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Finite Element Analysis of Human Tactile Sensing to Differentiate Thin Foils Through Comparison Between Vertical & Angled Loads

Mohammad Azzeim bin Mat Jusoh[a,b]*, Masahiro Ohka[a], and Tetsu Miyaoka[c]

[a]*Graduate School of Information Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, JAPAN*
[b]*Fakulti Kejuruteraan Mekanikal (FKM), UiTM Shah Alam, Selangor, MALAYSIA*
[c]*Shizuoka Institute of Science and Technology, 2200-2 Toyosawa, Fukuroi-shi, Shizuoka 437-8555, JAPAN*

Abstract

Due to increasing research demand on human tactile sensations for robot-human interfaces and new tactile sensors, this research studies human tactile sensing to differentiate the thicknesses of two extremely thin foils that are made of Cu and stainless steel (SUS). We performed finite element analysis (FEA) on the fingertip's 3D elastic model to improve previous simulations through error analyses, better selection of nodal points, and proper loading conditions. We obtained the optimum mesh size to achieve numerical error below 4%. We also compared the von Mises (VM) stress of Cu with one of the SUS foils under different loading states to monitor the t_c/t_s ratio calculated from the thicknesses of the Cu and SUS foils that cause identical VM stress. The simulated result shows that the ratio becomes considerably large when thicknesses t_c (Cu) and t_s (SUS) are calculated from the differences of the VM stress between the angular and vertical loads. Consequently, the difference between the twitch motion and the datum provides the best ratio, $t_c/t_s = 1.6$, which resembles the results of psychophysical experiments.

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1. Introduction

One of the latest trends in robotic design is the development of robots and devices with soft touch or compliant actuation due to the increasing developments in human-machine interfaces for rehabilitation. In general, the human

* Corresponding author. Tel.: +81-52-789-4861; Fax: +81-52-789-4800.
E-mail address: m_azzeim@yahoo.com, ohka@is.nagoya-u.ac.jp

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skin provides physical protection and delicate tactile sensations. One tremendous characteristic of tactile sensations is the ability to distinguish foil thickness until several 10 μms of thicknesses when such ultra-thin thickness cannot be monitored through joint sensory organs. Since tactile sensations play a major role in this thickness discrimination process of ultra-thin foils, elucidating this mechanism is the main focus of our study.

In previous psychophysical experiments that discriminated thickness, John, Goodwin, and Darian-Smith[1] found that humans were capable of discriminating the thickness between thin material using plates from t = 200 ~ 500 μm (within a 75-μm range). One of their conclusions was that the gripping angle between fingers was the key factor that improves discrimination ability. Miyaoka and Ohka[2,3] performed a similar experiment using thinner metal foils and proposed that humans can discriminate even thinner material from t = 8 ~ 50 μm thickness, which cannot be detected by the angular sensory organs of the human finger. Consequently, one hypothesis is that evaluations for material with less than 70-μm thickness must be made using SA-I mechanoreceptor units, which exist within the structured layer of the human skin; thickness over 350 μm seems to be monitored through the joint sensory organs of fingers. Our previous simulation work[4] also highlighted the importance of the index fingers in analyzing the differences in the properties between materials. The theoretical aspects related to this experimentation can be reviewed[2~4].

The objective of this research is to study the mechanism of delicate tactile sensations and apply our findings to the development of a new robotic sensor or other human-machine interface. One extremely difficult challenge is directly monitoring the physical behavior inside our skin during contact. Past research used primates as test subjects, but current experimentation on live animals is much stricter because of the increased awareness of animal rights. Based on the above situation, we used an indirect method and performed Finite Element Analysis (FEA) on a human finger model during contact with extremely thin foils, whose copper (Cu) and stainless steel (SUS) materials were used.

The application of FEA for the behavior study of mechanoreceptors under loading was proposed by Maeno, Kobayashi and Yamazaki[5], Gerling and Thomas[6], Wu et al.[7] and others. Other research by Dandekar, Raju and Srinivasan[8] and Sripati, Bensmaia and Johnson[9] provided a good fit between the rate of the spikes fired by the Slowly Adaptive Type I (SA-I) afferent and the Strain Energy Density (SED). Lesniak and Gerling[10] focused more on the response of a single SA-I receptor by comparing the result with the psychophysics data of Phillips and Johnson[11]. Consequently, we used the FEA method instead of microneurography, which directly obtains neuron activity through a micro needle that penetrates a specific nerve fiber.

In a series of simulations, we compare the differences between the von Mises (VM) stresses generated in the skin under different loading states when the Cu and SUS foils are grasped. Since VM stress is equivalent to SED, we can estimate the tactile sensations from VM stress variations. On the other hand, we obtained the equivalent thickness of copper foil t_c to stainless steel foil t_s from a series of psychophysical experiments; ratio t_c/t_s was a constant value of around 1.5 in t_c = 30 ~ 50 μm. In this simulation, ratio t_c/t_s is defined by the thickness that causes the same VM stress. However, since ratio t_c/t_s becomes larger than 1 through simple angled or vertical loading analysis, we use the difference of the VM stresses between angular and vertical loads (treated as a datum) to calculate it. On the basis of the simulated results, ratio t_c/t_s is evaluated to obtain optimal loading for the thickness of foils using t_s as the base and the projection value of t_c (Fig. 1).

2. Procedure of FEA

2.1. Optimal Meshing

Since the main objective of this simulation is to identify the value of the VM stress inside the dermis during contact, we need to re-evaluate the previous working procedure[4] to achieve the most optimum mesh model for our simulation. We conducted error analysis of our simulated result to validate the correctness of the mesh model.

We conducted a series of simulations using CATIA V5 with a 3D elastic model of the index finger and thumb (consisting of the epidermis, dermis, bones, and nails) while grasping the Cu or SUS foil with thicknesses between t = 25 ~ 1000 μm. The main focus for this analysis identifies the specific nodal points, which represent the contact areas and the location of the SA-I mechanoreceptor unit on the fingers. An OCTREE tetrahedron mesh was applied with a revised element type from linear to quadratic to reduce the aspect ratio, especially on the foil part. The mesh