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A Study of Frictional Property of the Human Fingertip Using Three-Dimensional Finite Element Analysis

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Abstract: Since the tactile perception detects skin deformation due to the contact of an object, it is important to understand contact mechanics, especially, frictional behavior of the human fingertip. The coefficient of friction is recently modeled as a function of the applied normal load in which case the traditional Coulomb's law does not provide a description for the skin surface. When a surface is a rubber-like material, the frictional behavior follows the frictional law of the rubber-like material. Therefore, we developed a three-dimensional Finite Element model of the fingertip and analyzed frictional behavior based on the frictional law of rubber-like material. We proposed a combined technique using both experimental and Finite Element analyses in order to investigate the frictional property of the fingertip. A three-dimensional Finite Element model of the fingertip was developed using MRI images. We hypothesized a frictional equation of the critical shear stress. Squared differences between equivalent coefficient of friction of the FE analysis and the coefficient of kinetic friction of the experiment while sliding was decreased and the Finite Element analysis iterated until the error was minimized, and thus the frictional equation was determined. We obtained the equation of the critical shear stress and simulated kinetic friction of the fingertip while sliding under arbitrary normal loading condition by using the Finite Element analysis. We think this study is an appropriate method for understanding the frictional property of the human fingertip using the Finite Element analysis.

Keywords: Finite Element analysis, human fingertip, kinetic friction

1 Introduction

Since the tactile perception detects skin deformation due to the contact of an object, it is important to understanding contact mechanics of the human skin. We

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contact an object by hand or fingertip in daily living, and the tangential force and incipient slippage, which are in relation to friction, play a crucial role on dexterous manipulation of the human being [1][2]. Therefore, it is essential to investigate the frictional property of the skin, especially, of the fingertip.

Several studies have developed Finite Element (FE) models to analyze frictional behavior, and most of FE models were two-dimensional [3] [4] and Dandekar et al. [5] developed a three-dimensional (3D) FE analysis. Since not only the human fingertip's structure is asymmetric but also the frictional behavior on an object is generally two-dimensional (one is the direction of sliding and the other is perpendicular to the sliding direction), a 3D model is necessary for accurate research of the frictional property. Therefore, we developed a 3D FE model of the fingertip in this study.

Furthermore, in the previous FE models [3][4], the coefficient of friction has been regarded as constant and followed Amontons-Coulomb friction law (According to Amontons-Coulomb friction law, the frictional force is directly proportional to the normal load and is independent of apparent contact area). However, the friction coefficient is recently modeled as a function of the applied normal load, that is, normal force dependency, in which case Coulomb's law does not provide an accurate description for the skin surface [6] [7] [8]. When a surface or a body is a rubber-like material, the traditional friction law no longer applies and follows the frictional law of the rubber-like material. The accurate modeling of the human fingertip's friction will afford an excellent insight into an understanding of the tactile sensation and thus we incorporated the frictional law of rubber-like material into the FE analysis to perform FE analysis precisely.

In this study, we developed a 3D FE model of the index finger and analyzed frictional behavior between the fingertip and a flat plane based on the frictional law of rubber-like material. This is the first step to simulate kinetic friction of the fingertip by using FE analysis.

2 Methods

2.1 Experiment using a tactile imaging system

A tactile imaging system is equipped with an orthogonal three-DOF manipulator (SGAM20-35 and SGAM33-50, Sigma Koki Co., Ltd.) and a six-axis force sensor (NANO1.2/1-S30, BL Autotec, Ltd.). The manipulator consists of three stages; indent stage, stroke stage, and base stage. The indent and stroke stages are served to drive the flat indenter to reproduce passive stroking against the fingertip. The linear stage is controlled to indent and stroke a transparent flat indenter made of an acrylic resin. This flat indenter is supported by the force sensor [9].

An index finger of a normal male subject (age 32, the length of the index finger is about 5cm from the distal end to the proximal inter-phalangeal joint) was rigidly fixed (the fingernail was glued to a cylindrical tube) with respect to the flat indenter at an angle of 30 degrees. While indented at four different depths (0.75, 1.0, 1.25, and 1.5 mm, respectively), the fingertip was slid on the indenter at a speed of 2mm/sec and the sliding direction was from proximal to distal. We measured forces in the normal and tangential directions three times for each kind of depth. Informed consent was obtained from the Ethics Committee of AIST.

2.2 3D FE model of the human fingertip

We took medical images of the index finger of the same subject in the experiment using a 4.7T MRI system (Unity INOVA, Varian, Inc.). The informed consent for using MRI was obtained from the Ethics Committee of AIST. The fingernail of right hand was glued to a cylindrical tube and inserted into a small coil in the center of MRI. The volume data was obtained using a 3D gradient echo sequence with TR/TE 20/10, FOV 120/30/30, and the image volume size of 512/128/128 voxels.

A 3D FE model of the fingertip was developed using the FE meshing software Hypermesh (Altair Engineering, Inc.) after the image volume was segmented into soft tissues and two bones (8-node linear brick) using the visualization open-source software 3D Slicer (www.slicer.org). The superficial layer of the meshed soft tissues was defined as the skin (epidermis and dermis) and the other region was set as the subcutaneous tissue. 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 8000 nodes and 7000 elements (Fig. 1).

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 assumed as isotropic linear elastic [3] [4].

The skin and the subcutaneous tissue were presumed as nearly incompressible hyperelastic because the dominant nonlinear elastic property of the human soft tissues is hypothesized to be hyperelastic [4] [10] [11]. We utilized an Ogden model as the hyperelastic model. The form of the Ogden strain energy potential U is

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

where λ_i are the principal stretches; N is a material parameter; α, μ, and D are temperature-dependent material parameters; and $J^{el}$is the elastic volume ratio. μ_i is calculated from the initial shear modulus μ_0 ($\mu_0 = \sum_{i=1}^{N} \mu_i$) and $D_i$is obtained from

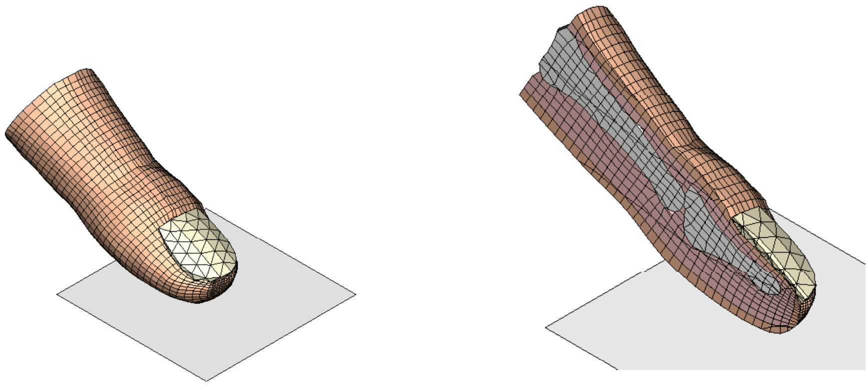

Figure 1: left: 3D FE model of the index finger (isometric view); right: 3D FE model of the index finger (mid-section)

the initial bulk modulus $K_0(K_0 = 2/D_1)$. The Ogden model was defined as N=1 for simplicity and we utilized μ_1=0.034 for the skin and μ_1=0.00684 for the subcutaneous tissue [3] [4] [12]. D_1=1.0 for the skin and D_1=10.0 for the subcutaneous tissue because the Poisson's ratio was assumed around 0.49. α was fixed to 1.4 [13].

2.3 Rubber friction to incorporate into the FE analysis

When a surface or a body is a rubber-like material, the traditional friction no longer applies and the area of true contact is proportionate to N^{β} (N is the normal force and β is the frictional constant) [14] [15] [16]. If a body is a truly elastic solid, β is equal to 2/3. If the contact in material is elastic, the contact area will be of the form $CN^{2/3}$ (C involves elastic modulus and geometric parameters). Then, the equation

$$F = SCN^{2/3} \tag{2}$$

is derived from the frictional law of the rubber-like material, where F is the frictional force and S is the shear breaking strength, and it is so-called rubber friction.

This frictional equation is satisfied in the global system (global criteria of friction), that is, when the fingertip is sliding on a flat plane, the normal force is equivalent to the reaction force of the vertical direction and the frictional force is derived from the reaction force of the horizontal direction in a coordinate system of the experiment or the FE analysis. On the other hand, it is considered that the frictional relationship in the local system, that is, at a point of contact between the FE model and a plane, will be expressed by a different form (local criteria of friction). We hypothesized that a frictional equation

$$\tau_{crit} = \lambda \sigma^{\beta} \tag{3}$$

is applied to the local coordinate system, where τ is the shear stress in the tangential direction (if the shear stress is more than the critical shear stressτ_{crit}, slippage occurs at a point of contact), σ is the pressure in the normal direction, and $\lambda$and β are constants of friction.

Relative motion is generally negligible when two bodies are stuck, however, it is more realistic to model sticking friction using an elastic behavior [10] [14]. The behavior is considered to be linear elastic according to the equation $\tau = k\gamma$, where γ 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. The stiffness k is bounded by the value of the critical elastic slip γ_{crit} (the critical value of elastic slip before slip occurs) which is specified in the commercial FE code ABAQUS (ABAQUS, Inc.) subroutine of friction FRIC as $k = \tau_{crit}/\gamma_{crit}$. The subroutine means a user implemented definition for the FE analysis. Since $\tau_{crit}$is pressure dependent, k will change during the analysis. Therefore, the elastic slip expression for sticking friction can be written as

$$\tau = \frac{\tau_{crit}\gamma}{\gamma_{crit}} = \frac{\lambda \sigma^{\beta} \gamma}{\gamma_{crit}} \tag{4}$$

For the contact problem of 3D model, there are two slipping direction and we assumed for simplicity that the frictional response was the same in both directions, that is, isotropic friction. Thus, the equation is $\tau_i = k\gamma_i$ (for i=1, 2) and this expression holds if $\tau_{eq} < \tau_{crit}$ ($\tau_{eq} = \sqrt{\tau_1^2 + \tau_2^2}$). If$\tau_{eq} > \tau_{crit}$, then the frictional shear stress is given by $\tau_i = \gamma_i \tau_{crit}/\gamma_{eq}$ ($\gamma_{eq} = \sqrt{\gamma_1^2 + \gamma_2^2}$) and γ_i are the components of the total slip.

In order to perform the FE analysis using the formulation of the rubber friction, it is necessary to calculate two frictional constants λandβ of the critical shear stress. By using a Downhill Simplex method, the frictional constants were determined such that an "equivalent coefficient of friction" of the FE analysis, which means that the ratio of the reaction forces in the horizontal and the vertical directions generated to a flat plane, corresponded with the coefficient of kinetic friction obtained from the experiment. The Downhill Simplex method, written using the programming language Python, is a kind of a numerical optimization technique widely used in a minimization problem that has non-smooth evaluation function. The boundary condition of the FE analysis was the same as that of the experiment. The fingertip, which was also fixed with respect to a rigid flat plane at an angle of 30 degrees, was slid on the plane at a speed of 2mm/s while indented at four different depths (0.75, 1.0, 1.25, and 1.5mm, respectively). 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 Ver6.6 was used for the FE analysis.

The detailed procedure for calculating of two frictional constants is as follows. Appropriate initial values for each frictional constant were input first and these constants were updated so that sum of squared differences between each coefficient of friction of the FE analysis and that of the experiment while sliding at four kinds of indentation depth was decreased, and the FE analysis iterated these procedures until the error was minimized. The optimization was performed iteratively until the diameter of the simplex was less than *tolx* and the function values of the simplex differed less than *tolf*. In this study, *tolx* of 0.001 and *tolf* of 0.001 were used in each optimization as the terminate criteria. The final values were determined frictional constants.

3 Results

3.1 Result of the experiment using the tactile imaging system

Table 1 shows experimental results of average force (three trials in each depth) in the normal direction and coefficient of friction (ratio of the frictional force to the normal force). The relationship between the friction force F and the normal force N led to the equation $F = 1.13N^{2/3}$ ($F/N = 1.13N^{-1/3}$) following the frictional law of rubber-like material.

Table 1: Results of the experiment using the tactile imaging system

Depth (mm)	Normal force (N)	Coefficient of kinetic friction	Contact area (mm^2)
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

3.2 Critical shear stress based on rubber friction

We obtained the equation of the critical shear stress as $\tau_{crit} = 0.086\sigma^{0.46}$ after the calculation of two frictional constants. A physical value of γ_{crit} was set as 0.006mm

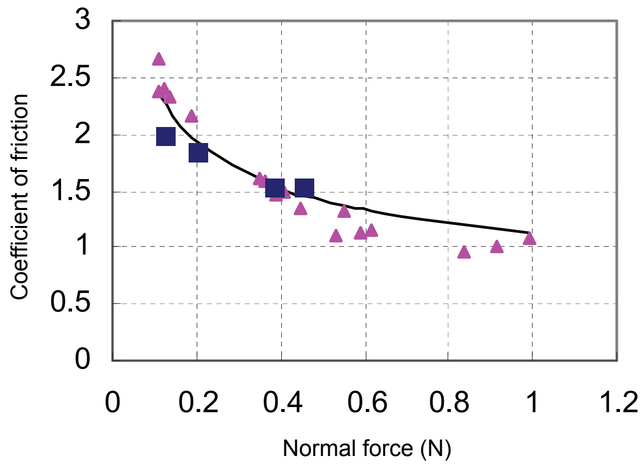

Figure 2: Comparison of coefficient of friction between experiment and FE analysis (Triangle: experimental data square: equivalent data, coefficient of kinetic friction calculated from FE analysis after optimization, curved line: theoretical equation of the rubber friction F/N=1.13N$^{-1/3}$)

because the allowable elastic slip γ_{crit} was calculated from the "characteristic contact surface length" (1.2 in this FE model) and the slip tolerance (the default value was set as 0.005) [10]. Figure 2 shows the result of "equivalent coefficient of friction" of the FE analysis, the frictional coefficient of the experiment, and the theoretical curve of rubber friction.

4 Discussion

Several studies investigated the frictional behavior of the human skin. In some models, the coefficient of friction has been regarded as constant [3] [4] [17] [18]. Maeno et al. [3] constructed a two-dimensional FE model of the finger using a coefficient of kinetic friction of 1.0. Wu et al. [4] analyzed, via a two-dimensional FE model of the finger, the contact interactions and the contact was considered to be frictionless. They performed great studies and contributed to the excellent results of the frictional behavior using the FE models of the fingertip. However, these researches did not sufficiently take into account frictional mechanics. If the boundary condition of friction is not appropriate, the results of the FE analysis will not be accurate.

In 1950s, load-dependent contact area between a rubber-like material and a flat surface was modeled by several researchers [15] [16]. The friction coefficient is recently modeled as a function of the applied normal load in which case Coulomb's law does not provide an accurate description for the skin surface [8]. Therefore, in this study, we developed an implemented frictional definition based on rubber friction and integrated it into the FE analysis to simulate the kinetic friction of the fingertip while sliding on a flat plane. Without the user subroutine, experimental measurement is requisite for input data of an FE analysis and it is difficult to analyze frictional behavior under an unknown normal loading condition. However, by using the user frictional subroutine, coefficient of friction measured from experiment is not necessary and it enables us to analyze the kinetic friction between the fingertip and a flat plane under arbitrary normal loading condition. It is possible that this result is applied to the human motion, for instance touching or grasping an object, in computer. The exact modeling of friction will afford an insight into the understanding of the incipient slip. The FE analysis of the frictional behavior in this study is considered to be practical and the knowledge of the frictional mechanics using the present FE analysis is significant to product design in the ergonomics field.

The frictional stress was hypothesized to be proportional to the pressure raised to the power of beta as the local criteria. There are several equations of the critical shear stress, including real contact area, to express the frictional relationship between human skin and an object. However, the frictional behavior of the skin can be simply modeled by the equation$\tau_{crit} = \lambda\sigma^{\beta}$. It is presumed that the frictional constant λ depends on the shape of a subject's fingertip and the constant β is regulated by the material properties of the fingertip but these parameters are modeled as nearly constant despite individual differences.

We investigated the frictional property of the fingertip by using the combination method of the experiment and the FE analysis. Tada et al. [9] measured frictional behaviors of five male subjects' fingertip and indicated that all data followed the theory of rubber friction. Although only one subject-specific FE model was developed in this study, it is possible to investigate the frictional behavior of other subject's fingertip in the same way. We should examine several subjects' frictional properties and perform statistically the FE analyses in the future.

Maeno et al. [3] and Dandekar et al. [5] examined the mechanistic bases of the human sense of touch using the FE analyses. They predicted the mechanoreceptor response to an object by utilized strain energy density of the skin. In this study, it is difficult to investigate the response of the tactile sensation because the present FE model has problems to be solved that there was only two-layered structure and material properties of the skin were not so accurate. We will reconstruct the FE model more precisely and study the response of the tactile sensation in future study.

There are several limitations in this study. First of all, the fingertip has a fingerprint and moisture which may significantly influence frictional behavior; however, we did not introduce these into the FE model because of the technical complexity that it would have added to the 3D analysis. We modeled friction isotropically in both slip directions for simplicity, however, the frictional behavior of the human skin is considered anisotropic slipping due to the existence of Langer's lines and of the fingerprint. We will improve the experimental device and plan to incorporate anisotropic friction in the future. In the experiment, although the condition of a subject's fingertip was not controlled, the frictional force did not vary widely at room temperature (Fig. 2). Therefore, moisture is not considered a main factor of "dry" friction in this experiment; however the result was significantly different from the frictional behavior when the fingertip was apparently "wet". Lastly, though we attempted to simulate kinetic friction of the fingertip using 3D FE analysis, the results of the analysis did not entirely coincide with that of the experiment because the FE model was not completely similar to the real index finger of the subject. We will improve the fidelity of the FE model meshes to obtain more accurate behavior of the kinetic friction. Despite these limitations, we simulated the kinetic friction between the fingertip and a flat plane using the FE analysis and we think that this study is advancement towards understanding the frictional behavior of the human skin.

5 Conclusions

The 3D FE model of the fingertip was developed using MRI images. We hypothesized the frictional equation of the critical shear stress and incorporated the equation of rubber friction into a user implemented frictional definition for the FE analysis.

By using the FE analysis we simulated kinetic friction of the fingertip while sliding on a rigid flat plane under arbitrary normal loading condition.

We think this study is an appropriate method for understanding the frictional property of the human fingertip and is the first step to simulate kinetic friction of the human fingertip using FE analysis.

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References

1. Howe, R., and Cutkosky, M., (1996), Practical force-motion models for sliding manipulation, International Journal of Robotics Research, 15(6), pp. 557-572.

2. Johansson, R. S., and Westling, G., (1990), Tactile afferent signals in the control of precision grip, Attention and Performance, 8, pp. 677-713.

3. Maeno, T., Yamada, D., and Sato, H., (2005), Analysis on Geometry of Human Epidermal Ridges, Transactions of the Japan Society of Mechanical Engineers, 71 (701), pp. 245-250.

4. Wu, J.Z., and Dong, R.G., (2005), Analysis of the contact interactions between fingertips and objects with different structure curvatures, Proceedings IMechE., 219, pp. 89-103.

5. Dandekar, K., Raju, B.I., and Srinivasan, M.A., (2003), 3-D Finite- Element Models of Human and Monkey Fingertips to Investigate the Mechanics of Tactile Sense, Journal of Biomechanical Engineering, 125 (October), pp. 682-691.

6. Han, H.Y., Shimada, A., and Kawamura, S., (1996), Analysis of friction of human fingers and design of artificial fingers, Proceedings of the IEEE International Conference on Robotics and Automation, pp. 3061-3066.

7. Liao, J.C., and Srinivasan, M.A., (1999), Experimental investigation of frictional properties of the human fingerpad, Technical Report 629, RLE Technical Report, Massachusetts Institute of Technology, Cambridge, MA.

8. Sivamani, R.K., Goodman, J., Gitis, N.V., and Maibach, H.I., (2003), Friction coefficient of skin in real-time. Skin Res. Technol., 9(2), pp. 235-239.

9. Tada, M., Mochimaru, M., Kanade, T., (2006), How Does a Fingertip Slip? -Visualizing partial slippage for modeling of contact mechanics-, EuroHaptics 2006, Paris, pp. 415-420.

10. ABAQUS Analysis User's Manual version 6.6, (2006), ABAQUS, Inc., Providence, RI.

11. Cheung, J.T., Zhang, M., Leung, A.K., and Fan, Y.B., (2005), Three-dimensional finite element analysis of the foot during standing -a material sensitivity study, Journal of Biomechanics, 38(4), pp. 1045-54.

12. Yoshida, H., Tada, M., and Mochimaru, M., (2006), 3D Finite Element Analysis of the Frictional Behavior of the Human Fingertip. Proceedings of 28th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBS), NewYork, pp. 91-94.

13. Yeoh, O.H., (1997), On the Ogden strain-energy Function, Rubber Chemistry and Technology, 70, pp. 175-182.

14. Brown, I., (1997), Abrasion and Friction in Parallel-lay Rope Terminations, Thesis, http://calcul.com/ian/thesis/node1.html.

15. Lincoln, B., (1952), Frictional and elastic properties of high polymeric materials, British Journal of Applied Physics, 3 (Aug), pp. 260-263.

16. Schallamach, A., (1952), The Load Dependence of Rubber Friction, Proc. Phys. Soc., B 65, pp. 657-661.

17. Cua, A.B., Wilhelm, K.P., and Maibach, H.I., (1990), Frictional properties of human skin: relation to age, sex and anatomical region, stratum corneum hydration and transepidermal water loss, British Journal of Dermatology, 123(3), pp. 473-479.

18. Zhang, M., and Mak, A.F., (1999), In vivo friction properties of human skin, Prosthet. Orthot. Int., 23(2), pp. 135-141.