Objective Evaluation of Tactile Sensation for Tactile Communication

We clarified the relationship between the surface shapes of touched objects and the strain energy density caused by deformation of human fingers by simulating various materials, aiming at achieving a form of tactile communication that allows transmitting tactile sensation. The correlation between the strain energy density and the physiological firing frequency of the tactile receptors in human fingers has already been clarified and it is thus considered to be possible to construct an electrically stimulated tactile display using the results of the simulation study presented in this article. This was conducted based on a contract research with the Maeno laboratory (Associate Professor Takashi Maeno), the Department of Mechanical Engineering, Faculty of Science and Technology, Keio University.

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1. Introduction

We humans use the five senses of "sight, sound, touch, taste and smell," to interact with other people and various objects around us. While remote communication with video and speech have become familiar to us lately, DoCoMo is currently working on research aiming at finding ways to communicate via tactile sensation, which is believed to be important in terms of information volume, which comes after sight and sound. By using various functions that tactile sensation has, new application fields that have not been achieved with conventional communication media only can be expected to appear in the near future.

In physiology, tactile sensation is called somatic sensation; it is classified into "deep sensation" caused by such as subdermal muscles, tendons, joints, and "cutaneous sensation" caused by receptors on the surface of the skin [1]. Deep sensation is caused by receptors existing in joints, and muscles, and provides motion-related information such as position sensation, sensation of speed and haptic sensation. Cutaneous sensation refers to the sense of touch perceived by the surface of the skin, such as the "harsh" or "smooth" feel of a fabric. This article focuses on cutaneous sensation.

DoCoMo has been carrying forward research on tactile displays using electrical stimulation [2]. By stimulating nerves connected to tactile receptors electrically, the firing of the tactile receptors can be reproduced and tactile sensation can be represented artificially. For example, tactile sensation felt when stroking an object is perceived through the following process: the fingers' "shapes are deformed" due to contact with "the surface shape," whereupon the "tactile receptors fire due to the finger shape deformation (launch of nerve impulse)," and "tactile sensation is felt when the signals are received and processed by the brain." There are many unresolved mechanisms involved in the human cognitive processes, and in order to construct a functioning tactile display, it is necessary to understand the process from "surface shape" to the "firing of tactile receptors due to finger shape deformation." For this reason, we focused on simulation of finger shapes deformation in this contract research. By obtaining quantitative indexes for "how should stimuli be presented to reproduce certain tactile sensations," our research will be able to take a big step forward toward realization of tactile communication.

2. Objective Evaluation of Tactile Sensation

2.1 Research Purpose

The purpose of this research is to objectively evaluate the tactile sensation when we touch a variety of objects. That is, we analyze contact between fingers and various materials to obtain a space-time distribution of Strain Energy Density (SED) inside the fingers caused by deformation of the finger shape.

It is already known that the frequency at which the tactile receptors fire nerve impulses is correlated with the SED in the area of the tactile receptors [3]. Based on this correlation, we examine the relationship between surface shape of objects and

SED, and then use the aforementioned correlation to derive a relationship between the surface shape and the firing frequency of the tactile receptors. It should then be theoretically possible to present the tactile sensation felt when touching a certain surface shape by meticulously reproduce the nerve impulse firing frequency of the tactile receptors obtained here.

Then, we apply the SED distribution obtained in this research to stimulation parameters of our electrocutaneous display.

2.2 Tactile Receptors

The tactile receptors that receive cutaneous sensation are largely classified into three types of sensation, mechanical deformation and pressure, heat/cold and pain. The tactile receptors that detect mechanical deformation and pressure such as "harsh" and "smooth" are called mechanoreceptors; and the mechanoreceptors consist of the Meissner's corpuscle, Merkel's disk, Ruffini ending, Pacinian corpuscle and so on (**Figure 1**). Each of these is explained below.

1) Meissner's Corpuscle

The receptive field* is narrow. It detects vibration of the skin and responds in the range from approximately 20 to 100 Hz, but is most sensitive around 30 Hz. The relationship between the skin vibration frequency and the firing frequency of the Meissner's corpuscle is almost 1:1.

2) Merkel's Disk

It has a narrow receptive field and is believed to detect skin displacement such as pressure. The firing frequency of the Merkel's disk is 0 to 200 Hz and increases according to the increase of SED.

3) Ruffini Ending

It has a wide receptive field and is believed to detect pressure and elongation, but there are many things unclear about it. No sensation occurs in case of neural electrostimulation by itself.

4) Pacinian Corpuscle

It has a wide receptive field and responds to vibrations with relatively high frequencies of 100 to 300 Hz, but is most sensitive around 200 Hz. The relationship between the skin vibration frequency and the firing frequency of the Pacinian corpuscle is almost 1:1.

* Receptive field: The width of the skin surface that can be detected by one tactile receptor.

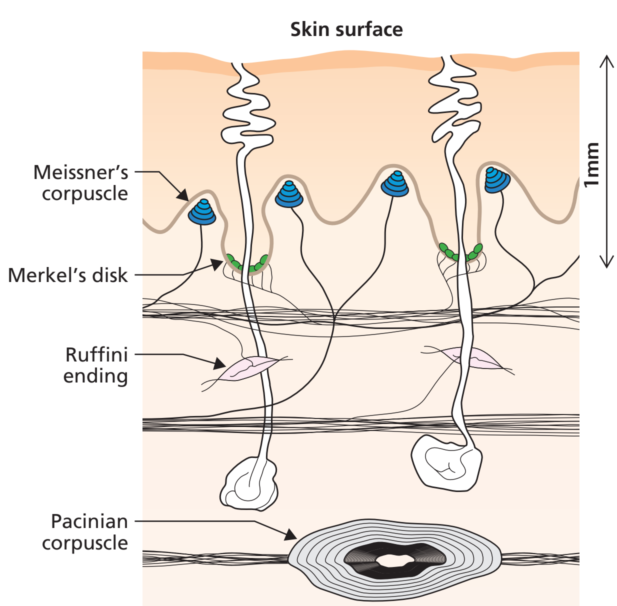

Figure 1 Mechanoreceptors

2.3 Strain Energy Density and Tactile Receptors

Reference [4] reported an experiment results of measuring mechanoreceptors activities when touching the surface of an object and recording nerve impulse firing by piercing the tactile receptor nerves of a monkey with electrodes.

Maeno, et al. also modeled cross-sections of finger tissues in detail and analyzed contact with various stimulating surfaces using finite element analysis [5]. As a result, it was found that the nerve impulse firing characteristics of the Merkel's disk receptors in the experiment using monkeys mentioned above and the SED simulation results for the locations where Merkel's disks are present in the finite element analysis model show mostly the same tendencies. Based on this result, we assumed that SED is detected by tactile mechanoreceptors and decided to use SED as an objective evaluation index of tactile sensation.

2.4 Analysis of Contact between Various Materials and Finger Tissue

1) Finger Tissue Model

Fabrics, metals, resins and other similar materials all have fine surface structures. With conventional finger tissue models, it is not possible to conduct contact analysis of materials with fine surface structures due to large element sizes. For this reason, we analyzed the contact between each of these materials and finger tissue using an improved finger tissue model, which divides the horny layer into three parts and reproduces the finger print area in detail. **Figure 2** shows the improved finger tissue model. Areas indicated by symbols are node positions

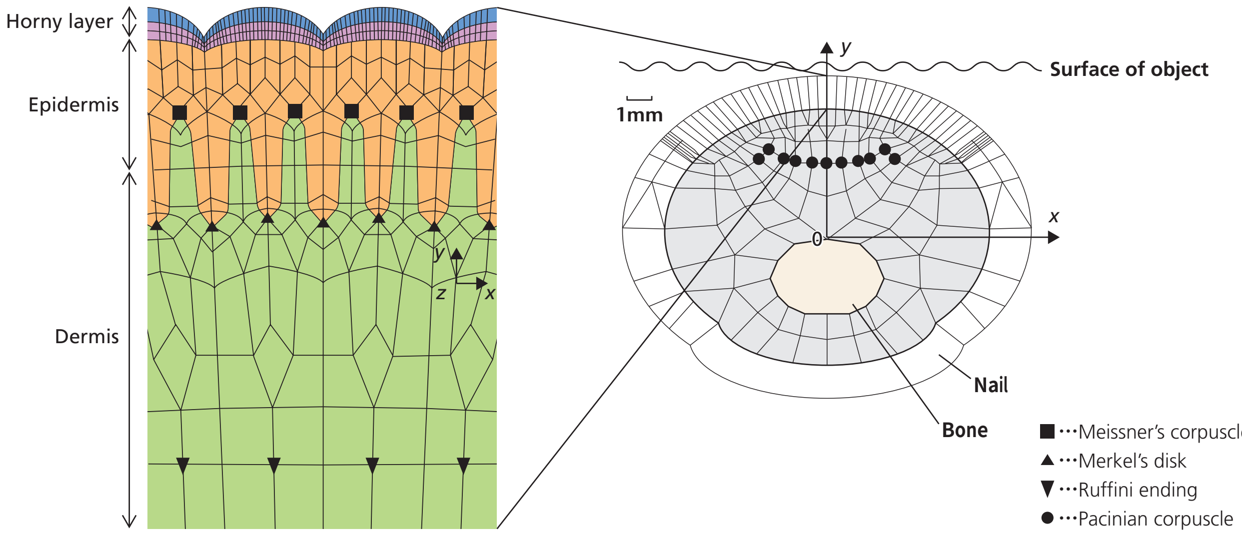

Figure 2 Improved finger tissue model

where tactile receptors of the four types mentioned above are located. Reference [5] describes the size, Young's modulus, density and other parameters of the finger tissue model. We used the finite element code MSC.MARC2005 for the analysis.

In the contact analysis, a 2.0 s long contact process was simulated using 10,000 steps (0.2 ms per step). First, an uneven pattern representing the surface of a rigid body was pushed onto the finger tissue at a constant speed (touch sensation) causing a deformation with a depth of 0.5 mm within 0.5 s. In the next 0.5 s, the rigid body was accelerated at a constant acceleration in the tangential direction up to a speed of 20 mm/s. After that, the body was slid at a constant speed of 20 mm/s for 1.0 s in the tangential direction. For comparison, humans normally tend to slide their fingers over objects at speeds of several tens to 200 mm/s when sensing by touch.

2) Material Analyzed

We selected polyester, aluminum and acrylic resin as the materials to be analyzed this time. Causes of tactile sensation can largely be divided into mechanical factors such as harshness, elasticity and friction and temperature-related factors such as temperature and heat conductivity. Here, we assumed that the sensation would eventually be reproduced in our electrocutaneous display and selected materials whose heat conduction characteristics are similar to those of the stimulating electrodes of our electrocutaneous display.

The surface shape of each material was measured using a super-depth color 3D shape measurement microscope. Based on the measurement result, we created two-dimensional surface shape patterns. **Figure 3** shows the surface shape pattern of polyester among the created two-dimensional surface shape patterns.

Moreover, the Coulomb friction coefficient, a physical property of a material, was set to 0.1 for polyester, 0.3 for aluminum and 1.5 for acrylic resin. To avoid excessive calculation costs, only the surface shape was reproduced for each material to represent the uneven shape of the rigid body whereas the elasticity of the materials was not considered.

3) SED Simulation Results

The SED is obtained for each material at the tactile receptor positions to obtain the space-time distribution of the SED when fingers get into contact with a material. **Figure 4** shows representative space-time distributions of the SED at the Merkel's

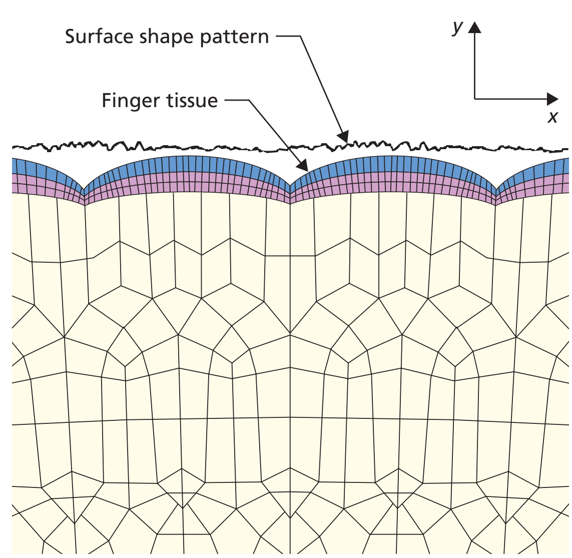

Figure 3 Surface shape pattern of polyester

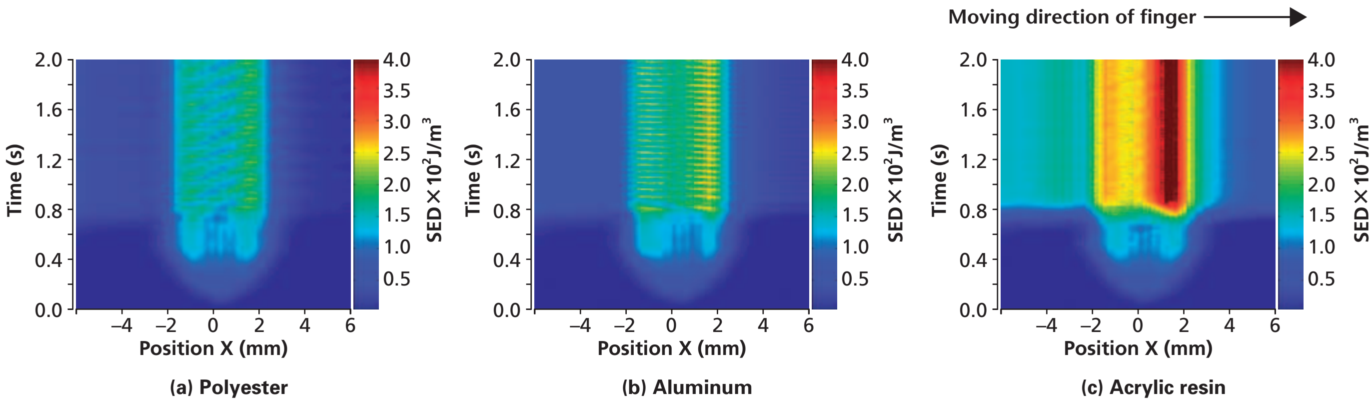

Figure 4 SED space-time distribution of merkel's disk positions

disk positions for each material. By comparing polyester, aluminum and acrylic resin, it is seen that the SED behaviors vary depending on the material.

2.5 Research Results

The results obtained in this research are summarized below.

- By dividing the horny layer into three sub-layers, the skin deformation conditions were reproduced more accurately than with conventional models. This allowed analysis of contact with minute protrusions, which was not possible before due to penetration and other factors.
- As a result of the simulation of contact with each material, it was found that the finger shapes are deformed differently for each material. By examining the relationship between this characteristic deformation behavior and the strain energy time-space distribution, it became possible to estimate the activity history of the tactile receptors when stroking various materials with the fingers.

The finger tissue model constructed this time can be a very effective tool for uncovering and analyzing novel micro phenomena of sensations generated in human hands, such as changes of deformation behaviors by uneven patterns and the relationship between adhesion and sliding phenomena and the tactile receptors.

3. Application to Tactile Display Research

3.1 Electrocutaneous Display

DoCoMo is currently promoting research on presentation of tactile sensations using an electrocutaneous display. **Figure 5** shows the configuration of electrocutaneous display. In addition to tactile sensations, we are considering to present characters at the fingertips in a manner similar to braille as well [6].

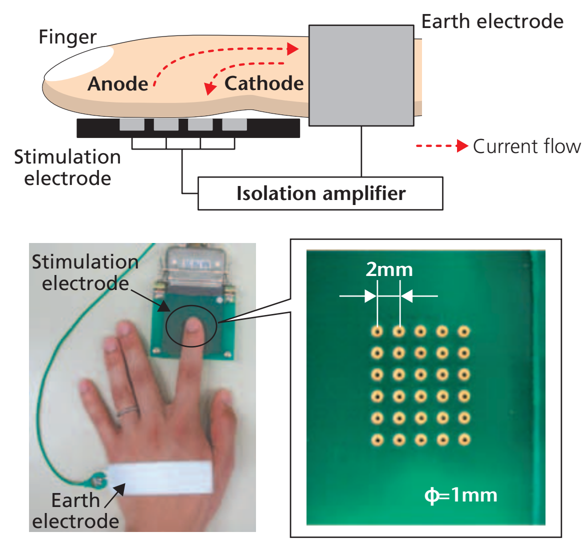

Figure 5 Configuration of electrocutaneous display

It is known that the nerves connected to the tactile receptors can be stimulated selectively by electrostimulation to some extent. The Meissner's corpuscles, which detect dynamic deformation of a finger, can be stimulated by anode current, while the Merkel's disks, which detect static deformation, can be stimulated by cathode current. The SED space-time distribution obtained in this research is used as an index for the wave patterns used in the electrostimulation. There exists a correlation between the SED and the nerve impulse firing frequency of the Merkel's disks. When converting the SED of the acrylic resin's graph in Fig. 4 into nerve impulse firing frequency, a graph of the nerve impulse firing frequency distribution of the Merkel's disks after 1.5 s can be obtained as shown in **Figure 6**.

Since the stimulation electrodes are placed at 2 mm intervals, it is not possible to reproduce the tactile sensation exactly,

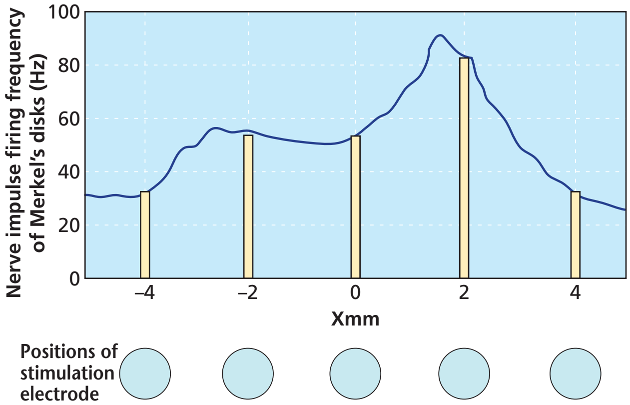

Figure 6 Nerve impulse firing frequency of each electrode

but we hope to be able to reproduce the feeling of stroking acrylic resin by changing the frequency output from each electrode as shown in Fig. 6.

4. Conclusion

With this contract research, it became possible to analyze contact between a human finger and various surfaces with fine protrusions by modeling the finger tissue with higher accuracy. This made it possible to estimate the activity history of the tactile receptors in the finger tissue when a finger strokes various materials.

Moreover, by presenting the obtained SED space-time distribution by means of an electrocutaneous display, the tactile sensation of a given material can be reproduced.

This technology is expected to play an important role in realization of tactile communication.

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Abbreviations

SED: Strain Energy Density