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Dependence of tactile sensation on deformations within soft tissues of fingertip *

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Abstract. Previous studies show that the fingertip deformation distribution characteristics produced by contacting objects affect the performance of tactile sensation, which plays an important role in artificial skin and fingers for Robotics. To investigate the effects of stimuli on the deformations within the soft tissues of fingertips and the dependence of the tactile sensation on the deformations during touching an object, in the present study, a finite element model is developed, based on the physiological structure of the fingertip, to simulate the contact interactions between a fingertip and a flat plate. The dependence of contact force on contact displacement is analyzed and compared to the existing experiment data. Characteristics of the contact pressure distribution, strain energy density distribution, stress and strain distribution within the soft issues are analyzed. The results show that the soft tissues of fingertips are very sensitive to stimuli, and the spatial distribution characteristics of strain energy density within soft tissues can best explain the evoked charging rate of mechanoreceptors.

Keywords: finite element method, contact interaction, fingertip, tactile sensation, strain energy density

1 Introduction

Human beings, especially human fingertips, have rich mechanoreceptors sensitive to object's geometric features and textures[4, 8, 11]. When fingertips span across object's surface, the contact force between them deforms the soft issues within fingertips, and then skin mechanoreceptors create coded neural signals in response to superficial static and dynamic skin deformation. Four specialized types of mechanoreceptors detect unique stimuli. The receptors convert the mechanical stimuli into trains of action potentials, conveyed along neural pathways to the nervous system. The combined signals from populations of mechanoreceptors are the data source from which humans form judgments. The level of the evoked action potential of mechanoreceptors is related tightly to deformation characteristics adjacent to them, and the stress/strain conveying forms and textures, especially the strain energy density are interpret as coded neural signals[4, 5, 11].

In the study of tactile discrimination of one or two-point stimulus and pathology of functional disorders within soft tissues in hand, there are two categories of fingertip models, including physical models [3, 13] and structural models, the latter refers to linear elastic half-space models[7, 10] and multi-layered finite element (FE) models[1, 6, 12]. The physical model is based on quasi-viscoelastic constitutive equation[2]. For example, by applying different relaxation functions, Jindrich[3] and Wu[13] were able to obtain different instantaneous response function of contact force (F) dependent on contact displacement (x), expressed by $F = 0.0811e^{(1.48x-1)}$ and $F = 0.2368x^{2.0696}$, respectively. Similar to physical models, the linear elastic half-space models simulate the total deformation characteristics of the skin in fingertip after loading. However, the model prediction does not agree well with experiments due to the neglect of anatomical multi-layered

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structure of the fingertip. It is, therefore, less suitable for them to simulate the local deformations within the soft tissues adjacent to mechanoreceptors. Most of the shortcomings in other models, however, can be overcome by using multi-layered FE models based on the anatomical structure of fingertip. By FE models, Wu[12] investigated the damage of manual work to soft tissues and bone, and Maeno[6] analyzed the effect of complex structure of the finger skin (e.g, epidermis edges, papillae) on deformation within soft tissues. Excellent prediction result by FE models demonstrates the feasibility of the models to simulate the response of soft tissues to loading. However, little attention has been paid so far to the dependence of deformation within soft tissues of fingertip on tactile sensation.

Using the similar method as in literature[1, 6, 12], this study develops a multi-layered structural FE model to analyze the deformation distribution characteristics within soft tissues of a fingertip where most mechanoreceptors embed, the area includes dermal layer and soft tissues adjacent to it. In addition, the contact interaction between a fingertip and a flat plate is analyzed. Finally, discussions are made on the sensibility of the model to weak stimuli.

2 Model of finite element analysis

The anatomy of the tissues within a fingertip is a multi-layered structure[8], including epidermis, dermis, subcutaneous, nail and bone, and different types of rich mechanoreceptors embed in soft tissues within fingertip, Merkel discs in epidermis, Meissner corpuscles and Ruffini endings in dermis, and Pacinian corpuscles in dermis and subcutaneous, respectively. In addition, the studies[2, 3, 13] show that, when experience large deformation, the epidermis behaviors hyperelastic and dermal tissues linear viscoelastic. The subcutaneous tissue is assumed to be a biphasic material composed of invicid fluid phase and hyperelastic solid phase. When under small deformation, the displacement of fingertip on loading, however, is linear and elastic.

In terms of the anatomical structure of the fingertip, the cross-section model of a fingertip is established. The dimensions of the fingertip are assumed to be representative of the index finger of a male subject[12, 13]. The cross section of the fingertip is assumed to be elliptical, as shown in Fig. 1, of which the major and minor diameters are 16.0 mm and 12.0 mm, respectively. The centre of the bone is 1.0 mm away from the geometrical center. Other constants of the fingertip skin are shown in Tab. 1. The tissue thickness is considered to be asymmetric about the bone, and the fingerpad is thicker than the dorsal that of a finger. The flat plate is assumed to be linearly elastic with Young's modulus 200 GPa and Poisson's ratio 0.3.

Table 1. Constants of fingertip structure [6, 12]

	Nail	Epidermis	Dermis	Subcutaneous	Bone
Elastic modulus/MPa	170	0.136	0.08	0.034	17 000
Poisson ratio	0.3	0.48			0.3
Thickness/mm	0.2	0.2	1.0		4.0

In studying the tactile discrimination task, the compressed or indented deformation of fingertip is less than 2.0 mm[5]. Therefore, the deformation of the soft tissues within the fingertip in the present study is considered to be linear and elastic when the compression depth is less than 2.0mm. Because of much higher Yong's modulus than that of soft tissues, the deformations of nail and bone are neglected. All the assumptions have been verified by experiments[1, 6, 7].

The Ansys software package is used for analyzing the contact interaction between a fingertip and a flat plate. The FE model is shown in Fig. 1. The original of the coordinate coincides the centre of the bone and the length of the contact area in x-axis is defined as the contact width. The initial contact interaction between the fingertip and plate is P (0, 7). With an increasing contact pressure, the soft tissues are compressed gradually and the contact width increases. By neglecting the deformation outside X-Y plane and the inertial effects[7], the elements of an eight-node quadrilateral with plane strain are chosen to establish the FE model.

The objective of the simulation is to calculate the deformation of soft tissues within the fingertip moving 2.0 mm toward the plate along y direction. The simulation procedures are as follows. First, the dependence of displacement on a normal force is calculated and compared the results with the existing data[3, 13]. Then, the contact pressure distribution, contact width change with loading, distribution of the strain energy density (SED) are derived. Finally, the dependence of sensibility to stimuli on deformation of the fingertip skin is analyzed, especially the dependence of the SED distribution characteristics on tactile sensation.

3 Results and discussion

4 The dependence of contact force on contact displacement

The normal contact force/displacement curve is shown in Fig. 2. In the figure, the contact force is normalized with respect to the force at the maximum displacement (2.0 mm). From the results it is seen that, at the initial stage, the soft tissues are very sensitive to loading. Then, the deformation becomes small at the same loading level. The compression depth reaches about 60% of the total value when the loading is about 20% of the maximum value. The contact force distribution curve from the present model agrees well with the existing data[3, 13], except a couple of isolated values. The error may result from the adopting structural constants in Tab. 1 from the processed cadaver tests and it suggests further studies.

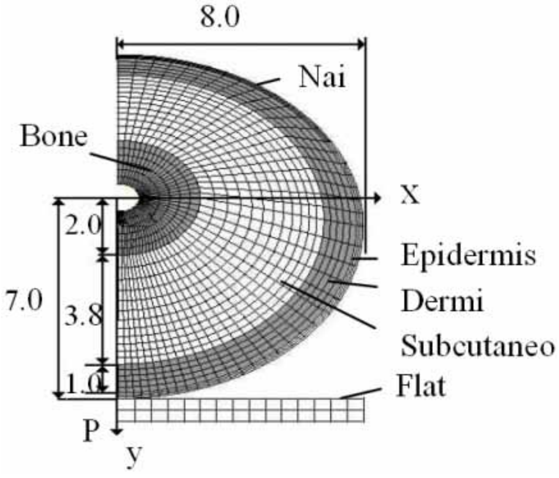


Fig. 1. 2-D FE model of the fingertip cross section

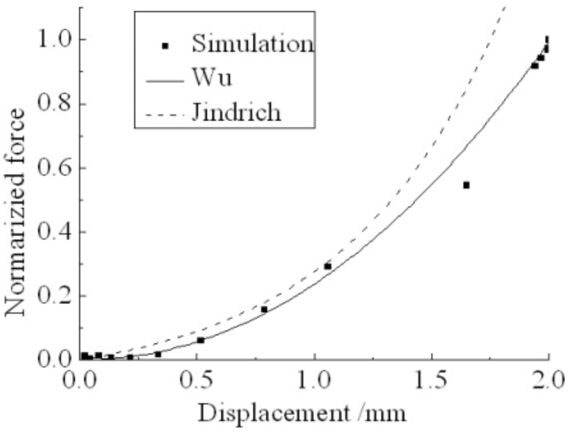
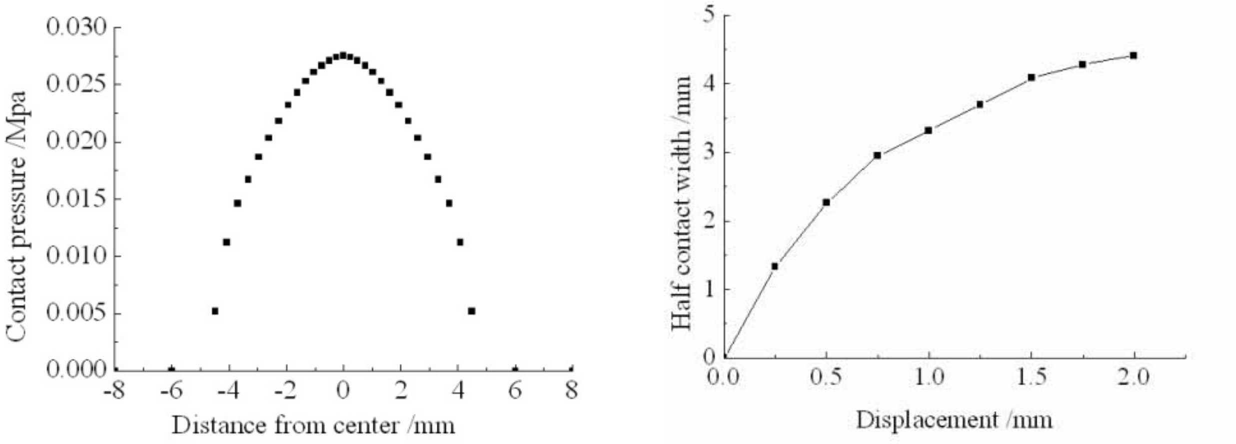


Fig. 2. Force-displacement relationship of contact interaction between fingertip and flat plate

4.1 The deformation distribution characteristics at the skin/object interface

The contact pressure distributions at 2.0 mm fingertip displacement and the dependence of contact width on displacement from the present model are illustrated in Fig. 3(a) and (b), respectively. Here, the contact width refers to the x coordinates value when the contact pressure is zero. Fig. 3(a) shows that the curve is an inversed parabola in shape, which is akin to the geometrical structure of the fingertip. In Fig. 3(b), the contact width increases rapidly with increase in contact deflection, and it is nearly equals to 75 percent of the maximum contact width when the contact deflection is the half-maximum displacement. The simulated contact deformation distribution characteristics using the present model are identical to Maeno's experimental results[6]. From Fig. 3, it is seen that both the contact pressure and contact width at the skin/object interface have apparent change, which plays an important role in tactile sensation by collecting rapidly more information of object features, especially in the case of weak stimuli, that is during the initial touching. It is also shown that both the contact pressure and contact width have little change, and it provides a good explanation why upper-limen contact force cannot improve the performance of tactile discrimination due to most of mechanoreceptors sensitive to deformation change[4, 5, 11].



（a） Contact pressure at 2.0mm displacement (b) Contact width—displacement curve

Fig. 3. Contact deformation distribution for the interaction between fingertip and flat plate

4.2 The SED distribution characteristics within soft tissues

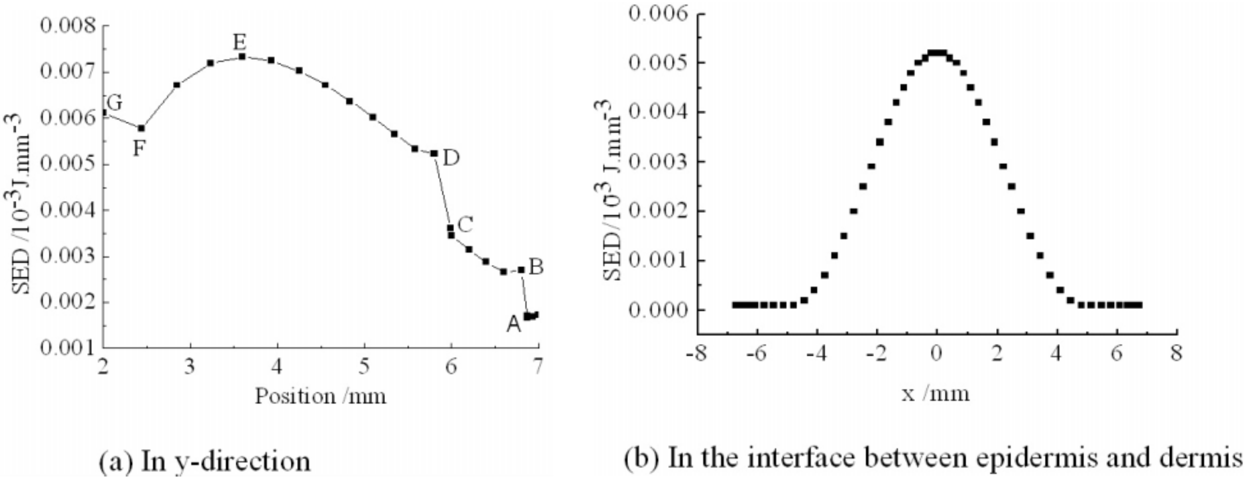
The electrophysiological experiments suggest that the evoked discharge rate can best be explained by using of SED[1, 4, 5, 11]. The spatial distribution characteristic of the SED within the tissues of fingertip is shown in Figs. 4 (a) and (b). In the figures, A, B, C and D are the representatives of four different locations adjacent to the interfaces between epidermis and dermis, and that between dermis and subcutaneous tissue, respectively. E, F and G are three different locations in subcutaneous tissue and adjacent to the bone, respectively. Fig. 4 (a) shows the distribution characteristics of SED along y-direction, from out-edge of the bone to the contact interface. It is seen that the SED has a sudden change from a layer to the next one, e.g, from A to B of from C to D, and a gradual change within the same tissue layer, e.g, from B to C or from D to F. At E, which is in the subcutaneous tissue, the SED reaches the maximum value because it experiences a large strain as a result of low Yong's modulus and small transverse expansion due to part of tissues tied to the bone. Fig. 4 (b) shows the range of spatial response of mechanoreceptors to the loading. It's seen that, contrast to Fig. 3, the individual mechanoreceptor located in different positions has distinctive level of response, and the range of response is consistent to that of stimuli, i.e. contact width, but little thinner than the contact width due to the shell effect of epidermis. The distribution characteristics of the SED help represent stimuli shape. The simulation results show that the distribution characteristic of the ESD is related closely to the soft tissues' structural properties and stimuli features. It explains the effect of the SED on mechanoreceptors embedded in soft tissues near the interface, which are sensitive to the change of SED. In addition, most mechanoreceptors are located in dermal layer from B to C.

The stress in soft tissues are calculated when the fingertip presses the plate by using the FE model in order to explain the spatial distributions of SED. Fig. 5 shows the equivalent Von Mises stress distributions at the maximum displacement (2.0mm). The results show the discontinuous deformation characteristics and the transverse tensile deformation within soft tissues of the fingertip. The spatial distribution characteristics of the equivalent Von Mises stress verify the results of the spatial distributions of the SED in Fig. 4.

From Fig. 3 to Fig. 5, it's seen that the deformation distributions are symmetric about y-axis, concentrated in soft tissues of the fingerpad, and dense in dermal and subcutaneous layers. Moreover, the deformations behave in distinctive change from a layer to the next layer. It is vital for the deformation distributions to improve tactile sensation because most of the mechanoreceptors sensitive to the changes of deformation are embedded densely in soft tissues of dermal layer and adjacent to it.

5 Conclusions

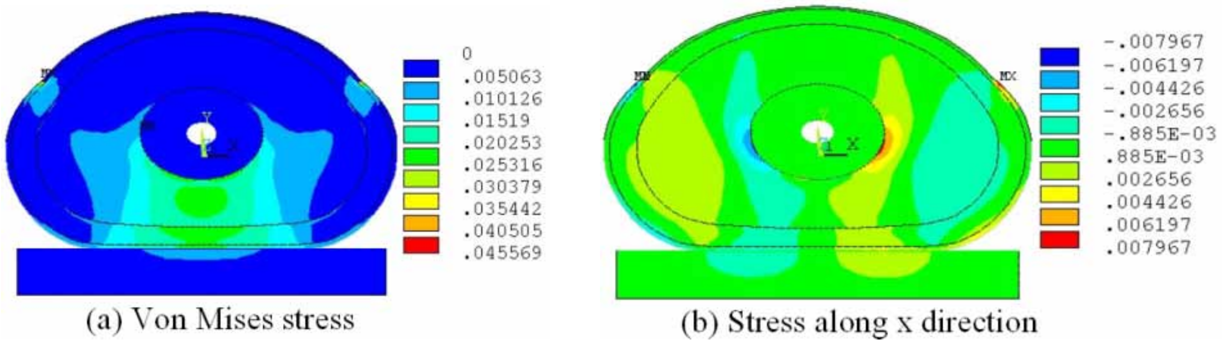
In the task of tactile discrimination of fingertip, distribution characteristics of contact deformation are related closely to the performance of tactile sensation. However, because of the difficulty in measuring the



(a) In y-direction

(b) In the interface between epidermis and dermis

Fig. 4. SED distribution



(a) Von Mises stress

(b) Stress along x direction

Fig. 5. Equivalent Von Mieses stress distribution within soft tissues of the fingertip for 2.0 mm displacement towards plate

on-line deformations within the soft tissues of a fingertip, model simulation is a frequently used method to study the response to stimuli, based on the data from in-vitro experiments.

In the present study, the responses of the soft tissues within a fingertip subject to compression loading are simulated. The results show that the contact width and contact interaction between a fingertip and a plate changes rapidly when weak stimuli is applied. The deformation is nearly 60 % of the total deformation when the contact force is less than 20% of the maximum value, and the contact width is 75% of the total for less than 50% of the total contact pressure, which is vital for the improvement of tactile sensation performance. The spatial distribution characteristics of SED can best explain the evoked discharge characteristics of mechanoreceptors. Therefore, the proposed multi-layer structural FE model can predict the response of the fingertip skin to stimuli in tactile exploration and explain the effects of object features on mechanoreceptors. In the long term, the intention of this work is to create a predictive model to predict texture detection touch and perceivable differences, and improve the intelligent system design for bio-Robotics.

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