Electrotactile Stimulation Based on Strain Energy Density of the Fingertip

Katsunari Sato, Hideaki Nii, Naoki Kawakami, and Susumu Tachi

Graduate School of Information Science and Technology,
The University of Tokyo, Japan
{Katsunari_Sato,Hideaki_Nii}@ipc.i.u-tokyo.ac.jp,
{kawakami,tachi}@star.t.u-tokyo.ac.jp

Abstract. The shape recognition of an object is important for dexterous manipulation by humans. Therefore, we have developed a haptic display that integrates both electrotactile and kinesthetic sensations to present shape information. However, the electrotactile display only presents the contact field between the object and the fingertip. Therefore, we propose a method of electrotactile stimulation using the strain energy density model at the fingertip to generate the tactile sensation of the fingertip deformation. The result of the shape recognition experiment verifies the efficiency of the proposed method.

Keywords: electrotactile display, strain energy density, shape recognition.

1 Introduction

When humans manipulate an object, they recognize the object properties such as the shape, posture, weight, and stiffness. Therefore, it is important for a haptic display to present such information by presenting both tactile and kinesthetic information. Recently, haptic displays that present both types of information have been realized [1] [2]. We have also constructed a haptic display that can present the shape of an object. We integrated a small electrotactile display with a kinesthetic display [3]. The electrotactile information allows us to perceive the exact shapes and reflective force of an object such as an edge or a concavo-convex surface. Therefore, humans can efficiently recognize the shape of an object by electrotactile-kinesthetic integration.

Conventional electrotactile displays present a two-dimensional contact field between the object and the fingertip by on-off signals [2] [3] [4]. However, humans perceive the exact shape of an object not from two-dimensional contacts fields but from a three-dimensional touch condition. When the fingertip touches an object, it gets deformed. Humans perceive this deformation via the firing of mechanoreceptors and recognize the shape of the object. Therefore, an electrotactile display that can reproduce the deformation of the fingertip is desired.

In this paper, we propose a method for generating an electrotactile stimulus based on the strain energy density (SED) to reproduce fingertip deformation at a peripheral level (Fig. 1). First, we use the finite element method (FEM) model to simulate the

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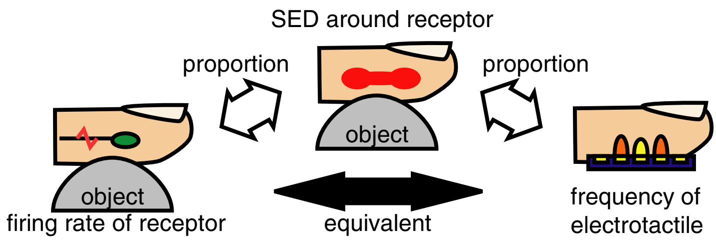

Fig. 1. Diagram of the proposed SED model that reproduces the fingertip deformation using an electrotactile stimulus

SED of a human fingertip when it touches objects. Then, we test the effectiveness of the electrotactile stimulus based on the simulated SED by means of a shape recognition test.

2 Electrotactile Stimulus Based on SED

In order to reproduce the fingertip deformation caused on touching an object, we use focus on the SED at the fingertip. Srinivasan and Dandekar [5] investigated the relationship between the SED around a mechanoreceptor and the receptor's firing rate at the fingertip. They showed that the firing rate of a Merkel cell is proportional to the SED around the cell. Furthermore, Kobayashi and Maeno [6] showed that the firing rate of the mechanoreceptors is proportional to and the SED around a Meissner's corpuscle.

From these relationships, we consider reproducing the fingertip deformation virtually by stimulating the mechanoreceptors at a firing rate proportional to the SED. We used an electrotactile stimulus to stimulate the mechanoreceptors [3]. The electrotactile display comprises a pin-electrode matrix. The stimulus directly activates the nerve fibers on the skin surface by means of an electric current from the surface electrodes. Since the electrotactile stimulus can stimulate the nerve fibers with an arbitrary frequency, it can reproduce the firing rate of the mechanoreceptors in proportion to the SED in the fingertip.

3 Simulation of SED

In order to stimulate the nerve fibers using the SED, we must calculate the SED around the mechanoreceptors when the fingertip touches an object. In this chapter, we simulate the SED using FEM software (FEMLAB, COMSOL AB.).

In the simulation, we constructed a simple two-dimensional fingertip model (Fig. 2). Merkel cells and Meissner's corpuscle were considered to assume a key role in the recognition of the exact shape of the object [7]. Therefore, the SED was measured on the boundary between the epidermis and dermis where the Merkel cells and Meissner's corpuscles exist.

The SED was measured by pushing an object to the surface of the fingertip model. As object shapes for the simulation, we focused on three extreme examples of

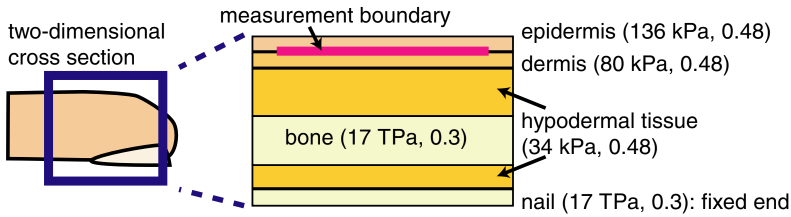

Fig. 2. Constructed fingertip model. We set the nail as the fixed end. Young's modulus and Poisson's ratio are indicated in the parentheses.

curvature radius: plane, curved face, and edge. The curvature radii of the plane, curved face, and edge surfaces were 0 mm^{-1}, 0.1 mm^{-1}, and ∞ mm^{-1}, respectively. We set the pushing distance of the objects to the fingertip at 0.2 mm, 0.4 mm, and 0.6 mm.

Figure 3 shows the simulation results. The SED of the edge surface is very high and that of the plane is low at all points. The SEDs at the contact boundaries of the curved face are higher than that of the intermediate. The SED increases with the pushing distance for all shapes. A high SED implies that the mechanoreceptors fire frequently when a human being touches an object. Therefore, this result is considered to be natural because humans perceive an edge surface and a contact boundary more strongly than a plane and an intermediate of the contact field, respectively.

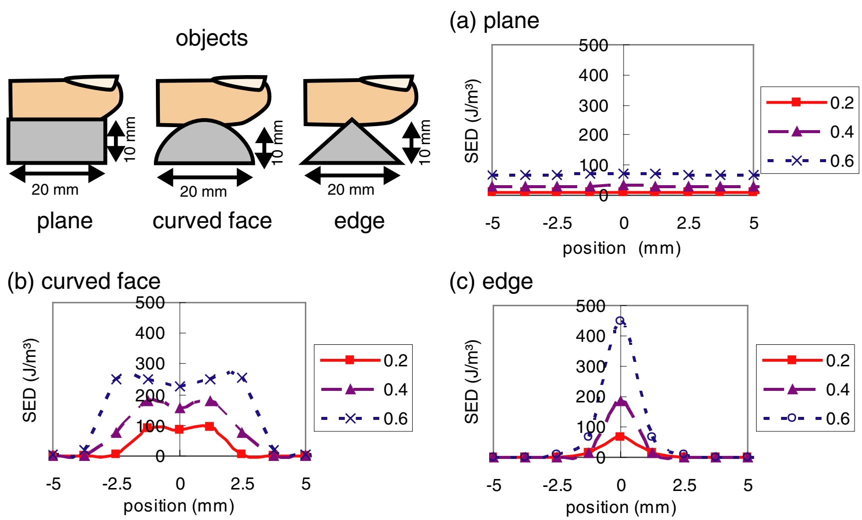

Fig. 3. Simulation results. The SED is calculated from –5.0 mm to 5.0 mm at 1.25 mm intervals. (a), (b), and (c) represent the SED when the fingertip touches the plane, curved face, and edge objects, respectively. The solid, broken, and dotted lines represent SED pushing distances of 0.2 mm, 0.4 mm, and 0.6 mm, respectively.

4 Shape Recognition Experiment

Using the simulated SED, we considered that the electrotactile stimulus can generate the sensation of the deformation of the fingertip when touching an object. In this chapter, we evaluate its efficiency by means of the shape recognition test.

4.1 Materials and Methods

The experiment was carried out in a virtual environment. The subjects were made to push a virtual object shape and identify the shape of the object they touched. The object shapes—plane (0 mm^{-1}), large curved face (0.05 mm^{-1}), medium curved face (0.1 mm^{-1}), small curved face (0.2 mm^{-1}) and edge (∞ mm^{-1})—were selected on the basis of the curvature radius.

Figure 4 shows the experimental setup used for the evaluation. An electrotactile display was mounted on the PHANToM Omni (SensAble Tech.) to function as the interface between the real and virtual worlds. The subjects placed the tip of their index finger on the electrotactile display and held the end effector of the PHANToM with the other fingers. They operated a virtual finger in the virtual world as they would operate their index finger by moving the end effector. The movement of the finger was restricted to a two-dimensional area (xy plane).

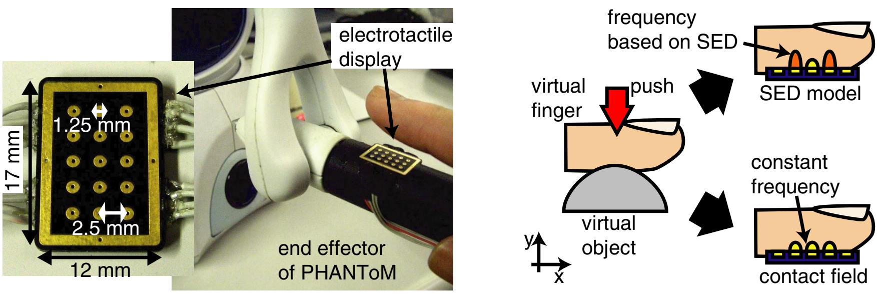

Fig. 4. Experimental setup. The left-hand side shows the electrotactile display on the PHANToM. The right-hand side shows the virtual world and the electrotactile stimulus corresponding to the touching condition.

When a subject pushed a virtual object along the y-direction, he/she felt a reflective force of the object along the same direction. The reflective force was proportional to the involved distance of the fingertip and the object. In addition, the subjects felt an electrotactile stimulus corresponding to the finger position and the reflective force.

In this experiment, we compared SED-based and contact-field-based electrotactile stimuli. The frequency of the SED-based electrotactile stimulus varied in proportion to the simulated SED same way as described in chapter 3. This experiment used five frequencies—20 Hz, 30 Hz, 60 Hz, 90 Hz, and 120 Hz—to reproduce the firing rate of the mechanoreceptors. Meanwhile, the frequency of the contact-field-based electrotactile stimulus was set constant at 60 Hz.

It should be noted that we used an anodic stimulus as the electrotactile stimulus in this experiment. Cathodic and anodic stimuli are considered to capable of stimulating Merkel cells and Meissner's corpuscles, respectively [4]. However, this selective stimulation has not been proven quantitatively, and the cathodic stimulus causes undesirable pain. Therefore, we used an anodic stimulus to fire both receptors.

The subjects were nine adults in their 20s and 30s. They were made to practice the procedure before the real experiment. Each shape was presented 10 times under both electrotactile conditions. The subjects were not provided with a visual key of the shapes for their reference. After the experiment, we asked the subjects for their feedback about the experiment.

4.2 Results and Discussion

The graphs in Fig. 5 show the results of the experiment. There is a tendency that the accuracy of shape recognition is better for the SED-based electrotactile stimulus when subjects touched the plane, curve L, curve S, and edge. Moreover, the feedback from the subjects was positive: they mentioned that they felt a realistic sensation in the case of the SED-based electrotactile stimulus, especially in the case of the edge object. Therefore, we consider that an SED-based electrotactile stimulus is effective for exact shape recognition.

However, the significant difference does not appear other than the result of the plane ($t(8) = 2.41$, $p < .05$). Moreover, the correct answer ratios of the curved faces are not good (< 50 %). Therefore, we consider that we could not clearly reproduce the three-dimensional touch condition in this experiment. There could be two reasons for this. First, the spatial resolution of the electrotactile display was not appropriate, that is, the diameter of the electrode (= 1.25 mm) and the distance between the centers of two electrodes (= 2.5 mm) did not favor the reproduction of the SED of the fingertip. Second, selective stimulation of the mechanoreceptors is required. Since the role of different mechanoreceptors is different [7], we have to measure the SED around the Merkel cells and Meissner's corpuscles, and then selectively stimulate each mechanoreceptor.

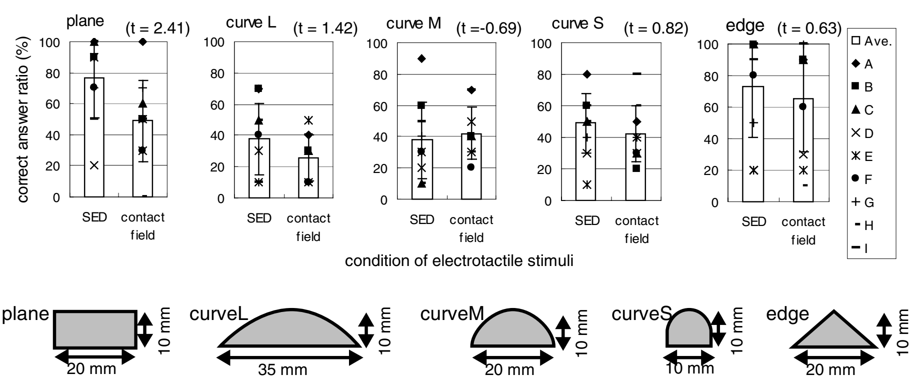

Fig. 5. Results of the shape recognition experiment. Each dot represents the result of each subject and the bars represent their average. The error bar represents the standard deviation. The results of t-test are indicated in the parentheses.

5 Conclusion

We proposed a method for generating electrotactile stimuli based on SED. First, we simulated the SED of a human fingertip when touching some objects by using the FEM model. Then, we confirmed the effectiveness of the electrotactile stimulus based on SED by a shape recognition test. We concluded that this method of generating electrotactile stimuli can potentially improve the efficiency of shape recognition.

In future, we plan to examine the relationship between SED and the firing rate of mechanoreceptors more closely. Then, we will construct a more rigorous simulation model and electrotactile stimulation to generate a realistic sensation of touching the shape of an object.

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