Wearable Tactile Device using Mechanical and Electrical Stimulation for Fingertip Interaction with Virtual World

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ABSTRACT

We developed "Finger Glove for Augmented Reality" (FinGAR), which combines electrical and mechanical stimulation to selectively stimulate skin sensory mechanoreceptors and provide tactile feedback of virtual objects. A DC motor provides high-frequency vibration and shear deformation to the whole finger, and an array of electrodes provide pressure and low-frequency vibration with high spatial resolution. FinGAR devices are attached to the thumb, index finger and middle finger. It is lightweight, simple in mechanism, easy to wear, and does not disturb the natural movements of the hand. All of these attributes are necessary for a general-purpose virtual reality system. User study was conducted to evaluate its ability to reproduce sensations of four tactile dimensions: macro roughness, friction, fine roughness and hardness. Result indicated that skin deformation and cathodic stimulation affect macro roughness and hardness, whereas high-frequency vibration and anodic stimulation affect friction and fine roughness.

Keywords: FinGAR, mechanical stimulation, electrical stimulation, virtual touch.

Index Terms: H.5.2 [Information Interfaces and Presentation]: User Interfaces—Haptic I/O

1 INTRODUCTION

Recent advances in computer graphics head-mounted displays have promoted the prevalence of virtual reality applications. Virtual reality allows not only visual stimulation but also other realistic sensations of the virtual environment [1][2]. For example, by reproducing tactile sensation with rich information for tactile feedback, the user can experience feeling and touching virtual objects.

While there are huge number of studies in haptics, we mainly focus on fingertip tactile display. Numerous studies have reproduced tactile sensations for fingertip. Minamizawa et al. [3] developed GravityGrabber using a belt to deform the skin on the thumb and index finger to provide a sensation of gripping a virtual object. Several studies have developed and used a pin matrix to simulate shape sensation to users [4][5][6]. Vibration is the most popular technique for providing texture sensation [7][8][9], whereas electrostatic force is commonly used for friction sensation [10][11]. Each technique succeeded in reproducing some sort of tactile feeling, but only in a relatively small range, which is not versatile enough to support a variety of VR applications.

In principle, any tactile sensation can be reproduced if the skin can be driven with sufficient spatial (1.5 mm to 3.0 mm at fingertip) and temporal (0 to 1 kHz) resolution. However, in practice, developing such a versatile machine remains challenging. The skin has a large effective mass and damping effect and requires a strong power actuator. To achieve high responsiveness and small size, several studies have proposed using direct electrical stimulation of the nerves [12][13][14][15]. However, reproducing realistic tactile sensations using this method remains a challenge.

To optimize the size and weight of a versatile tactile feedback device, we proposed using both electrical and mechanical stimulation [26]. Our system, named Finger Glove for Augmented Reality (FinGAR), employs electrical stimulation to provide pressure and low-frequency vibration, and mechanical stimulation to provide high-frequency vibration and skin deformation. Each stimulation mode is related to the activities of each type of mechanoreceotors in our skin. The four-mode stimulation can be used in combination to reproduce almost any tactile sensation. This paper describes the detail of our design concept and a psychological experiment to investigate the tactile sensations participants perceive when receiving stimulation from each of these four modes. Our result contributes to understanding the selective stimulation required from each mode when reproducing tactile feedback of a virtual object.

2 BACKGROUND

2.1 Mechanoreceptor Selective Stimulation

Human touch sensation is a result of activities of four types of mechanoreceptors in the skin, corresponding to four tactile sensations [16]. As shown in Figure 1, these are Merkel cells for pressure, Meissner's corpuscles for low frequency vibration, Pacinian corpuscles for high-frequency vibration, and Ruffini endings for shear deformation. If these four receptors could be selectively activated, individually or in combination, any tactile sensation could be simulated. This is similar to how the primary colors (red, green and blue) in vision are perceived and combined by the three types of cone cells in the retina. Kajimoto et al. [21] had named this approach tactile primary colors.

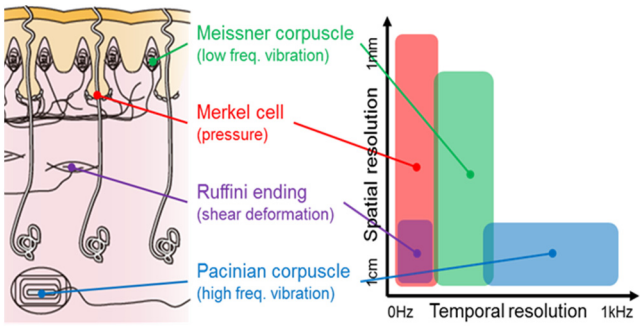

Figure 1: Four types of mechanoreceptors in the skin (left), and their spatial and temporal response characteristics (right).

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Mechanoreceptor characteristics have been widely studied and each has been reported to have a different response frequency (temporal resolution) and size of receptive field (spatial resolution) [16]. Merkel cells and Ruffini endings respond to very low-frequency vibrations (under 0.1 Hz to several Hz), whereas Meissner's corpuscles and Pacinian corpuscles respond to high-frequency vibrations (10 Hz to 100 Hz, and 60 Hz to 800 Hz, respectively). The optimal sensitivities of Meissner's corpuscles and Pacinian corpuscles are 30 Hz and 250 Hz, respectively. The receptive fields of Ruffini endings and Pacinian corpuscles are large, in the order of several centimeters, and mostly located deep in the skin. In contrast, the receptive fields of Merkel cells and Meissner's corpuscles are several millimeters in size and mostly located nearer the skin surface. These characteristics must be considered, to selectively activate the receptors and to properly optimize the size of tactile feedback device.

Some studies have attempted to selectively activate mechanoreceptors using mechanical vibration actuators. Konyo et al. [17] proposed a selective stimulation method based on temporal response characteristics of mechanoreceptors and vibration amplitude. Their method succeeded in selectively activating Merkel cells, Meissner's corpuscles and Pacinian corpuscles. Asamura et al. [18] controlled depth of vibration attenuation to selectively stimulate Meissner's corpuscles and Pacinian corpuscles. Though these studies reported the effectiveness of their methods, selective stimulation of all four modes has not yet been achieved. Moreover, spatial resolution, which can increase the size of the device, was not considered.

Other studies have proposed the use of electrical current flowing through the skin to directly stimulate tactile sensory nerves [19][20]. Electrical stimulation can be produced by anodic or cathodic current (Figure 2). Kajimoto et al. [21] has found that sensations of pressure and low-frequency vibration can be simulated by changing the polarity of the current. By considering Activating Function [22][23], they suggested that Merkel cells and Meissner's corpuscles are selectively activated by each polarity. This approach is mainly used to simulate the shape of an object through stimulation by an electrode array because of its high responsiveness and small size compared with a mechanical pin array [5][6]. However, this approach is difficult to apply to Ruffini endings and Pacinian corpuscles that are mostly deep under the skin.

From above background, we aimed to selectively stimulate all four modes of tactile sensation by using both mechanical and electrical stimulation. We developed a device that activates Ruffini endings and Pacinian corpuscles using a mechanical actuator, and stimulates Meissner's corpuscles and Merkel cells directly using an electrode array. The details of our device are described in the next section.

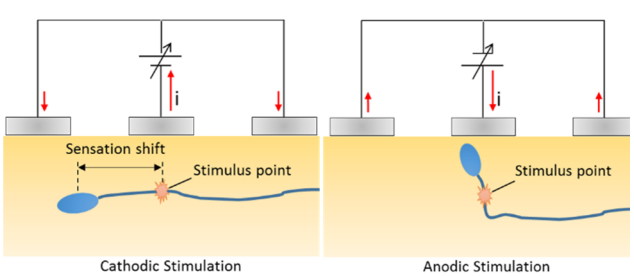

Figure 2: Cathodic (left) and anodic (right) stimulation. Cathodic pulses efficiently depolarize nerves that run parallel to the skin surface (mostly nerves of Merkel cells), whereas anodic current efficiently depolarizes vertically oriented nerves (mostly nerves of Meissner's corpuscles).

2.2 Four-Mode Stimulation and Four Tactile Perception Dimensions

From mechanoreceptors point of view, tactile sensation is the result of combining four mode of stimulation: low frequency vibration from Meissner corpuscle, pressure from Merkel cell, shear deformation from Ruffini ending, and high-frequency vibration from Pacinian corpuscle. However, the relationships between these four modes and the sense of touch in reality remains unclear. For example, when we touch an object, we will perceive texture and feel of the object but we do not distinguish which of the four modes are involved to produce such a feeling. Several studies have suggested that roughness sensation can be controlled by frequency modulation [17][24]. However, sensations produced by temporal and spatial stimulation of each of the four modes has not yet been studied.

Okamoto et al. [25] suggested that there are five psychological dimensions of tactile perception. They are hardness, friction, fine roughness, macro roughness and warmness. The four-mode stimulation cannot simulate temperature but might simulate perception of the other four dimensions. The present study aimed to investigate which of the four modes stimulated by our device contribute to the reproduction of each tactile dimension (Figure 3).

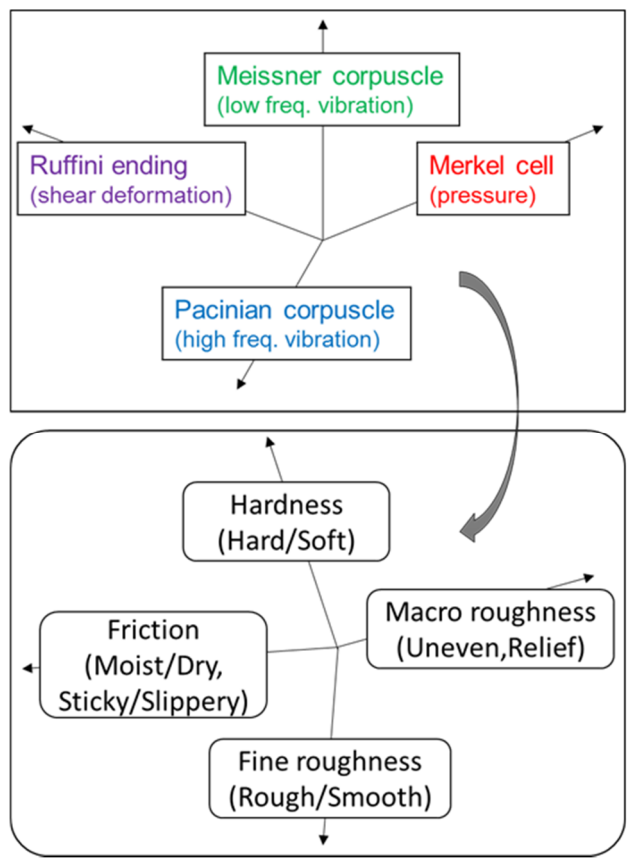

Figure 3: Dimension transformation of four-mode stimulation (top) to four psychological dimensions of tactile perception (bottom).

3 FINGAR

FinGAR is designed to be attached to the fingertip to provide four-mode stimulation. To be useful for tactile feedback in a wide variety of virtual or augmented reality tasks, such as touching or grasping, tactile feedback should be provided to at least two or three fingers. It must also be lightweight, simple in mechanism, easy to wear, and must not disturb the natural movement of any finger. With this

consideration, we designed three FinGAR devices to be worn on the thumb, index finger and middle finger, as shown in Figure 4. FinGAR was preliminarily developed and shown at SIGGRAPH 2016 Emerging Technology for demo experience [26]. The present paper describes the detail of device design and a user study for device's evaluation. Each FinGAR device can be divided in to five parts, a finger glove, a DC motor, a DC motor stopper, an arm and an electrode film (Figure 5). The finger glove is made of 3D-printed ABS, and grips both sides of the finger. Each sample device weighs 15 g and is approximately 47 mm × 20 mm × 30 mm.

3.1 Mechanical Stimulation: Skin Deformation and High-Frequency Vibration

A DC motor (Maxon 118386) with 16:1 gear ratio was used to provide vibrations. In our previous study, we found that a DC motor is able to serve as a high-fidelity vibration unit [27]. To the DC motor, we attach an arm with contact area of 12 mm × 15 mm to transmit vibrations to the finger pad. Vibrations from the DC motor are transmitted through this arm to the skin of the finger. Because the receptive field sizes of Ruffini endings and Pacinian corpuscles are large, this single arm is sufficient to simulate skin deformation and high-frequency vibration without any additional vibration actuator.

Users can perceive a realistic rubbing sensation regardless of the skin deformation direction [28]. Therefore, although this arm stretches the skin only left or right, it can be used to provide a rubbing sensation even when the finger is moved forward or backward. This eliminates the need for another actuator to deform the skin in other directions.

The above DC motor can be driven from 0 to 500 Hz; the peak amplitude of vibration is at 50 Hz. The maximum lateral force applied to stretch the skin is 1.0 N. The motor is controlled by electrical hardware that consists of a microcontroller (NXP Semiconductors, mbed NXP LPC1768), a D/A converter (Linear Technology Inc., LTC1660) and an analog motor driver (Texas Instruments Inc., amplifier OPA2544). The microcontroller communicates with a PC via a serial port.

3.2 Electrical Stimulation: Pressure and Low-Frequency Vibration

Owing to the small receptive field size of Meissner's corpuscles and Merkel cells, we decided to use electrical stimulation to provide pressure and low frequency vibration sensation. This approach can achieve a high spatial resolution by using an electrode array. Such an array is dense and smaller than an equivalent mechanical structure such as a pin array. Electrical current can stimulate Merkel cells and Meissner's corpuscles by changing the polarity of the electrodes. Therefore, we can simulate pressure and low frequency vibration sensation on the skin.

We attached a 4 × 5 electrode array film to the skin over the contact area of the mechanical arm. Electrodes have diameter 1.5 mm and are 2 mm apart. The whole array is surrounded by a ground electrode (Figure 5). The electrical current of each electrode is controlled by an electrotactile feedback device kit that is similar to the HamsaTouch [29]. It consists of a microcontroller (NXP Semiconductors, mbed NXP LPC1768), a high-speed D/A converter (Analog Devices Inc. AD5452), a voltage-current converter and a 64 channels serial-to-parallel converter (Supertex inc., HV507).

By combining mechanical and electrical stimulation, our setup achieves four-mode stimulation and can provide sufficient spatial and temporal resolution for each mode, as shown in Figure 6.

Figure 4: FinGAR devices worn on the thumb, index finger and middle finger.

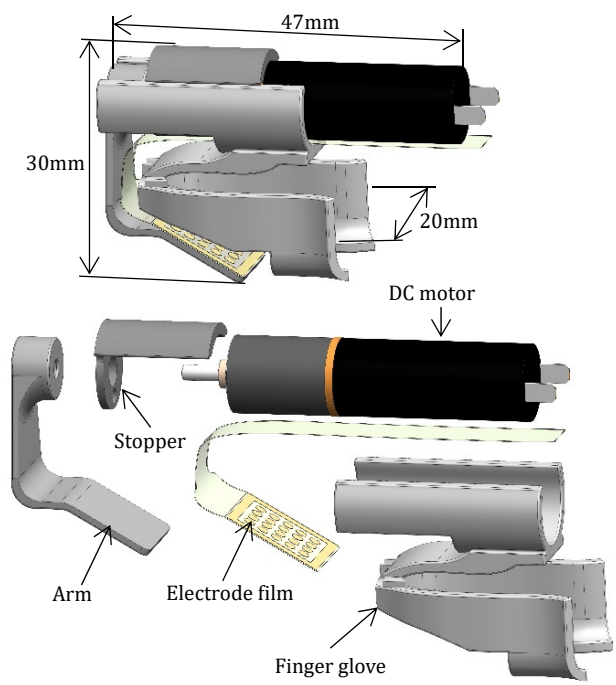

Figure 5: Exploded view of one FinGAR device.

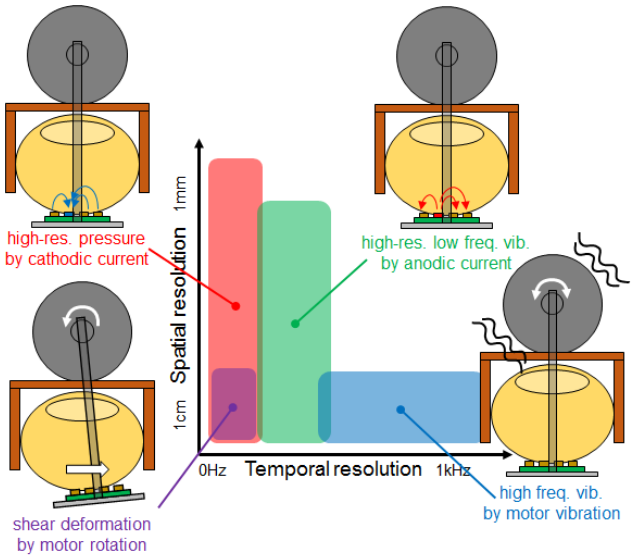

Figure 6: Role of each mode stimulation.

4 User Study

4.1 Algorithm for Four-Mode Stimulation

The following algorithm for each mode stimulation was designed in order to study how clearly participants perceive tactile sensations when receiving stimulation from each of the modes.

4.1.1 Shear Skin Deformation

Because users can perceive friction independent of skin deformation direction [28], we designed this algorithm to present absolute shear skin deformation while ignoring the movement direction of the finger. The value of DC motor input voltage for stretching the skin depends on the height above a reference plane of the 3D virtual object that a finger is touching (Figure 7):

$$V_{t,stretch} = \min\left(k \times Height_t, V_{max,stretch}\right) \quad (1)$$

where $V_{t,stretch}$ is the input voltage for skin deformation, k is constant, and $Height_t$ is the height of the 3D virtual object at the finger position. To prevent damage to the device, the value of $V_{t,stretch}$ was limited to $V_{max,stretch}$. With this algorithm we expected users to perceive the shape of the 3D virtual object.

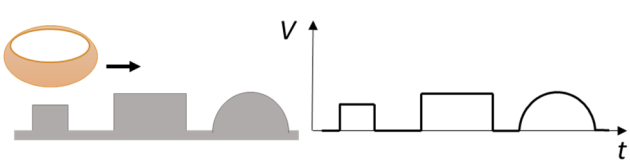

Figure 7: Waveform of DC motor input voltage for skin deformation

4.1.2 High-Frequency Vibration

The DC motor input voltage for high-frequency vibration follows a sine waveform with amplitude dependent on the finger movement velocity:

$$V_{t,vib.} = \min(C \times v_t, V_{max,vib.}) \times sin(2\pi f t) \quad (2)$$

where $V_{t,vib}$ is the input voltage for high-frequency vibration, C is constant, v_t is the finger velocity, sin is a sine waveform function, and f is the frequency (fixed at 200 Hz for this experiment). The amplitude of $V_{t,vib.}$ was limited to $V_{max,vib.}$. At this amplitude, all participants can sense the vibration clearly.

4.1.3 Anodic and Cathodic Current

The anodic and cathodic currents have pulse width 200 µs and electrical vibration frequency 50 Hz. The intensity (pulse height) is:

$$I = \min(D \times v_t, \frac{I_{th} + I_{max}}{2}) \quad (3)$$

where I is the current intensity and D is constant. I_{th} is the threshold and I_{max} is the strongest current at which the participant perceives the stimulation but does not experience pain.

The electrode array can provide shape information by stimulating only the electrodes inside the contact area. As the contact area becomes larger, the electrodes that their surroundings (up, down, left and right side) are turning on, are switched off to the ground level voltage (Figure 8).

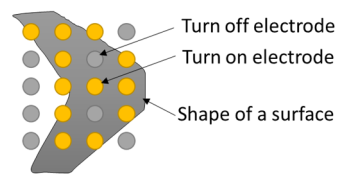

Figure 8: Electrode array pattern.

4.2 Participants and Procedure

Nine males and one female, age 21–34 years, participated in this experiment. All participants were right handed.

Each participant was asked to sit on a chair. FinGAR devices were worn on the thumb, index finger and middle finger of the right hand. A 3D virtual object was presented to the participant on a computer monitor. A virtual hand on the monitor represented the participant's hand. Using the same right hand that is wearing FinGAR, the participant moved a computer mouse to move this virtual hand to touch the surface of a virtual object. The 3D virtual object we used in this experiment was a puzzle shape as shown in Figure 9.

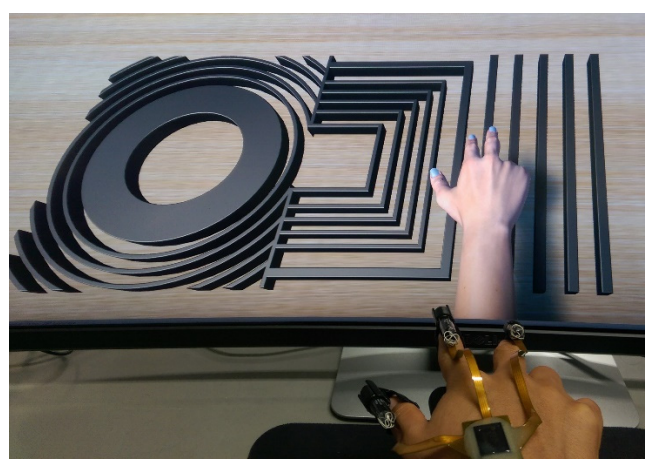

Figure 9: Overview of the experiment.

Before the experiment, participants were asked to adjust the electrical current to calibrate I_{th} and I_{max}. After this, they were asked to move the mouse so that the virtual hand touched the object on the screen. Each of the four modes was stimulated individually and participants were asked to remember the associated sensations.

Participants touched the object until they were comfortable with the different signals and could remember the sensations. This training took 5 to 10 min. After this, 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.)

After hearing each question, participants were asked to move the mouse and touch the virtual object again for as long as they wanted. They were allowed to score and rescore how clearly each sense was reproduced by comparing each of the four stimulation modes. Scores were assigned on a six-point scale where 0 indicates that they did not perceive this sensation at all and 5 indicates the perception was very clear.

4.3 Result

Figure 10 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.

The Friedman test was conducted to analyze the data for each tactile dimension. There were significant differences between skin deformation and high-frequency vibration ($p<.01$) and skin deformation and anodic stimulation ($p<.01$), and marginally significant differences between cathodic stimulation and anodic stimulation ($p=.07$) and cathodic stimulation and high-frequency vibration ($p=.09$) for macro roughness sensation. There was a significant difference between high-frequency vibration and skin deformation ($p<.01$), and a marginally significant difference between cathodic stimulation and skin deformation ($p=.05$) for friction sensation. There were significant differences between high-frequency vibration and skin deformation ($p<.01$) and anodic stimulation and skin deformation ($p<.05$), and a marginally significant difference between cathodic stimulation and skin deformation ($p=.05$) for roughness sensation. There were significant differences between skin deformation and high-frequency vibration ($p<.05$) and skin deformation and anodic stimulation ($p<.05$) for hardness sensation.

5 Discussion

Experimental results show that four-mode stimulation by FinGAR can provide four-dimensional tactile simulation. Though each stimulation mode produces sensations in almost all dimensions, we can observe 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. We believe cathodic stimulation can also be used for force feedback when pressing or grasping a virtual object. The hardness sensation can be improved by changing the contact area (i.e. electrode array) and intensity of electrical current (i.e. pressure), similar to the method proposed by Fujita et al. [30].

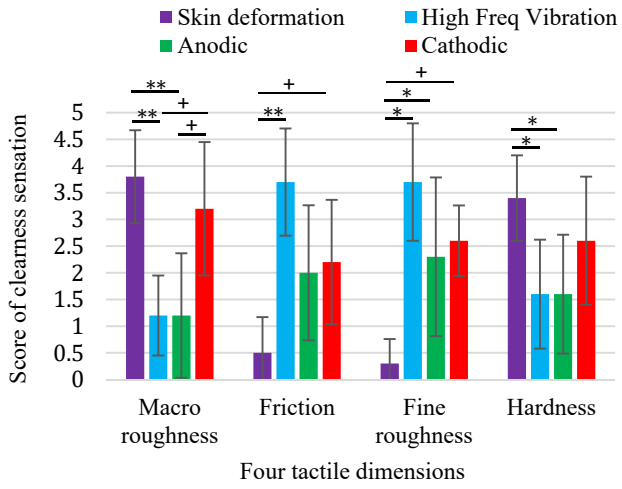

Figure 10: Comparison scores of clearness of sensation for four tactile dimensions stimulated by each of four modes. "+", "*" and "**" denote significant differences at $p<.1$, $p<.05$ and $p<.01$, respectively.

For friction and fine roughness, high-frequency vibration obtained the highest score among all modes of stimulation. This confirms the findings of Konyo et al., [17][31] who reported that high-frequency vibration produces sensation of friction. 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 [32]. Therefore, cathodic stimulation also affects roughness sensation.

FinGAR was presented at SIGGRAPH 2016 [26] and more than 1000 people took part in our demonstration. At that time, we presented only three modes: skin deformation, high-frequency vibration and anodic stimulation. Most people were surprised by the tactile feedback, especially the realism of the macro roughness. Our improved device was demonstrated at a local conference and at AsiaHaptics 2016 [33]. Most attendees were interested to experience four modes of stimulation. They commented that mechanical stimulation seemed to provide sensation of four tactile dimensions more clearly than electrical stimulation. However, when experiencing the combination of electrical and mechanical stimulation, it gave a richer and more realistic experience. Based on the results of the present study and these comments, we intend to study how to control the intensities of the four modes.

We believe that our device also can be used for tactile feedback in teleoperation or augmented reality. Similar to the method proposed by Asano et al. [34], FinGAR can be used to modify the roughness or hardness sensation while the user's finger is moved over real materials. This also has potential application in assisting product design.

6 Conclusion

We developed FinGAR, a tactile feedback device that uses mechanical and electrical stimulation. FinGAR can provide four-mode stimulation: skin deformation, high-frequency vibration, anodic (i.e. low frequency vibration) and cathodic (i.e. pressure) stimulation. These four modes in combination can be used to

simulate any tactile sensation. FinGAR is lightweight, simple in mechanism, easy to wear and does not disturb the natural movement of the finger.

The experimental results show that skin deformation and cathodic stimulation affect the sensation of macro roughness and hardness, whereas high-frequency vibration and anodic stimulation affect the sensation of friction and fine roughness. In future work we intend to develop an algorithm to control the intensities of these four tactile dimensions.

Acknowledgements

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