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Relationship between the Structure of Human Finger Tissue and the Location of Tactile Receptors*

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Abstract

There are several tactile receptors in the tissue of human fingers. In this study we calculate in detail the deformation of finger tissue when a finger comes into contact with a rigid plate using a FE (finite element) model to clarify the reason for the precise location of the receptors. The FE model is constructed using measured geometry and material properties. As a result, we found that the strain energy is concentrated at the tactile receptor locations. When a frictional force is applied, the stress/strain is concentrated near the edge of the contact area. By calculating the stress/strain distribution using models with/without epidermal ridges/papillae, we found that the shape of the epidermal ridges/papillae influences the stress/strain distribution near the tactile receptors.

1. Introduction

Human beings have excellent tactile receptors. They can detect the texture and shape of surfaces by moving their fingers over an object. In addition, they can lift the object without entire slippage or applying excessive force.

There are many research projects that study the tactile sensation of human beings. Johansson (1), (2) clarified the receptive field and response patterns of different types of tactile receptors of human beings using microneurography. Noro (3) and Akamatsu and Sadamoto (4) measured the relationship between normal force and the velocity of fingers while touching objects with different surface roughness. Naganuma (5) clarified the effect of the deformation of finger skin on the tactile receptors using viscoelastic equations. Srinivassan and Dandekar (6) analyzed the deformation of the finger skin using the finite element (FE) method. In the above studies, the relationship between the structure of human finger skin and the location of the tactile receptors was not considered.

In this study, we pay attention to the complex structure of the finger skin, including the epidermal ridges and papillae. We calculate, in detail, the degree of deformation of finger tissue when the finger comes into contact with a rigid plate using FE analysis. The reasons for the precise location of the tactile receptors in fingers are clarified.

2. Model of finger section

2.1 Structure of the finger

Figure 1 shows a structure of the human finger and the location of the tactile receptors (7), (8). The finger skin consists of an epidermis, dermis and subcutaneous fat tissue. There are papillae at the interface of the epidermis and dermis underneath the epidermal ridges. There are tactile receptors such as Meissner's corpuscles, Merkel's discs, Ruffini endings and Pacinian corpuscles incorporated in the skin (See Fig. 1). Response characteristics of the tactile receptors are shown in Table 1.

We analyze the deformation of the finger using a FE code MARC. Figure 2 shows the FE mesh model of the finger section of an index finger. The plane strain element is used because the deformation outside the modeled plane is negligible when the finger is moved in the x-direction. Nodes at the surface of the nail and bone are constrained in the x and y-directions. The nail and bone are not modeled because their Young's moduli are large compared with that of the skin. Figures 2 (b) and (c) show the partial models of the skin underneath one epidermal ridge. Model (b) has the epidermal ridge, and the surface of model (c) is flat. The effect of the epidermal ridge on tactile sensation can be analyzed by arranging the model (b) or (c) throughout the entire model (a). The effect of the papillae on tactile sensation can be analyzed by changing the material properties of the dermis and epidermis as well. The model is made of about 3700 elements and 3900 nodes. Four symbols in the figure represent the nodes where the four tactile receptors are located. The precise size and properties of the model are determined by the measurement technique discussed in section 3.

2.2 Method of FE analysis

We analyzed the contact between the finger pad at the top of the finger section model and the straight line which represents a rigid plate. Nonlinearity due to the material property of the soft tissue is not considered because the appropriate relationship between load and deformation can be calculated by a linear analysis as discussed in detail in section 3. Nonlinearity due to the large deformation of the model is considered. The effect of inertia is negligible.

First, we analyze the contact when the plate does not slip. The straight line is moved in the negative y-direction for several steps. We analyze the contact in which the following condition is satisfied: the sign of the normal reaction force is positive when the nodes at the surface of the finger pad are in contact with the line. On the other hand, the nodes and the normal reaction force is zero for noncontact nodes. Then, normal contact force distribution is obtained.

Next, we analyze the contact for entire slippage. We apply the Courone friction law, i.e., the tangential reaction force is proportional to the normal reaction force at each contact node. All the contact nodes slip during analysis when the straight line slides in the x-direction after penetrating the straight line in the negative y-direction. So the normal and tangential reaction force at the contact surface of the finger pad is obtained.

These conditions represent movement of the finger in a lateral direction, which is a motion that human beings use for detecting the texture of the object surface. The value of the dynamic friction coefficient, the ratio between the tangential and normal reaction force, is designated as 1.0 referring to the average friction coefficient between the human finger pad and several objects measured by Yamaha (9) . Hence, the normal and tangential forces at each contact node have the same value.

3 Measurement of model properties

3.1 Measurement of geometric properties

The outline of the plaster of the index finger is measured using a reading microscope. The geometry of the outline corresponds to an ellipse with a long axis of 17.44 mm and a short axis of 13.60 mm within the error of 3.5 percent and 6.5 percent for the finger pad and nail surface, respectively. Hence, the outline of the FE model is designated as the above ellipse. The thickness of the dermis and epidermis, and the shape of the bone and nail of the finger are measured from a cadaver. The thickness of the dermis and epidermis used for the FE model are 1.0 mm and 0.75 mm, respectively. Detailed geometry of the FE model is decided using the photograph of the finger section shown in a reference (10). The height and pitch of the epidermal ridge are about 0.1 mm and 0.35 mm, respectively.

3.2 Measurement of stiffness

The material properties of human skin have been measured by several researchers (5), (9), (11). However, the material properties of the dermis and epidermis have not been determined. Therefore, we measured the material properties of human skin using a U-shaped thin wire shown in Fig. 3. Stiffness of the finger tissue is measured by penetrating the finger of cadaver with a U-shaped wire 0.2 mm deep as determined by micrometer and by reading the deformation of the wire. Strictly, we should measure the deformation of the skin by changing the depth of penetration because the relationship between the load and displacement of the finger tissue is not linear. However, the relationship is linear when the deformation is small as shown by Fung (11). Therefore we fix the depth of penetration at 0.2 mm. Figure 4 shows the experimental result. From this, we determine the stiffness ratio among the epidermis, dermis and subcutaneous tissue as 8:5:2.

3.3 Material Properties

We designated the Young's moduli of the epidermis, dermis and subcutaneous tissue so that the relationship between the load and contact area calculated by FE analysis corresponded with the measured one. The FE analysis is conducted by changing the Young's moduli to maintain the ratio of Young's moduli for the three types of tissues at the above value. The measurement is conducted using the equipment shown in Fig. 5. A transparent plate is connected to a micrometer head and to two plate springs with a bonded strain gage. When the micrometer head is screwed down, the plate springs deform and the transparent plate moves vertically. Hence, deformation of the finger is obtained by subtracting the deformation of the plate spring from the displacement of the micrometer head. The applied load is measured by the strain gages. The contact area between the finger and the plate is measured by detecting the scattered light from the opposite side of the transparent plate. The measured contact region between the finger pad and the plate is shown in Fig. 6. The measured contact width, normal load and displacement of the finger are shown in Fig. 7 along with the calculated values. The relationship between the displacement and the contact width does not change significantly, even when the Young's moduli of the tissue are changed. The calculated contact width is slightly smaller than the measured value. When the Young's moduli of the epidermis, dermis and subcutaneous tissue are 1.36×10^5 Pa, 8.0×10^4 Pa and 3.4×10^4 Pa, respectively, the calculated values are in agreement with the measured ones. Now, we can explain the nonlinear relationship between load and displacement by the nonlinearity due to the contact instead of the nonlinearity of the material properties. The Poission's ratio of the skin is 0.48 according to a study by Fung (11).

4 Results of the calculation and discussion

4.1 Effect of normal/tangential load

We calculated the contact condition when the plate moves in a negative y-direction for 0.8 mm and also slides in the x-direction using the FE model with epidermal ridges and papillae (see Fig.2(b)) in order to discuss the effect of normal and tangential load on the stress/strain distribution of the skin near the tactile receptors. Figures 8 and 9 show the equivalent Von Mises stress distribution for both cases. The Von Mises stress, σ, can be written by the following equation;

$$\begin{aligned}\sigma &= \frac{\sqrt{2}}{2}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2}\\ &= \sqrt{2}\sqrt{\tau_1^{\,2}+\tau_2^{\,2}+\tau_3^{\,2}}\end{aligned} \tag{1}$$

where, σ_1, σ_2 and σ_3 are principal stresses and τ_1, τ_2 and τ_3 are principal shear stresses. Although the Von Mises stress is conventionally used for plasticity, we use it to compare the stress distribution because it is proportional to the shear strain energy. The Von Mises stress is concentrated at the location of Meissner's corpuscles, Merkel's discs, Ruffini endings, and Pacinian corpuscles, shown as A, B, C and D, respectively in Fig.8 and 9. This is primarily due to the fact that the tactile receptors are located near the interface between the tissues.

Figure 10 shows the Von Mises stress distribution on the y-axis of Fig. 2 when the penetration of the plate is changed. The stress value is not continuous at y=5.62 and y=6.37 because the Young's moduli change at these points. The local maximum of the stress near the Pacinian corpuscles changes due to the change of the penetration of the plate unlike the case of other receptors. This is seen as a contact problem between an isotropic cylinder and a plate (12). We can say that the Pacinian corpuscles can detect the stress concentration at any depth of the skin tissue caused by normal contact forces with various values because they are located at various depths.

Figure 11 shows the Von Mises stress distribution of the tissue near the four tactile receptors indicated in Fig. 2. The stress distribution near the Meissner's corpuscles, shown in Fig. 11(a), is axisymmetric only when a normal load is applied. On the other hand, stress near the leading edge of the contact greatly increase when a tangential load is applied by sliding the plate. Since the receptive field of the Meissner's corpuscle is small (see Table 1), it must detect the local change of stress due to the application of the tangential force. The stress value of adjacent plots differ from each other because the Meissner's corpuscle is located in a pair of papillae beneath the epidermal ridge.

Fig. 11 (b) shows that the stress distribution near the Merkel's disc is also axsisymmetric only when a normal load is applied. On the other hand, stress near the leading edge of the contact greatly increase when a tangential load is applied. Since the receptive field of the Merkel's disc is small (see Table 1), it must detect the local change of the stress due to the application of the tangential force.

Fig. 11 (c) shows that the stress distribution near the Ruffini ending is also axsisymmetric only when a normal load is applied. On the other hand, stress near the leading edge of the contact greatly increase when a tangential load is applied. However, the receptive field of the Ruffini ending is large (see Table 1). From this, we can say that the Ruffini ending is not detecting the local change of stress due to the application of the tangential force.

The stress distribution near the Pacinian corpuscles, Fig. 11 (d), does not change much, even when a tangential force is applied. The Pacinian corpuscles must not detect the tangential force.

4.2 Effect of ridges/papillae

The effect of the epidermal ridges and the papillae on stress distribution near the tactile receptors is analyzed using the partial models shown in Fig. 2. Figure 12 shows the results of our analysis. Looking at Fig. 12 (a), we find that stress distribution for the models without the epidermal ridge is uniform, and those with the epidermal ridge is not uniform. From this, the structure of the epidermal ridge is not only made to prevent slippage (13) but also plays an important role in increasing the sensitivity of tactile sensation.

When there are papillae, the stress value at the Merkel's disc location is large in Fig. 12 (b). From this, we can say that the geometry of the papillae is also important to increase the sensitivity of tactile sensation. On the other hand, the geometry of the epidermal ridges and papillae do not affect the tactile sensation of the Ruffini ending and Pacinian corpuscles as seen in Figs. 12 (c) and 12(d).

5. Conclusions

We constructed the FE model of the finger section using the measured geometry and material properties of the finger tissue. By analyzing the relationship between the structure of the finger pad and the location of the tactile receptors, we found that the tactile receptors are located where stress is concentrated. The contact force and the geometry of the finger pad affect the tactile sensation of the receptors that have a narrow field. (See Table 2.)

Dynamic response of the tactile receptors will be studied in our future work. Development of the artificial sensors from a biomimetic point of view will be obtained as well.

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References

(1) Johansson, R.S., Tactile Sensibility in the Human Hand: Receptive Field Characteristics of Mechanoreceptive Units in the Glabrous Skin Area. J. Physiol. 281, (1978), 101-123

(2) Johansson, R.S., Tactile Sensibility in the Human Hand: Relative and Absolute Densities of Four Types of Mechanoreceptors in the Glabrous Skin Area. J. Physiol. 286, (1979), 283-300

(3) Noro, K., Journal of the Society of Instrument and Control Engineers, (in Japanese), 23-3, (1989), 283-288

(4) Akamatsu, M. and Sadamoto, Y., Experimental Study on the Roles of Finger Movement in Roughness Discrimination by Active and Passive Touch, The Japanese Journal of Ergonomics, (in Japanese), 25-3, (1989), 183-191

(5) Naganuma, H., Journal of the Society of Instrument and Control Engineers, (in Japanese), 3-14, (1975), 263-280

(6) Srinivassan, M. A. and Dandekar, K., An Investigation of the Mechanics of Tactile Sense Using Two-Dimensional Models of the Primate Fingertip, Trans. ASME, J. Biomech. Eng., Vol. 118 (1996), 48-55

(7) Iwamura, Y., Structure and Function of Human Tactile Receptors, Journal of the Robotics Society of Japan, (in Japanese), 2-5, (1984), 54-60

(8) Shepherd, G. M., Neurobiology, Oxford Univ. Press, (1988)

(9) Yamaha, K., Biomechanism 3, (in Japanese), (1975), 27-45

(10) Ogawa, K., Soshikigaku 2nd Edition, Bunkoudou, (in Japanese), (1993)

(11) Fung, Y. C., Biomechanics: Mechanical Properties of Living Tissues, Springer-Verlag (1981)

(12) Johnson, K. L., Contact Mechanics, Cambridge Univ. Press (1985)

(13) Okajima, M., Dermatoglyphics, (in Japanese), 4-6, (1974) 160-172

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