

Relevant Stimuli and their Relationships to Primate SA-I Mechanoreceptive Responses under Static Sinusoidal Indentation

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Abstract -- *The key event in tactile sense about an object in contact with the skin surface is how the stress and strain subjected to the mechanical loading are transduced into neural impulses by the mechanoreceptors within the skin. In order to investigate the mechanism of transduction by the mechanoreceptors, a biomechanically validated three-dimensional finite element model for primate fingertips was used to simulate neurophysiological experiments involving static indentations by sinusoidal objects. Altogether, eighteen mechanical invariants were obtained from the computed stress and strain components at nine receptor locations. Further investigation has been done to study the influence of external load, size of the indenter and vertical location of the mechanoreceptors on the spatial response profiles.*

Keywords: *Somatosensory, skin biomechanics, spatial response, sinusoidal indenter*

1 INTRODUCTION

During manual exploration and manipulation, primates predominantly use their fingertips to obtain tactile information about an object. The whole process of the tactile sense about an object can be divided into four events. First, the object comes into contact with the fingerpad, the skin is deformed and the pressure distribution is created over the contact region. Then, the deformation and pressure field are filtered through the skin and resulted in mechanical stress and strain. Next, mechanoreceptors within the skin transduced the stress and strain into neural impulses. Finally, the object is perceived after the brain decodes the information contained in the neural impulses. The key event is how the mechanical stress and strain are transduced into neural signals. Since at present, no experimental techniques exist to observe the stress and strain state at the mechanoreceptor locations, one feasible approach is to develop realistic models capable of simulating neurophysiology experiments.

Phillips and Johnson [1,2] developed an idealized model of the fingertip as a flat and homogeneous elastic medium of infinite extent and were able to predict the responses of SA-Is to static indentations of rectangular gratings very well. However, because this model does not take into account either the geometry of the fingertip, or the inhomogeneous composition of tissues within, it is unable to model the mechanics of contact with arbitrarily shaped objects adequately. An alternative idealization is the “waterbed” model [3] in which the fingertip was viewed as a membrane enclosing a fluid and which predicted the surface profiles under line loads very well, but was unable to predict the spatial variation in SA-I response to various stimuli. We then developed several two dimensional (2D) finite element models of the primate fingertip, one of which was able to predict the static responses of SA-I receptors along a cross-section [4] and showed that model geometry had a strong influence in governing contact conditions with objects. Only the 2D model developed by Maeno and Kobayashi

[5] has more detail in that it takes into account the geometrical structures associated with fingerpad skin ridges and grooves, but the predictions of this model however have not been empirically validated.

In this study, we used a three-dimensional finite element (FE) model for primate fingertips to study the mechanism of the transduction from mechanical stress and strain into neural impulses. The model was biomechanically validated with consideration the realistic external geometry of the fingertip and the multiple layers of the internal tissues [6,7]. The focus in this paper is to determine the relevant stimulus for the slowly adapting fibers and how factors influence the spatial response profiles of the mechanoreceptors..

2 METHODS

2.1 Simulating the contact between the sinusoidal indentors and the monkey fingerpad

Selected neurophysiological experiments were simulated by use of a three-dimensional multilayered finite element model for the monkey fingertip, as shown in Fig. 1. The details of the model are described in previous publication from our lab [6]. Briefly, the model was based on accurate external geometry from a primate fingertip. Moreover, it consisted of four layers -- epidermis, dermis, fat, and bone. Each layer was considered to comprise linear elastic materials, and the elastic moduli for the four layers were determined by matching experimentally obtained biomechanical data. The Young's moduli from the skin surface were 0.14, 0.014, 0.014, and 1400 MPa, respectively. The Poisson's ratio for all the layers was chosen to be 0.48. In order to simulate the contact between the sharp curvatures of the indenter and the fingerpad, the FE model was refined with about 30,000 nodes; moreover, it has a large number of nodes in the pulp region of the finger where contact occurs and fewer nodes in other regions. The spacing between the nodes in the contact region is reduced to be 0.17 mm, about one third of that in the previous model [7]. Commercial FE software ABAQUS was used for all the simulations.

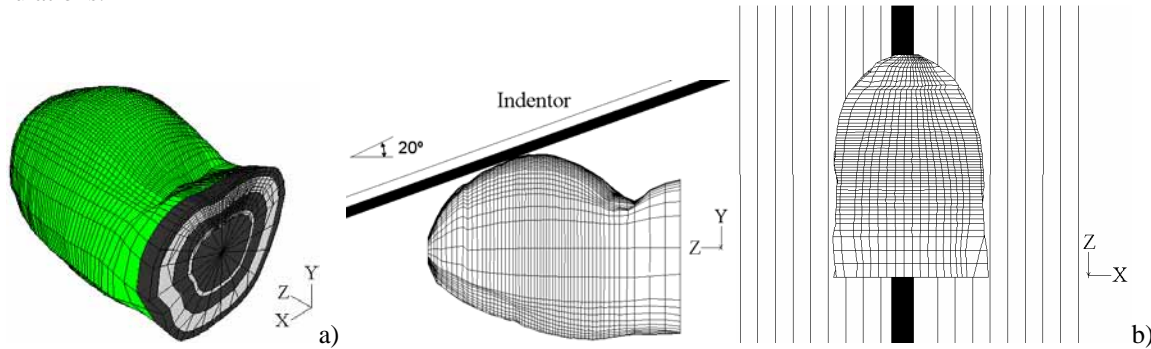


Fig. 1. a) The three-dimensional finite element model for primate fingertip. One slice is shaded to show the various layers used in the model. Maximum sizes along X, Y and Z directions are 8.8, 9.4 and 12.6 mm respectively. The minimum element near the surface of the fingerpad is of 0.17 mm. b) two-dimensional view of the model showing the relative position and size between the indenter and the fingertip. The angle between them is 20°. The indenter is long enough and can be regarded as infinite compared to the length of the fingertip.

The model was used to simulate the neurophysiological experiments where indentors in sinusoidal shape were used to indent the primate fingertip. In this paper, three indentors were chosen which correspond to number 1, 3 and 5 in reference [8]. The height of the sinusoidal part is 0.45 mm for all the three indentors, and the width or half cycle is 0.45, 1.23 and 3.318 mm, respectively. They were denoted as indenter 1, 2 and 3 in this paper, with information for indenter 2 shown in Fig. 2a. In order to construct the spatial response profile, the indenter was moved across the fingerpad along X direction. The distance between two adjacent locations is 0.17 mm, mostly. There are about 20 locations for each of the indentors. The lateral (X direction) locations of Indenter 2 are shown in Fig. 2b.

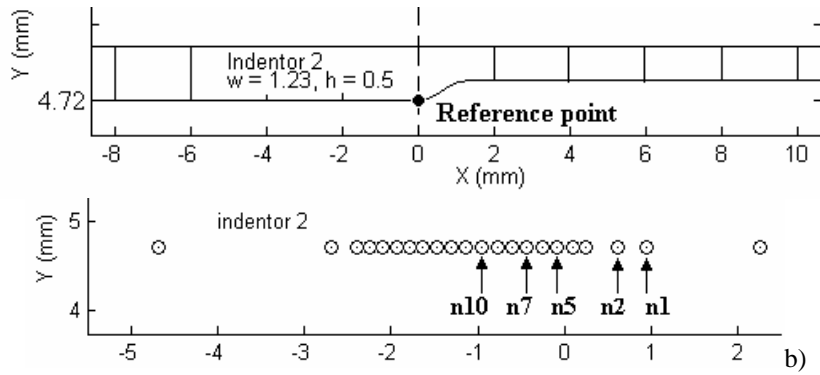


Fig. 2. a) Definition of one sinusoidal indenter (Indenter 2). It consists of four sections: lower flat, convex, concave, and upper flat. ‘w’ and ‘h’ stand for the half-cycle wavelength and height for the sinusoidal part (in mm). The black dots indicate the reference point for each indenter and the dashed line indicates one location of the indenter ($X = 0$ mm) marking the beginning of the convex curvature on the thick side of the indenter. b) Illustration of the various locations of the indenter by showing the X coordinates of the reference points. So, when the fingertip is fixed, the indenter is moved along negative X direction, or from right to left. Most of the spacing between two adjacent steps is 0.17 mm, same as that between the nodes in the FE model. Five locations are indicated by arrows and numbered for further reference. The coordinate system in Fig. 2 is the same as that in Fig. 1.

2.2 Choosing candidates for relevant stimuli

When the indenter comes into contact with the fingertip under prescribed load, the deformation of the fingertip causes stresses and strain beneath the skin surface. The available candidates for these stress/strain components (relevant stimuli) are summarized in Table 1.

Table 1 Candidates for relevant stimuli

No	Symbol	Category	Full Name
1	s11	Normal stress	-
2	s22		-
3	s33		-
4	e11	Normal strain	-
5	e22		-
6	e33		-
7	e12	Shear strain	-
8	e23		-
9	e13		-
10	ep1	Principal strain	Min principal strain or Max comp strain
11	ep2		Intermediate principal strain
12	ep3		Max principal strain or Max tensile strain
13	sp1	Principal stress	Min principal stress or Max comp stress
14	sp2		Intermediate principle strain
15	sp3		Max principal stress or Min comp stress
16	press	Invariant	Mean normal stress
17	inv3		Third stress invariant
18	sener		Strain energy density

3 RESULTS

3.1 Influence of receptor locations on the spatial response profiles of relevant stimuli candidates

Our objective was to determine, for a given relevant stimulus candidate, if any of the receptors would show the trend consistent with the peak-dip feature observed in the experiments (Srinivasan and LaMotte, 1987). Although simulations were done for all 18 candidates, about 20 locations for each indenter, and altogether 3 indentors, for the sake of clarification, here we only illustrate the results for one candidate with regard to indenter 2 due to the limited space. The results are shown in Fig. 3.

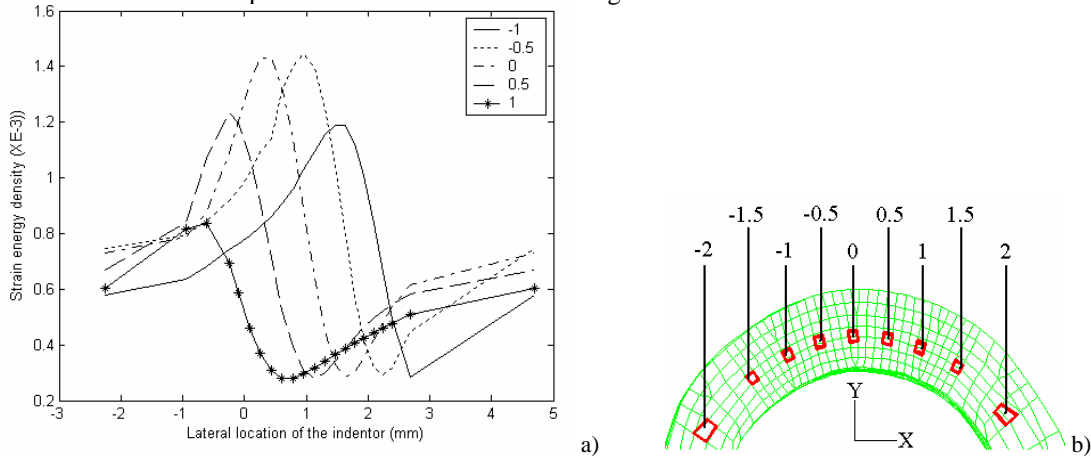


Fig. 3. a) Simulated spatial response profiles of strain energy density regarding 5 receptor locations. B) Locations of the 9 receptors in XY plane with FE mesh overlapped.

3.2 Determination of the relevant stimulus

The spatial response profiles based on all the 18 stimulus candidates were obtained at 9 receptor locations. The match between recorded neural discharge rates and computed candidate stimuli are studied for each case with one shown in Fig. 4. It is concluded that there are nine stimulus candidates who have at least one common receptor location for the three indentors. Those candidates are: normal stress s22, normal stress s33, normal strain e11, normal strain e22, maximum compressive strain ep1, maximum tensile strain ep3, maximum compressive stress sp1, mean normal stress and strain energy density.

Moreover, stress are directional quantities, that is, they denote stress components along particular directions. From the point of continuum mechanics, the directions are the ones whose shear stress components are zero. In order to determine these stresses, not only the magnitude but also the direction of stress components must be determined; while, the stimulus is influenced by the indenter shape, location of indentation, intensity of indentation, etc. As for strain component, the similar problem exists. On the other hand, strain energy density is a scalar quantity that has no directional preference and is an invariant of the amount of distortion of the receptor at that location. It does not require the computation of strain component directions. Irrespective of changes in indenter, orientation of the receptor within the skin, such property as indenter shape can be encoded by a population of receptors when they respond proportionally to the energy of distortion imposed on each of them. Thus, strain energy density should be the best compared to the other three candidates.

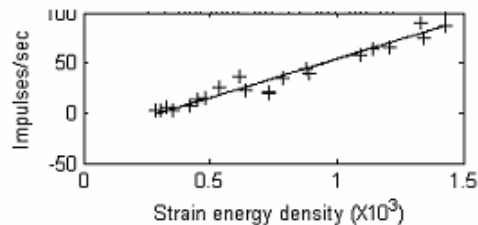


Fig. 4. Recorded neural discharge rates vs. computed candidate stimuli based on data.

3.3 Influence of various loads on strain energy density

Since 30-50 gwt has been commonly used in monkey studies, the change of the response from the fingerpad was investigated when the external load was ranged from 8 to 50 gwt. Relevant stimulus strain energy density was chosen as the candidate to show the changes, as can be seen in Fig. 5.

From the Figure, it can be seen that, when the external load is changed within the range from 8 to 50 gwt, the profiles of the strain energy density are similar to each other. Except for the case of 8 gwt, the profiles for all the other cases have two peaks instead of one. The first peak has larger magnitude than that of the second peak. With the increase of the load from 8 to 50 gwt, the peak magnitude of the strain energy density is also increased and the relationship is approximately linear; moreover, the first peak is increased at a little faster rate than that of the second one.

3.4 Influence of indenter size on strain energy density

With regard to the influence of indenter size on the spatial response profile, there are two folds. One is the location of the indenter, and the other is the size of the indenter.

Referred to the neural discharge experimentally recorded, it can be seen that, the simulated strain energy density shows the peak-dip feature with respect to all the three indentors. It can also be seen that, when the size of the indenter is increased, or the half cycle of the sinusoid is increased (from indenter 1 to 3), the magnitude of the peak is reduced on the other hand. There is no obvious difference regarding the magnitude of the dip. This phenomenon may be explained as, when the indenter is wider with larger half cycle of the sinusoid; the indenter becomes less sharp, the strain change is less serious, and subsequently triggers fewer neural responses.

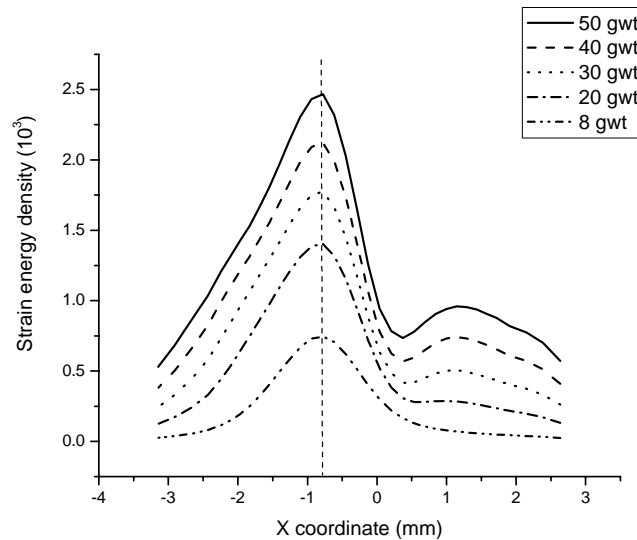


Fig. 5. Strain energy density vs. the location of the sinusoidal indenter along lateral (X) direction. The profiles show the ‘peak-dip’ characteristics, observed in the experiments. When the sinusoidal part of the indenter is narrow, the characteristic is more evident.

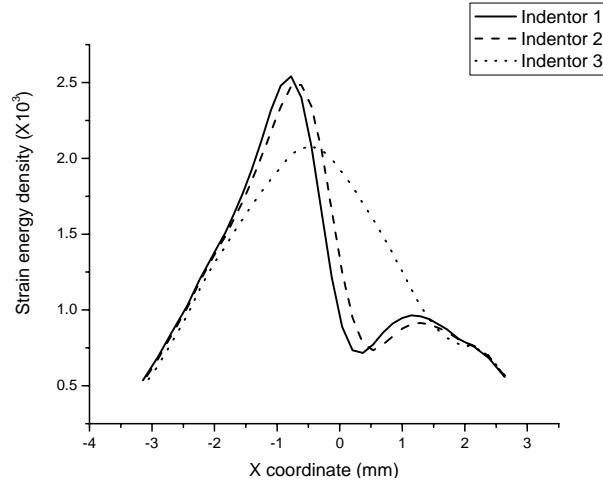


Fig. 6. Strain energy density vs. the location of three sinusoidal indentors along lateral (X) direction. The profiles show the ‘peak-dip’ characteristics, observed in the experiments. When the sinusoidal part of the indenter is narrow, the characteristic is more evident.

3.5 Influence of vertical location of mechanoreceptors on strain energy density

For all the studies presented in this paper so far, if the mechanoreceptors are involved, they are located 0.76 mm beneath the skin surface. In this part, five different vertical locations of the receptors were considered, as shown in Fig. 7. Compared to the location of 0.76 mm, one location is closer to the skin surface, while the other three are deeper. The relationship between the strain energy density and the relative vertical location of the receptors is presented in Fig. 7b. It can be seen that, when the receptor is nearer to the skin surface, the strain energy density becomes smaller. This relationship has been approximated by a linear function as follows. The correlation coefficient is 0.996.

$$y = 2.9589 - 0.3177x \quad (4)$$

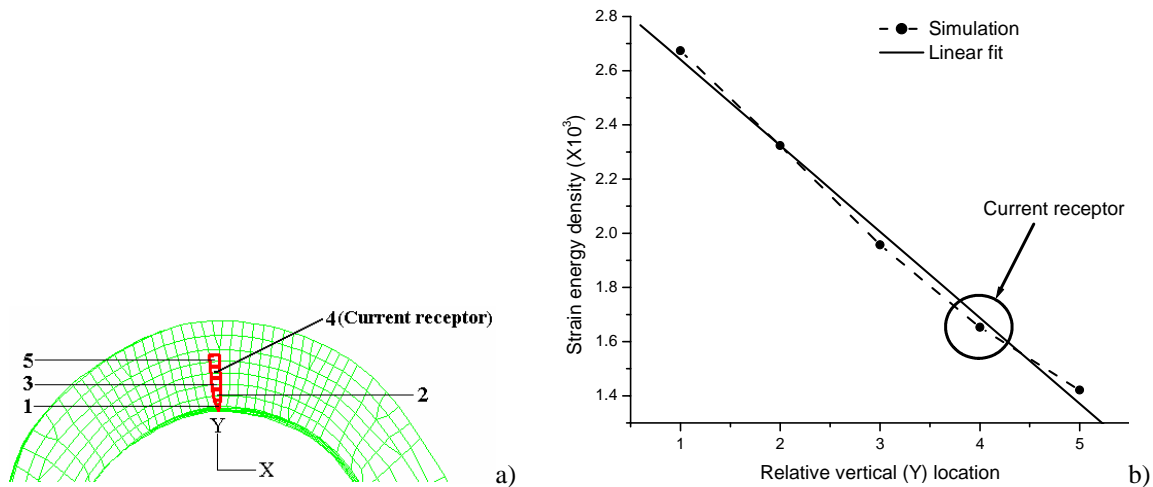


Fig. 7. a) Alternative locations along vertical (Y) direction of the receptors with FE mesh overlapped; b) Strain energy density vs. lateral location when the vertical location of the receptor is varied. Their relationship can be approximated as linear.

4 CONCLUSIONS AND DISCUSSIONS

By use of a biomechanically validated three-dimensional finite element model for primate fingertip and simulating neurophysiological experiments involving static indentation by sinusoidal indentors, we investigated how the mechanoreceptors transduced the stress and strain resulted from the external load on the fingertip. Since 30-50 gwt is used for most of the primate studies, we chose 50 gwt as the maximum load for the simulations. The influence of the load ranges from 8 gwt to 50 gwt has also been studied. The following conclusions have been reached.

- 1) When the indenter is moved across the fingertip, the profiles of the deformation of the fingerpad keeps changing gradually. The lateral (X direction) location of the peak is shifted in an opposite direction relative to the moving direction of the indenter.
- 2) The spatial response profile of the mechanoreceptor is dependent on the lateral location of the receptor regarding any of the stress or strain components.
- 3) Among the eighteen stress and strain components, which are also called relevant stimulus candidates, strain energy density are linearly related to the neural response of SA-I afferents. Strain energy density has been found to be the best candidate for relevant stimulus.
- 4) When the external load is varied from 8 to 50 gwt, the maximum of the relevant stimulus is increased linearly, approximately.
- 5) Regarding the variation of the size of the indenter, when the width of the sinusoidal part is wider, the peak value of the relevant stimulus is decreased on the other hand.
- 6) The relationship between the relevant stimulus and the depth of the mechanoreceptors' location shows to be linear.

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