on their left arm, compared with the referential vibration on their right arm.

3.3. Experimental procedure

The participants first sat down on a chair and wore headphones that output white noise and mask any sound cue by the vibration motor and the vacuum pump. Then the experimenter attached six vibration motors on the participants' left arms by adhesive tape to present referential vibration.

Two participants tried under direct condition first, and Via-particles condition second. The other two participants tried in the opposite order. After every trial, the participants scored the vibration intensity of experimental vibration. We repeated the trial under one condition for three times.

4. RESULTS

Figure 4 shows average of vibration intensity felt on the right arm. In direct condition, palmar side forearm (position where the vibration motor was attached) is much higher than all the other

positions, as we expected.
We performed a two-way (2 conditions × 6 positions) analysis of variance (ANOVA) with between-subjects design using R. The analysis found a significant difference among the evaluation positions at the direct condition ($F(5, 36) = 39.32, p < .01$), while no significant difference was found among the via-particles conditions ($F(5, 36) = 1.54, p = 0.20$, n.s.) . We applied a post-hoc test using Holm method between the evaluation positions at the direct condition, showing that the vibration at the palmar side forarm was significantly stronger than all the other positions ($MSe= 124.68, p < .05$).
Focusing on each evaluation positions, there was significant difference between vibration conditions at two evaluation positions. First, the vibration at palmar side forearm under via-particles condition was significantly weaker than that of under direct condition ($F(1, 36) = 77.57, p < .01$). Second, the vibration at palmer side of hand under via-particles condition was significantly stronger than direct condition ($F(1, 36) = 7.10, p = 0.011 < .05$). There was also marginally significant difference between two conditions at dorsal side of hand ($F(1, 36) = 2.99, p=0.092 < .10$).

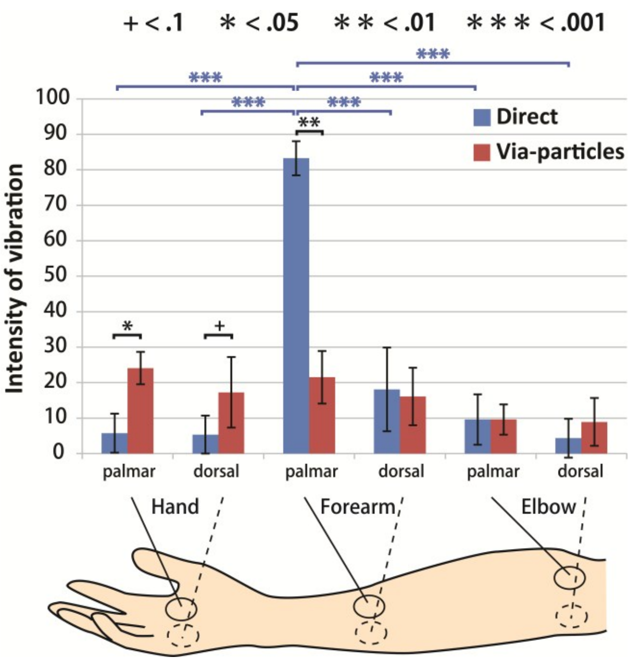

Figure 4: Intensity of vibration felt on the right arm. Error bars indicate the standard deviation. 100 in vertical axis means the same vibration intensity with referential stimuli.

5. DISCUSSION

5.1. Vibration transmission to large-area of the arm

According to the experimental result, the vibrotactile stimuli via jammed particles were felt relatively uniformly, and no significant difference was found at all evaluation positions. It means that a single common vibration motor attached on the surface of the vacuum bag can provide vibration to wider area than direct vibration, especially at palmar side of hand and forearm.

On the other hand, no significant difference between vibration conditions was found at dorsal side of forearm, and both sides of elbow. This might be attributed to the difference of sensitivity of the human arm. In general, human elbow joints were known to have less tactile receptors and less sensitivity so that the participants might not feel the transmitted vibration. This sensitivity also explains the strong vibration felt in the hand, which involves a lot of tactile receptors.

5.2. Comments from the participants

All four participants commented that they felt their whole right arm was blurry oscillating and could not identify the source of vibration under the via-particles condition. This comment supports the hypothesis that the vibration transmission via jammed particles can cover whole-arm vibrotactile stimulus.

6. TOWARD THE WHOLE-BODY HIGH-FIDELITY VIBROTACTILE DISPLAY

Toward the whole-body vibrotactile display that enriches audiovisual experiences, we implemented several types of vibrotactile display using vibration transmission via jammed particles. We used full-range speakers (W2-800SL, Tang band Ltd.), which has high-bandwidth capability, to generate vibration and sound simultaneously. Other specifications were similar with the experimental setup (see Section 3.1).

6.1. Whole-arm

We developed a whole-arm vibrotactile display, which is shown in Figure 1. Four speakers (forearm/upperarm × two sides) are attached on both sides of the vacuum bag.

6.2. Legs

Figure 5 presents an overview of the legbath-type vibrotactile display. This system uses four speakers (two legs × two sides) for vibrotactile stimuli below the knees.

Figure 5: Legbath–type vibrotactile display.

6.3. Torso

While the two previous setups place the arms or legs directly in contact with the particles, we can achieve a similar effect without direct contact between the particles and body surface by mounting the vacuum bag on the body. Figure 6 shows an example of a vibrotactile display for the torso. The concept of surrounding the body with a particle-filled mattress and fixing the body by evacuating the air is already in practical use as a temporary splint for emergency treatment [11]. Hence, our system also has high adjustability to various body shapes. However, we observed that the perceived intensity of the vibration across the vacuum bag was weaker than putting the body directly into the particles because of the weak tightening force.

Figure 6: Vibrotactile display for torso without direct contact with particles.

6.4. Whole-body

As shown in Figure 7, we tested whole-body vibrotactile stimulation by sinking the body into the particles. Although this is still a rough prototype, users clearly perceived vibration through the jammed particles.

Figure 7: Vibrotactile display for whole body.

6.5. User study

We performed a test to verify whether users can feel the speaker's vibration via the jammed particles. Three participants (males, aged 21–24, right-handed) experienced using the vibrotactile display for the whole right arm with classical music and the sound of fireworks. To cancel the noise generated from the vacuum pump, we used noise-canceling headphones (QuietComfort 15, BOSE Corp.) to output the sound.

All participants reported that they clearly felt the vibrotactile stimulus on the whole right arm when the particles hardened. In particular, they clearly felt instantaneous strong vibrations such as the explosive sound of fireworks compared with the music. All participants commented that the experience became more dynamic and immersive with the device.

One interesting comment was "I felt an explosion inside my arm." This comment may suggest that our system can be used to present an illusory haptic sensation inside the user's body. Internal body sensations are known to be provoked by vibrotactile stimuli from both sides of the body [12] (i.e., phantom sensation [13]), or by visually bloating the body and presenting vibrotactile sensation [14][15]. We speculate that our observed internal body sensation is related to both of these known phenomena.

When the arm position leaned to one side and the thicknesses of the particles were different on either side, the participants felt weaker vibration on the thicker side. Based on this observation, the thickness of the particle layer should be kept even to equalize the vibration intensity. The characteristics of vibration transmission as a function of pressure and thickness of the particle layers should be verified in future work.

7. CONCLUSION AND FUTURE WORK

We presented a method for realizing a large-area vibrotactile display by vibration transmission through jammed particles in order to enrich audiovisual experiences. We developed a prototype whole-arm vibrotactile display and conducted a test to verify whether users can feel clear vibrations via jammed particles. The results showed that all participants clearly felt the vibrations in large-area of their arm and that the whole-arm vibration enriched the audio experience.

One of our future works is to extensive evaluation of our approach by developing a precise pressure control system using electromagnetic valves. We will also develop a whole-body vibrotactile display with a bathtub-type interface to enrich the audiovisual experience.

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