Wearable Tactile Device for Fingertip Interaction with Virtual World

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ABSTRACT

Author developed a wearable tactile device mounted to the fingertips for interaction with objects in the virtual environment. The device can provide sensations of pressure, low-frequency vibration and forward-flexion illusionary force in thumb, index and middle fingers by electrical stimulation; and high-frequency vibration and skin deformation by mechanical stimulation.

1 INTRODUCTION

In recent years, along with the technological progress in computer graphics and head mounted displays, various virtual reality (VR) systems with high quality have been actively developed. For fully immersive virtual reality, beside visual cure other sensations are also required. For example, by reproducing tactile sensation with rich information, the user can experience touching various virtual objects. Author's study aimed to reproduce any kind sensation on the fingertips during rubbing, touching or grasping the objects, by presenting mechanical and electrical stimulation on the fingertips.

Some studies used grounded actuator for touching sensation feedback in the virtual environments [1][2]. However, this technology requires a large space, and the stimulation involves a tool-based interaction that limits the movement of the user's fingers. Other studies have developed the devices that deliver kinesthetic sensations using a wearable robotic mechanism [3][4]. However, the devices are large in size, heavy, and complicated in mechanism. Other wearable devices provide tactile feedback to the finger pads by presenting vibration, pressure or skin deformation sensation [5][6]. Several of these studies reported that, skin deformation can enhance the stiffness perception, but relatively in a small range.

Previously, author proposed to use the combination of mechanical and electrical stimulation to reproduce any touching sensation on the fingertip by selectively activating four kinds of mechanoreceptors [7]. Moreover, author used electrical stimulation to induce the sensations of the softness-hardness and stickiness of a virtual object in the fingertip [8]. This proposed method can generate an illusory sensation of a force flexing the fingertip forward by stimulating the tendons in the finger, or extending the finger backward by cathodic electrical stimulation. This paper summarized author's previous studies about the device's mechanism and its effect on the perception of properties of the virtual materials.

2 DEVICE AND ALGORITHM

2.1 Wearable Tactile Device

Figure 1 shows the proposed device. The mechanism detail can be found in our previous study [7]. For the current version, author used ESP32 (Espressif System Co., LTD.) microcontroller instead of Mbed (LPC1768, Arm Limited), to enable the device to communicate with the PC via Wi-Fi wireless network.

Figure 2 (above) shows an application of rubbing the surface of a VR material with the sensation feedback of electrical and mechanical stimulation. For figure 2 (bottom), author used only electrical stimulation to induce the sensation of softness-hardness and stickiness while pressing/releasing a virtual ball.

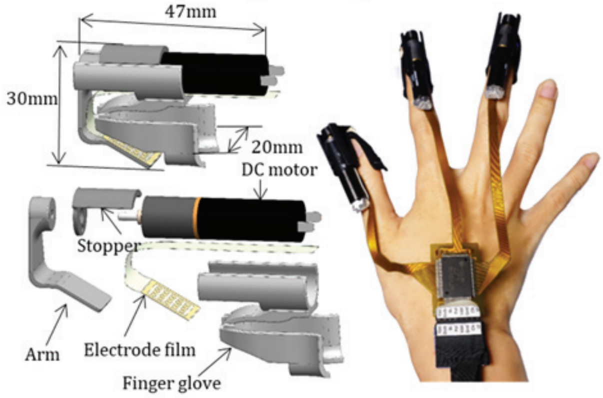

Fig. 1 Proposed device worn on the thumb, index finger and middle finger (right).

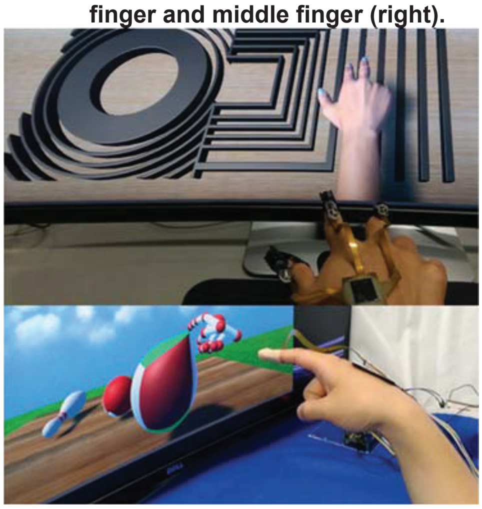

Fig. 2 VR applications for investigating the perception of material properties.

2.2 Electrical Stimulation

Electro-tactile can be stimulated in two modes: anodic and cathodic stimulation (Fig. 3 (above)). Anodic stimulation is when the electrode of a stimulation point is connected to the high voltage and other electrodes connected to the ground. In contrast, it becomes cathodic stimulation when the polarity of all electrodes are reversed. Our previous studies found that, anodic stimulation mainly activates Meissner's corpuscles whereas cathodic stimulation mainly activates Merkel cells. Therefore, author considered that pressure and low frequency vibration sensation can be stimulated on the skin by these electro-tactile methods.

Currently, author found that electrical stimulation can stimulate tendons in the fingertip (Fig. 3 (bottom)). Author proposed using this stimulation for stickiness feedback while releasing the fingertip from the sticky object. Author also proposed using cathodic stimulation for presenting softness-hardness sensation while pressing a deformable material.

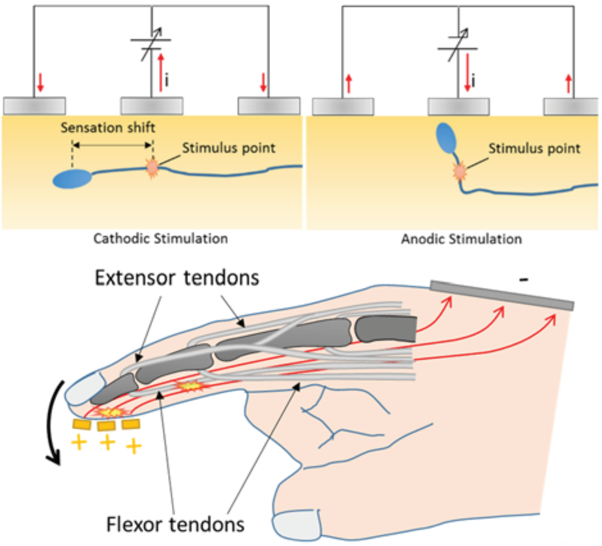

Fig. 3 Cathodic and anodic stimulation (above) and tendons stimulation in the fingertip (bottom).

2.3 Mechanical Stimulation

The mechanical arm contacted to the finger pad is actuated by a DC motor (Fig. 1). This arm can transmit vibrations and force to deform the skin to the finger pad. The DC motor can be vibrated in wide range of frequency by audio signal input voltage and rotated to deform the skin of fingertip by DC signal input voltage. Figure 4 shows the waveform of DC motor to deform the skin when rubbing an uneven surface of a virtual object.

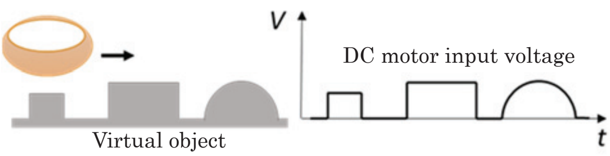

Fig. 4 Waveform of DC motor input voltage.

2.4 Visual Feedback and Force Feedback When Pressing or Releasing a Deformable and Sticky Virtual Object

Figure 4 shows the visual interaction of a deformable and sticky object when it was pressed or released by a finger. There is a common issue that, the virtual finger can easily move inside the virtual rigid body when the user attempts to touch or press it because there is no physical force to resist the finger. In the current study, author sought to address this issue. To achieve this, author considered to make the virtual finger invisible when it moved inside the virtual rigid body, and showed a copy of the finger moving on the surface of the object (Fig. 5).

When pressing, the real finger gets inside the virtual object with the distance of Δx and the object surface deforms with the distance of dx. When releasing, Δx is the deformation distance of the object, which equals to dx. Δx was used for intensities of deformation of the visual object and the electro-tactile feedback with the follow equations.

$$dx = \begin{cases} \dfrac{\Delta x}{k} & \text{(for pressing)} \\ \Delta x & \text{(for releasing with stickiness)} \\ \dfrac{\Delta x_{max}}{k} e^{-c \times t} \cos(\omega t) & \text{(after releasing)} \end{cases} \quad (1)$$

$$i = (1 + k_i \Delta x) i_{th} \quad (2)$$

where k and c represent the spring and damping coefficients of the virtual object, and t is time. Δx_{max} is a constant that limits the amount of deformation when releasing (Fig. 5 (right)). ω is the frequency of virtual surface vibration. i is the intensity of the electric current (i.e., pulse height) for force feedback applied to the finger, k_i is a constant and i_{th} is the sensation threshold of the electric current.

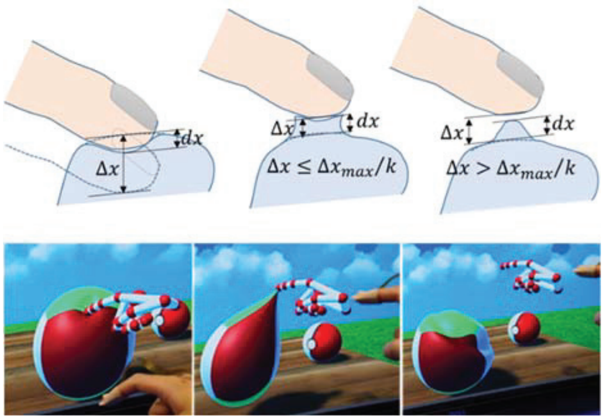

Fig. 5 Visual feedback algorithm when pressing with a finger (left), releasing with stickiness (middle) or after releasing (right).

3 EFFECT OF EACH STIMULATION MODE ON PERCEPTION OF MATERIAL PROPERTIES

3.1 Rubbing Process

Nine males and one female, age 21–34 years, participated in this experiment. All participants were right handed. They wore the device on the thumb, index finger and middle finger of the right hand and moved a virtual hand on the monitor represented the participant's hand by a PC mouse. The 3D virtual object was a puzzle shape as shown in Fig. 2 (above).

After each of the four modes (cathodic and anodic electrical stimulation, and vibration and skin deformation of mechanical stimulation) was stimulated individually and participants were asked the following questions:

1) How clearly did you feel unevenness (Macro roughness) when you touched each shape?
2) How clearly did you feel friction when you moved your finger across the surface of a shape?
3) How clearly did you feel the roughness of the material when you touched a surface? (The surface might be rough or smooth, but please provide a score for how clearly you felt this.)
4) How clearly did you feel the hardness of the material when touched each shape? (The material might be soft or hard, but please provide a score for how clearly you felt this.)

Figure 6 shows the average scores of the participants when they were received stimulation from each of the four modes. The horizontal axis represents the four tactile dimensions, and the vertical axis represents the score. The error bars represent the standard deviation.

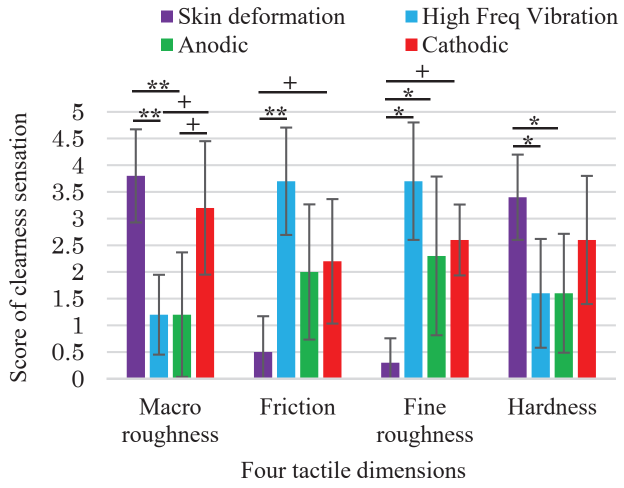

Fig. 6 Perception of each four modes tactile stimulation. "+", "*" and "" denote significant differences at p<.1, p<.05 and p<.01, respectively.**

Figure 6 shows that four-mode stimulation by the tactile device can provide four-dimensional tactile simulation (macro roughness, friction, fine roughness, and hardness). Though each stimulation mode produces sensations in almost all dimensions, it can be observed which mode is the most effective for each of the four tactile dimensions.

For macro roughness and hardness, skin deformation and cathodic stimulation earned higher scores than the other two modes of stimulation. Most participants commented that it was difficult to discern the hardness of material when they touched only a flat surface but they could clearly feel both unevenness and hardness when they moved from one shape to another. They also commented that cathodic stimulation was felt like pressure on their fingers, rather than the hardness of the material. For friction and fine roughness, high-frequency vibration obtained the highest score among all modes of stimulation. Most participants commented that they were unable to clearly distinguish the difference between friction and fine roughness when they moved their fingers on a surface of a shape. Anodic and cathodic stimulation also affected these tactile dimensions but the average scores are lower than those for high-frequency vibration. Anodic stimulation mainly produces low-frequency vibration sensation; thus, participants perceived the roughness of material. Cathodic stimulation does not produce only pressure sensation. Because the stimulus current is a pulse waveform, it also produces vibration sensations of a similar level to those of anodic stimulation.

3.2 Pressing and Releasing Process

The 3D virtual object was a deformable and sticky ball as shown in Fig. 2 (bottom). Equation (1) and (2) were used for visual and force feedback. Spring and damping coefficients of the visual object were $(\{k, c\}, \{2k, 3c\}, \{3k, 9c\})$, and the coefficients of the electric current were $((k_i, 2k_i, 3k_i)$ for pressing; and $(0.5k_i, k_i, 1.5k_i)$ for releasing). Eight participants took part in this experiment: six males and two females, ranging in age from 21 to 24 years. All participants were right-handed. After presenting each condition in random order, and they were asked to respond with intensity scores for softness-hardness and stickiness from 1 to 9.

Figure 7 and 8 show the relationship between softness and hardness for the pressing and releasing action, restively. Figure 9 shows stickiness intensity when releasing for the electrical stimulation conditions for each visual feedback condition. The results revealed that the rate of increase of the electrical intensity affected the sensation of softness for both pressing and releasing. When this intensity rate was increased, participants interpreted the material as being softer. It indicated that when participants interpreted the object as being soft through visual feedback, the intensity of their perception could be enhanced by increasing the electric current used for cathodic electrotactile stimulation and tendon stimulation. In contrast, electrical stimulation was found to have a significant effect on the sensation of hardness for pressing, but not for releasing. Author also found that electrical stimulation had a significant effect on stickiness perception. As Fig. 9 shows, when the intensity of the electrical stimulation was increased, participants perceived the material as being stickier.

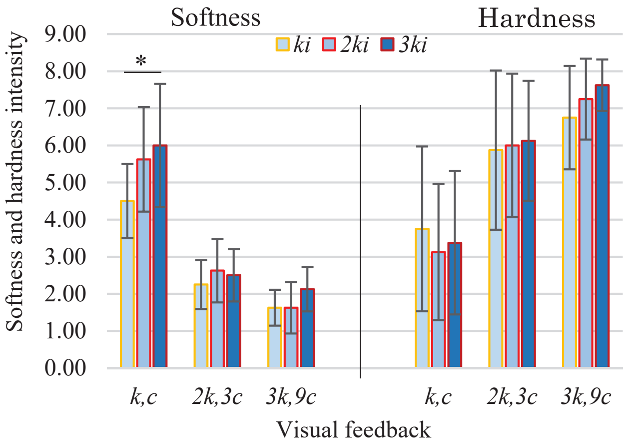

Fig. 7 Result of softness and hardness intensity when pressing the virtual ball.

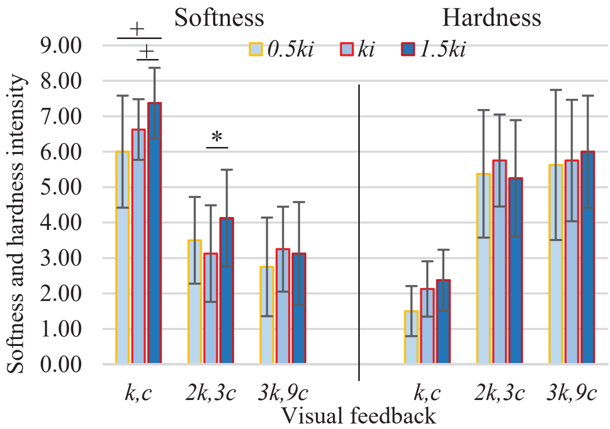

Fig. 8 Result of softness and hardness intensity when releasing the virtual ball.

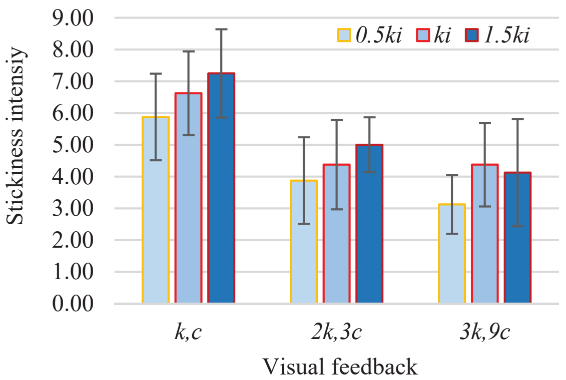

Fig. 9 Result of stickiness intensity for the electrical stimulation levels for when releasing the ball.

4 CONCLUSIONS

This paper introduced a wearable tactile device with electrical and mechanical stimulation for reproducing any tactile sensation to the thumb, index and middle finger. The electrical stimulation can provide sensations of pressure, low-frequency vibration and forward-flexion illusionary force in thumb, index and middle fingers; and mechanical stimulation can provide high-frequency vibration and skin deformation. Author also found the technique of tendons stimulation in the fingertip. Author proposed using the combination of cathodic stimulation and tendons stimulation for presenting softness-hardness and stickiness feedback. Experiment results show that the increasing rate (i.e. electrical coefficient) affect the intensities of these tactile perception.

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