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# 3D Finite Element Analysis of the frictional behavior of the human fingertip

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*Abstract*— **Although the tactile sensation is one of the most important senses, little quantitative research has been carried out to investigate the sense of the touch of the fingertip. We developed a three-dimensional Finite Element model of the fingertip and performed a determination of material properties using an optimization technique so that the contact area of Finite Element analysis corresponded with that of the experiment when a rigid plane was indented. The estimated material properties agreed with published data and the optimization method is considered to be effective. The Finite Element model slid on the rigid plane while indented using determined material properties and ABAQUS subroutine based on the rubber friction. At the low indentation depth, the stick-slip behavior of the Finite Element analysis mostly agreed with the experimental. However, when the indentation depth was increased, the frictional behavior in the tangential direction of the analysis was not consistent with that of the experiment because of the anisotropic in the shear direction. This study is an approach to understanding the friction and tactile sensation of the fingertip.**

## I. INTRODUCTION

The tactile perception is one of the most important senses and detects skin deformation due to the contact of an object. Understanding mechanical and frictional properties of the skin is essential to examine the function of the fingertip quantitatively.

Although it has been suggested that partial slippage, which means that a part of the contact area on the fingertip slips and the other part sticks when a body begins to slip, plays an important role [1], there is little study that evaluated these slippages and frictional properties quantitatively. Several studies have performed Finite Element (FE) analyses to investigate the tactile sensation and the frictional behavior, and most of FE models remain two-dimensional [1] [2], however, three-dimensional (3D) FE analysis [3] [4] is preferable for quantitative research.

Determining the material properties of human soft tissue is important to analyze frictional mechanics accurately, but the question of how to measure the material properties of the soft tissue non-invasively is one of the more difficult problems to be solved [3]. In this study, we propose a combination method using both experiment and FE analysis using an optimization technique to estimate the material properties [4]. If the FE analysis is conducted using the determined material properties, the analysis is assumed to simulate the experiment and it allows a quantitative study for the frictional mechanics of the fingertip.

According to Amontons-Coulomb friction law, the friction force is directly proportional to the normal load and is independent of apparent contact area. However, when a surface or a body is a rubber or elastomer, this frictional law no longer applies and the area of true contact is proportionate to $N^{\beta}$ ($2/3<\beta<1$) [5] [6]. If a body is a truly elastic solid, $\beta$ is equal to 2/3. If the contact in material is elastic, the contact area will be of the form $CN^{2/3}$ (N is the normal force and C involves elastic modulus and geometric parameter). Then, the equation $F=SCN^{2/3}$ is derived from the rubber friction, where F is the frictional force and S is the shear breaking strength. This theory is suitable to results of our experiment for the frictional behavior between the fingertip and a flat plane [7] and we incorporated the rubber friction into the FE analysis.

In this study, we developed a 3D FE model of the index finger and material properties of the human soft tissues were determined using an optimization method. After estimation of the material properties, we investigated stick-slip friction behavior between the fingertip and a rigid plane quantitatively based on the rubber friction.

## II. METHODS

### A. Experiment using a tactile imaging system

A tactile imaging system consists of an orthogonal three-DOF manipulator, a light source, a CCD camera, and a six-axis force sensor [7]. The manipulator controlled a transparent flat indenter of an acrylic resin supported by the force sensor. The CCD camera is set up to capture an image sequence of a contact region between the fingertip and the indenter. If partial slippage occurs, the fingerprint pattern is slightly deformed and we can detect stick-slip regions by image processing. An index finger of a normal male subject was rigidly fixed with respect to the flat indenter at an angle of 30 degrees. While indented at four kinds of depths (0.75, 1.0, 1.25, and 1.5 mm, respectively), the finger was slid on the plane at a speed of 2mm/sec and the sliding direction was from proximal to distal. We measured forces in normal and tangential directions, contact areas, and stick-slip regions.

### *B. 3D FE analysis for the friction*

We took medical images of the index finger of the same subject in the experiment using 4.7T MRI system (Varian, Inc.). A 3D FE model of the fingertip was developed using the FE software Hypermesh (Altair Engineering, Inc.) after the image volume was segmented into skin, subcutaneous tissue, and bone (8-node linear brick) using the visualization open-source software 3D Slicer. The fingernail (4-node linear tetrahedron) was not visible by MRI and was created separately using the CAD software Solidworks (Solidworks Corporation). The FE model had about 8000 nodes and 7000 elements (Fig. 1).

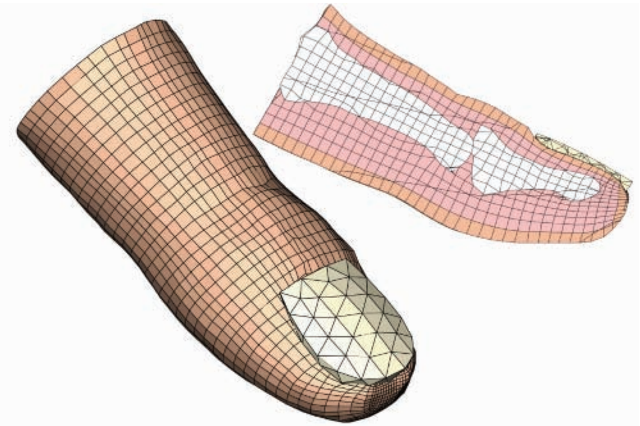

Fig.1 3D FE model of the index finger

We determined material properties of both skin and subcutaneous tissue using an optimization technique. The FE model was also fixed with respect to a rigid flat plane at an angle of 30 degrees and was indented into the plane with four kinds of depth (0.75, 1.0, 1.25, and 1.5 mm, respectively). The contact area of FE analysis was optimized to correspond with that of the experiment using a Downhill Simplex method written using the programming language Python. Because we estimated the optimum range, it was possible to obtain the optimal value in only a few iterations. To validate this optimization method for determination of material properties, we performed a simplified FE analysis of a three-layer silicone rubber in advance. An error of each estimated material property was less than 7% and thus this technique was verified [10]. An appropriate initial value was input first and the FE analyses were performed iteratively until the diameter of the simplex was less than *tolx* and the function values of the simplex differed less than *toleval* (*tolx* and *toleval* were used as a termination criteria). The skin and the subcutaneous tissue were assumed as an Ogden model and almost incompressible because the dominant nonlinear elastic property of the soft tissues is hypothesized to be hyperelastic [8] [9]. The form of the Ogden strain energy potential is

$$U = \sum_{i=1}^{N} \frac{2\mu_i}{\alpha_i^2}(\lambda_1^{\alpha_i} + \lambda_2^{\alpha_i} + \lambda_3^{\alpha_i} - 3) + \sum_{i=1}^{N} \frac{1}{D_i}(J^{el} - 1)^{2i}$$

where $\lambda_i$ are the principal stretches; N is a material parameter; $\alpha$, $\mu$, and D are temperature-dependent material parameters; and $J^{el}$ is the elastic volume ratio [8]. Young's moduli were 10GPa for the bone and 100MPa for the fingernail and both of the Poisson's ratios were set as 0.3 (linear elastic) [1] [2].

The equation $F= SCN^{2/3}=KN^{2/3}$ is derived from the rubber friction (F: the friction force, N: the normal force, K: constant) [5] [6]. If the equation is divided by the total contact area A,

$$\tau = \frac{K\sigma^{2/3}}{A^{1/3}}$$

where $\tau$ is the shear stress and $\sigma$ is the contact pressure. Relative motion is generally negligible when two bodies are stuck, however, it is more realistic to model sticking friction using an elastic behavior. The behavior is considered to be linear elastic according to the equation $\tau=k\gamma$, where $\gamma$ is the elastic slip (the reversible relative tangential motion from the point of zero shear stress) and k is the current stiffness in the stuck region [8]. The stiffness k is bounded by the value $\gamma_{crit}$ (the critical value of elastic slip before true slip occurs) which is specified in the ABAQUS (ABAQUS, Inc.) subroutine FRIC as $k=\tau_{crit}/\gamma_{crit}$. Since $\tau_{crit}$ is pressure dependent, k will change during the analysis. Therefore, the elastic slip expression for sticking friction can be written as

$$\tau = \frac{\tau_{crit}\gamma^{el}}{\gamma_{crit}} = \frac{K\sigma^{2/3}\gamma^{el}}{A^{1/3}\gamma_{crit}}$$

If the friction stress exceeds the critical shear stress $\tau_{crit}$, slipping must begin so that the equation $\tau=\tau_{crit}$ is satisfied. In order to evaluate the subroutine, we conducted the FE analysis based on the basic friction using each coefficient of friction from the experimental result separately and compared results of equivalent coefficient of friction (ratio of the reaction force in the tangential direction to the reaction force in the normal direction at the rigid plane) while sliding.

We analyzed stick-slip and frictional behavior using the ABAQUS subroutine mentioned above. The fingertip was also slid on the plane using the identified material properties at a speed of 2mm/s while indented at four depths. The sliding direction was from proximal to distal and both the fingernail and the proximal end of the fingertip were fixed. The FE solver ABAQUS Ver6.5 was used for the FE analysis.

## III. RESULTS AND DISCUSSION

Table 1 shows the experimental results of average force in the normal direction, coefficient of friction (ratio of the frictional force to the normal force), and contact area [7]. The relationship between the friction force F and the normal force N led to the equation $F=1.06N^{2/3}$ following the rubber friction. The contact area A was approximately $A=180N^{2/3}$.

TABLE 1
RESULTS OF EXPERIMENT USING THE TACTILE IMAGING SYSTEM

| Depth (mm) | Normal force (N) | Coefficient of friction | Contact area (mm²) |
|---|---|---|---|
| 0.75 | 0.120 | 2.46 | 49.4 |
| 1.00 | 0.198 | 2.00 | 62.8 |
| 1.25 | 0.384 | 1.53 | 83.2 |
| 1.50 | 0.454 | 1.42 | 97.7 |

The results of the optimization to determine the material properties are as follows. The Ogden model was defined as N=1 and $\mu$ was the only calculated variable. In the case of $\mu=0.034$, $\alpha=15$, $D=1$ for the skin and $\mu=0.00684$, $\alpha=1$, $D=12$ for the subcutaneous tissue, the contact areas for the FE analysis (44.1, 56.6, 84.7, and 97.0mm$^2$, respectively) were the closest to those for the experiment in Table 1. The result indicates that Young's modulus is 0.1MPa for the skin and 0.02MPa for the subcutaneous tissue. According to various published literatures about material properties of the skin and the subcutaneous tissue [1] [2], the Young's modulus of the skin is from 0.1MPa to 0.4MPa and the subcutaneous tissue is around 0.03MPa. If individual variation is taken into account, the results of the FE analysis are appropriate and this proved that the FE model could simulate the behavior in the indentation direction. Therefore, the optimization method utilized in this study could be effective to estimate the material properties.

Since a physical value of $\gamma_{crit}$ is the order of 0.002mm [6], we assumed that $\gamma_{crit}$ is varied according to the indentation depth and was hypothesized to be proportional to N/A. Normalized coefficients of friction using the ABAQUS subroutine were compared with those using the coefficient of friction from the experiment based on the basic friction while sliding (Fig. 2). Those frictional behaviors were almost the same and the occurrence of the partial slippage using the subroutine was slightly earlier. Therefore, the FE analysis using the subroutine is considered to be adequate.

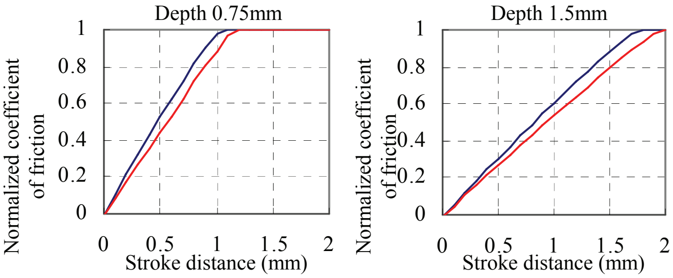

Fig. 2 Comparison of normalized equivalent coefficient of friction between using the subroutine ( —— ) and the basic friction ( —— )

The results of the stick-slip behavior for the FE analysis are shown in Figure 3. The values in Figure 3 show amounts of the stroke distance. If velocity of a node at a given time is equal to that of the rigid plane (2mm/s), we defined this node as stick; otherwise, it was regarded as a slip node. Since the fingertip is asymmetrical, the stick-slip contact regions are asymmetrical. The partial slippage occurred at the periphery of the contact region and the stick region decreased gradually in accordance with the increase of the stroke distance as observed in the experiment.

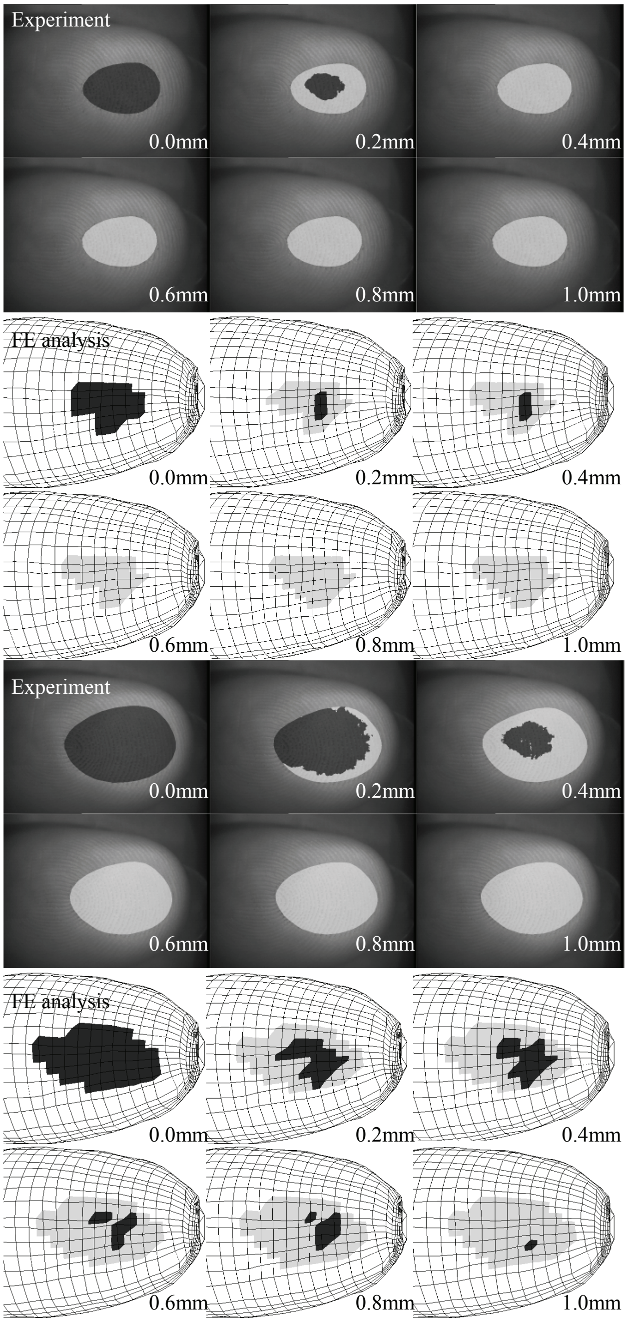

Fig. 3 Comparison of stick-slip regions between experiment and FE analysis at the depth 0.75mm (above) and 1.5mm (below)
( ■ : stick region, ▨ : slip region)

We defined the ratio of the stick region to the contact region as a stick ratio and the results of the experiment were compared with those of the FE analyses (Fig. 4). The change of the stick ratio for the FE analysis agreed with that of the experiment at the depth 0.75mm. This result indicates that the FE analysis simulated the stick-slip behavior in the range of small deformation. However, at the depth 1.5mm, the stick-slip behavior of FE analysis and experiment were different.

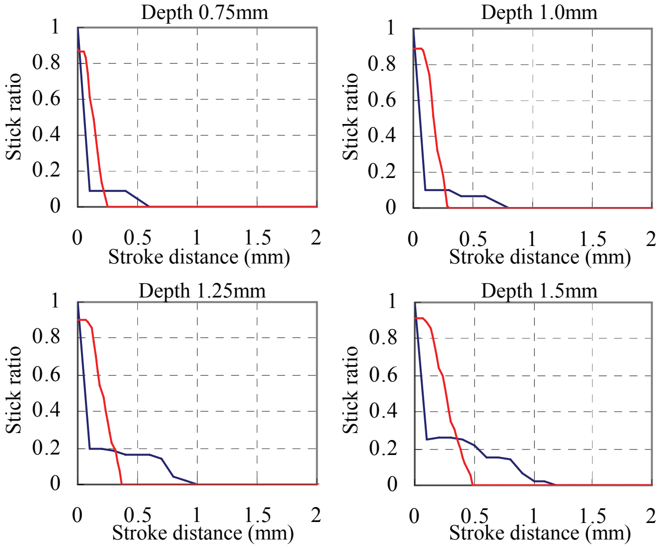

Fig.4 Comparison of the stick ratios between experiment ( — ) and FE analysis ( — )

Figure 5 shows the result of the reaction forces in the tangential direction of both the experiment and the FE analysis. The start time of the whole slippage of the FE analysis was slower than that of the experiment even at the low indentation depth. This indicates that the frictional behavior of the FE analysis is not coincident with that of the experiment.

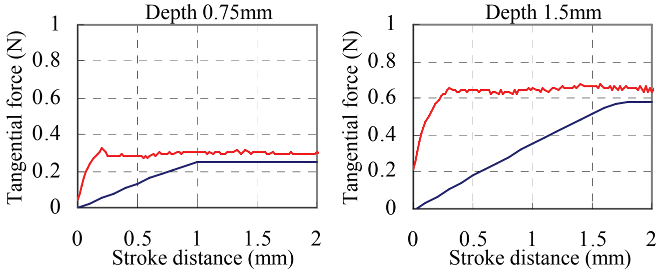

Fig.5 Comparison of the tangential reaction forces between experiment ( — ) and FE analysis ( — )

The property of the skin is anisotropic with different elastic moduli in the normal and the tangential directions. The determination of the material properties using the optimization technique was performed only for the indentation direction and we did not account for the anisotropy of the skin. Therefore, we supposed that the difference of the frictional behavior between the FE analysis and the experiment resulted from the anisotropic nature and the large deformation of the skin. We will measure the anisotropic property of the skin using a revised tactile imaging system and incorporate the anisotropic nonlinearity, which means that strain dependent modulus of an exponential form will be introduced, for the tangential direction to improve the accuracy of the FE analysis in the future.

## IV. SUMMARY

The 3D FE model of the fingertip was developed and the material properties of the soft tissue were determined using the optimization technique so that the contact area of the FE analysis was consistent with that of the experiment while the rigid plane was indented. The determined material properties mostly agreed with published data and this proved that the FE analysis could simulate the behavior in the indentation direction. Therefore, this optimization method is considered to be effective to estimate the material properties.

The stick-slip frictional behavior on the fingertip was examined when indented using the determined material properties and the ABAQUS subroutine based on the rubber friction. When the indentation depth was lower (less than 1mm), the stick-slip behavior of the FE analysis almost agreed with that of the experiment. However, when the indentation depth was increased, the frictional behavior of the tangential direction for the FE analysis was different with that for the experiment. We should incorporate the anisotropic nonlinearity into the skin of the FE model to improve the accuracy of the analysis.

Although the tactile sensation is one of the most important senses, little quantitative research has been carried out to investigate the sense of the touch and frictional behavior of skin. We think this study is one of the approaches to understand the friction and the tactile sensation of the fingertip.

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