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Role of Fingertip Geometry in the Transmission of Tactile Mechanical Signals

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Abstract

An investigation of the mechanistic aspects of tactile sense in primates is carried out using simple models of the fingertip. Four models that range in geometry from a semi-infinite medium to a cylindrical finger with a rigid bone, and composed of linear elastic media under plane strain conditions are analyzed using the finite element method. The results show that the model geometry has a significant influence on the spatial distribution of the mechanical signals, and that the elastic medium acts like a low-pass filter in blurring the signals imposed at the surface. In order for the biomechanical calculations to match the neurophysiological data, it is likely that the models will have to take into account the inhomogeneity of the primate fingerpad.

Introduction

The biomechanics of skin and subcutaneous tissues plays a fundamental role in the human sense of touch. Physical contact with an object causes the skin to deform, and the mechanosensitive nerve terminals embedded within the skin respond with trains of electrical impulses. The frequency of the impulses emitted by each mechanoreceptor is believed to depend mainly on the intensity of a particular combination of the stresses and strains in the local neighborhood of the receptor. Since these stress and strain fields within the skin are directly dependent on the mechanical stimulus at the skin surface, the response of a population of receptors represents a spatio-temporal code for the applied stimulus. This code is conveyed through peripheral nerve fibers to the network of neurons in the central nervous system, where appropriate processing enables us to infer the surface features of the objects in the contact regions, and the type of contact by touch alone.

Monkeys are used as experimental models for somatosensory mechanisms in humans, since the morphological types of mechanoreceptors, their innervation density in the skin, and the sensory capacities to detect and discriminate vibratory stimuli are similar in the two species. Although electrophysiological recordings of the neural signals transmitted by a single peripheral nerve fiber are possible, the stress or strain state of the associated mechanoreceptors is not empirically observable at present. Therefore, reliable mechanistic models of the skin and sub-cutaneous tissues are needed to gain a deeper understanding of the mechanics of contact, the transmission of the mechanical signals through the skin, and their transduction into neural signals by the mechanoreceptors. In particular, our focus in this paper is the primate fingertip, due to its predominant use during manual exploration and manipulation, as well as the availability of biomechanical and neurophysiological data for model verification.

The structure of the primate fingertip is complex: from a macroscopic viewpoint, it mainly consists of two layers of skin, the epidermis and the dermis, which enclose subcutaneous tissues mostly composed of fat in a semi-liquid state, together with a relatively rigid bone. When viewed as a block of material, it exhibits complex mechanical behavior such as nonlinearities of various kinds, anisotropy, rate and time dependence. Quantitative data on the external and internal geometries of a typical fingertip, as well as the constitutive relations for the materials that make up the fingertip are unavailable at present. Although some data on the *in vitro* and *in vivo* mechanical properties of the skin are available (Fung 1981; Lanir et. al. 1990; for a review, see Lanir 1987), they are inappropriate for the whole primate fingertip of which skin is one part. Furthermore, the consitutitive equations and the models (for example, Danielson 1973) that have been proposed contain a number of unknown material parameters. Therefore, our strategy is to develop a sequence of models starting with the simplest mathematically tractable model containing minimum number of parameters and gradually approach the actual physical structure of the primate fingerpad. This sequence is guided by agreements as well as mismatches between the model predictions and the results of biomechanical and neurophysiological experiments.

Models

In the absence of quantitative data on the geometry and material properties of the primate fingertip, the natural starting point is the Elastic half-space model proposed by Phillips and Johnson (1981). They recorded the responses of mechanoreceptors innervating the monkey fingerpad to steady indentations by gratings with rectangular bars, and to calculate the corresponding stress and strain fields within the skin they assumed the fingertip to be mechanically equivalent to a homogeneous, isotropic, incompressible and linearly elastic half-space in a state of plane stress or strain with infinitesimal deformations. The application of the Boussinesq solution for a line load together with appropriate superpositions enabled calculation of the strain components, some of whose spatial variations matched the receptor responses. However, a direct experimental observation of skin surface deflection profiles under line loads showed that the Boussinesq solution only roughly approximates the observed profiles for both monkey and human fingerpads (Srinivasan, 1989). An alternative model of the fingertip as an elastic membrane enclosing an incompressible fluid (the "waterbed" model) predicted the observed surface profiles quite accurately, but failed to match the spatial response profiles of the receptors, owing to the uniform pressure field in the fluid.

In order to examine the role of fingertip geometry in predicting both the surface deflections as well as the mechanoreceptor spatial response profiles, we consider here a sequence of four models composed of isotropic, incompressible and linear elastic media whose uniform cross-sections are as shown in Fig. 1. We confine ourselves to indentations by line loads and long bars that are used as stimuli in biomechanical and neurophysiological experiments, so that the plane strain assumption of these models is justified. Since the loads are static and the receptor responses are generally steady, we ignore the viscoelastic behavior of the fingerpad for this initial analysis It should be noted that robotic tactile sensing systems also have a similar structure of mechanoreceptive sensors embedded in a compliant medium, and that the models proposed here are valid for robot tactile sensing as well.

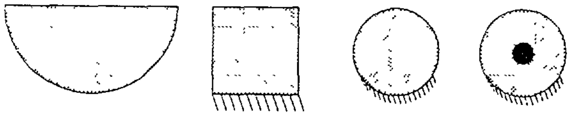

(a) (b) (c) (d)

Figure 1: *Cross-sections of each of the four models composed of an incompressible elastic material and assumed to satisfy plane strain conditions. (a) semi-infinite medium, (b) finite square (8 mm × 8 mm) (c) homogeneous cylinder (8 mm diameter) (d) cylinder (8mm diameter) with a central rigid bone (2 mm diameter).*

We began our analysis by using a model with rectangular cross-section to simulate a semi-infinite medium, so that the numerical solution could be compared with the analytical solution based on the Boussinesq solution for line loads. Model dimensions of 40mm x 18mm containing plane strain, 8 noded isoparametric elements were sufficient to match the analytical results in the region of interest. The next step was to remove the assumption of semi-infiniteness and model the finger as a finite medium. The second model was of square cross-section (8 mm x 8 mm), with dimensions comparable to the actual monkey fingerpad. To account for the effects of curvature of the central cylindrical region of typical monkey fingertips, the next refinement was to model the fingertip as a cylinder of 8 mm diameter, with and without a central rigid bone of 2mm diameter. In order to simulate the relatively stiff fingernail, nodes spanning the bottom boundary of the finite square model, and a third of the boundary at the bottom of the cylindrical models were constrained such that all the degrees of freedom were suppressed.

In the primate fingerpad, majority of the mechanoreceptors are embedded in the skin at a depth of about 0.5 mm to 1.0 mm from the surface, and the receptor spacing is of the order of 1.0 mm. In order to simulate a population response of these receptors with sufficient spatial resolution, we used square elements of 0.125 mm. sides in the top 1.0 mm thick layer of each model. The element size was gradually increased for deeper locations from the top surface. The aspect ratio was maintained as close to 1.0 as possible by using layers of transition elements. This also helped to reduce the size of the problem, thereby reducing the computational effort.

For this first analysis, the material was assumed to be linear elastic and isotropic, which required the specification of only the Young's modulus and the Poisson's ratio. If the prescribed loading and boundary conditions are in terms of displacements, it can be shown that for a homogeneous model the strains are independent of the Young's modulus. Empirical observation of the *in vivo* behavior of the human fingerpad suggest that it is almost incompressible (Srinivasan et. al., 1992), and thus the Poisson's ratio was assigned a value of 0.48. Finite element models of nearly incompressible materials in plane strain require special care in the formulation. We used the mixed displacement-pressure (u-p) formulation which treats pressure also as a nodal variable (Sussman and Bathe, 1987).

We used the ADINA finite element software together with our own codes for preprocessing and generating transition elements. The cylindrical model had 836 plane strain, isoparametric elements and 1824 nodes. The semi-infinite model had 10859 nodes and 3190 elements. Depending on the model size, we used either a DEC3100 workstation or the MIT CRAY X-MP supercomputer.

Results

The surface deflection of the fingerpad under a known loading provides a clue to infer the mechanical nature of its constituent materials. We therefore compared the experimentally observed surface deflection profiles of monkey and human fingerpads under 1 mm indentation by a single line load with the corresponding predictions of each of the models. As explained earlier and shown in Figure 2, the Boussinesq solution does not match the experimental data points, whereas the waterbed model does predict the observed profile quite well. It should be noted that both of these analytical solutions have as a free parameter the horizontal distance from the load to the point where the deformed surface profile crosses the undeformed profile. In Figure 2, this distance has been chosen for both the models to be the same as the one observed in the experiments. Also shown in the figure are the profiles predicted by the four finite element models. In each of these profiles the kink observed near the load is a numerical artifact and should be ignored. It occurred closer to the load as we reduced the element size, due to the singular nature of the concentrated load coupled with the plane strain assumption. An appropriate choice of the free parameter in the Boussinesq solution, different from the one shown in figure 2, matched the analytical and numerical profiles for the semi-infinite medium quite well. It can be seen that the profiles for the semi-infinite and finite flat models are close together, as are those for the cylinder with and without the bone. If the vertical deflection, say at 2 mm from the load, is taken as a measure of the overall compliance of the models, then the four finite element models in increasing order of stiffness are the finite flat, semi-infinite, cylinder and cylinder with bone. It is clear from figure 2 that the models composed of homogeneous linear elastic medium do not predict the experimental profile as well as the inhomogeneous waterbed model.

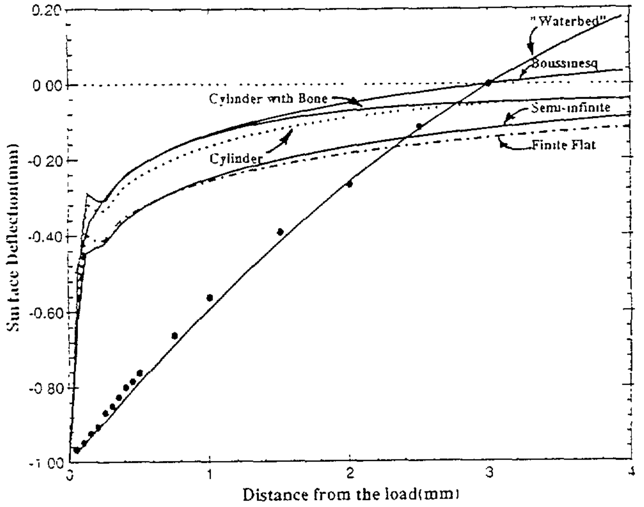


Figure 2: *Deflection profiles of the skin surface under a line load perpendicular to the model cross-sections shown in Fig. 1. Only half the profiles are shown due to symmetry. The experimental data points are the averages of the corresponding points on the left and the right side of a sharp wedge indenting a monkey fingerpad (Srinivasan, 1989).*

The subsurface stress or strain state in the skin, especially at the mechanoreceptor locations, is of fundamental importance in the neural coding of stimuli contacting the skin surface. Since the emission of neural impulses by the receptors is due to the opening of ionic channels caused by mechanical strains, the state of strain is considered important in predicting the receptor response. The question then is which strain component or combination is the relevant stimulus for each class of mechanoreceptors. Shown in figure 3 are three possible candidates, each evaluated using the cylinder model at three depths in the region where the receptors are known to be located. For each of the components, the deeper the location, more blurred is the spatial distribution. This illustrates the spatial low-pass filtering of the elastic medium and shows that the quality of mechanical information about the spatial variation of the surface stimulus decreases with depth of receptor locations. The distinct differences in the three component distributions indicates that if a fine enough probe (say 0.2 mm dia) is used in neurophysiological experiments, the spatial response profiles of the receptors might enable the determination of the relevant stimulus for each class of receptors. It should be noted that the stresses corresponding to the strain measures shown here are similar in form, and the rest of the stress and strain components have not been shown due to lack of space as well as the lack of their promise as relevant stimuli for the receptor response. For the three other models described in this paper, the magnitudes of the stress and strain state at a given location are different, but the general spatial profile of each component is approximately the same as the corresponding one for the cylinder.

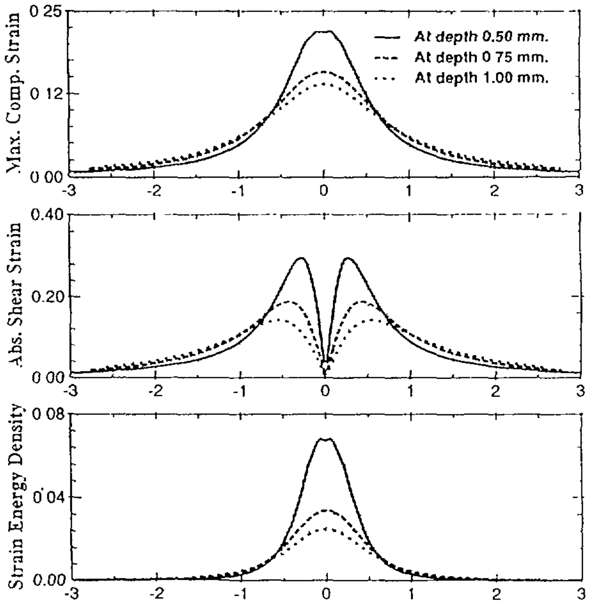
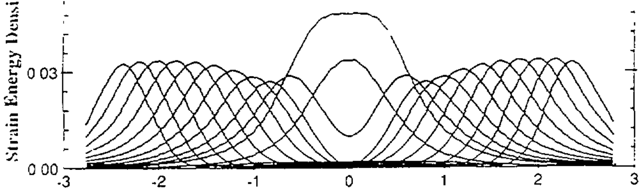


Figure 3: *Spatial distribution of sub-surface strain measures under a line load applied normally to the cylinder model. Distributions are calculated at three possible depths from the surface in the region where mechanoreceptors are typically located.*

The spatial resolution of the tactile sensory system is usually tested by stimulating the skin with two sharp probes at variable distances apart. In order to investigate the biomechanical basis of such a test, we analyzed the cylindrical model subjected to two equal line loads at successively increasing distances apart. Two loading conditions were studied: Prescribed displacements or forces, each of which were maintained constant for all the load spacings. The corresponding strain energy density distributions are shown in Figure 4, such that for the single load (i.e, zero spacing) the solutions are identical in (a) and (b). In the prescribed displacement case, as the load spacing increases from zero, the peak value of strain energy density increases at first, then decreases sharply, followed by a gradual increase till it attains a steady value. On the other hand, in the prescribed force case, the peak value monotonically decreases and settles down to a steady value at a load spacing much smaller than the corresponding one in the prescribed displacement case. The explanation for the difference stems from the fact that surface displacement due to each load spreads much wider than the corresponding sub-surface strain energy distribution. An implication to the neural coding of two-point stimuli is that when the loads are more than about 1.5 mm apart, the discrimination between two load pairs may be based on intensity information in the case when displacements are kept the same for the pairs, but is based on purely spatial information when forces are kept the same.

A question of considerable interest in the study of human tactile sense is the mechanism by which shapes of objects are perceived. We studied the biomechanical aspects of this issue for the case of indentations by a long bar of rectangular cross-section. The results for the four models indented to a depth of 1 mm by a 1.5 mm wide bar are shown in figure 5. For each model, the intensity of the surface pressure is very high under the edge of the bar, relative to the pressure at the center of the bar. The spatial distribution of the three strain measures shown are essentially low-pass filtered versions of the surface pressure distribution. The

(a) Prescribed Displacement



(b) Prescribed Force

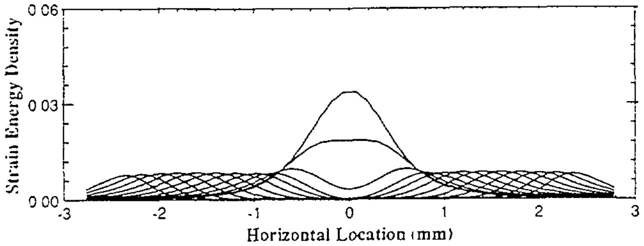


Figure 4: *Spatial distribution of strain energy density for a pair of equal vertical line loads applied on the cylinder and spaced at variable distances apart. (a) Prescribed displacement: the depth of indentation under each load is kept constant for the succession of load spacings. (b) Prescribed force: each force is kept constant for the succession of load spacings. The traces for the single load case (in zero load spacing) are identical in (a) and (b).*

extent of the filtering depends on the model as well as the particular strain measure. For example, among the models, all the strain measures for the finite flat case have superior contrast between the edges and the center of the bar, and absolute shear strain has the best contrast among the strain measures for each model. Therefore, if a robot tactile sensing system needs to be designed to detect edges, the models predict that the best performance would be achieved by shear strain sensors. In the case of primate tactile sense, by identifying the best match between the receptor spatial response profile and the distribution of a strain measure, Phillips and Johnson (1981) concluded that maximum compressive strain was the relevant stimulus for the steady response of slowly adapting mechanoreceptors. Our studies, part of which are described here, show that strain energy density might be a better candidate. Further improvements in modeling as well as additional biomechanical and neurophysiological data are needed to resolve this issue.

Conclusions

Understanding the mechanisms by which human sense of touch operates requires a study of the mechanics of skin and subcutaneous tissues. In this paper a sequence of mechanistic models of the primate fingertip under plane strain conditions have been analyzed using the finite element method. It is shown that in spite of radical differences in model geometry, surface deflection profiles of models containing homogeneous linear elastic media do not match the experimentally observed ones under line loads. On the other hand, the inhomogeneous "waterbed" model performs very well. In the models, the spatial distribution of the sub-surface stress or strain measures are blurred versions of the surface pressure distributions, due to the low-pass filtering of mechanical signals by elastic medium. The severity of filtering depends on both the model and the particular measure of interest. The matching of the spatial distribution of strain measures and the corresponding experimentally recorded receptor spatial response profiles provides a means by which the relevant mechanical signal transduced by each class of mechanoreceptors can be inferred. It is likely that to match both the surface deflection and receptor response profiles, a thick elastic layer supported by an incompressible fluid is needed.

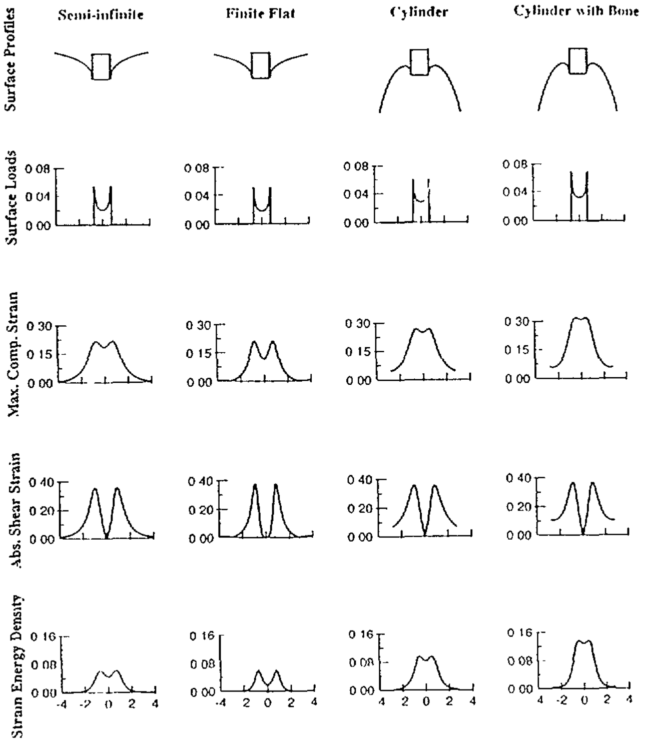


Figure 5: *Vertical indentation of each model by a 1.5 mm wide rectangular bar to a depth of 1 mm. Calculated spatial distributions of surface deflection and contact pressure, as well as maximum compressive strain, absolute value of shear strain and strain energy density at 0.75 mm depth are shown.*

Acknowledgements

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References

[1] Danielson, D. A., "Human skin as an elastic membrane", *J Biomechanics*, Vol 6 pp 539-546, 1973.

[2] Fung, Y C, "*Biomechanics*", Springer, New York, 1981

[3] Lanir, Y, "Skin Mechanics", *Handbook of Bioengineering*, eds: Skalak, R and Chien, S, McGraw-Hill, pp 11 1-11 25, 1987

[4] Lanir, Y, Dikstein, S, Hartzshtark, A and Manny, V, "In-vivo indentation of human skin", *J of Biomechanical Eng*, Vol 112, pp 63-69, 1990

[5] Phillips J R, and Johnson, K O, "Tactile spatial resolution III A continuum mechanics model of skin predicting mechanoreceptor response to bars edges and gratings" *J Neurophysiol*, Vol 46, No 6, pp 1204-1225, 1981

[6] Srinivasan, M A, "Surface Deflection of Primate Fingertip under Line Load", *J. Biomechanics*, Vol. 22, No 4, pp. 343-349 1989

[7] Srinivasan, M A, Gulati, R J, and Dandekar, K, " In vivo compressibility of the human fingerpad", Proc of Bioeng div of ASME, winter annual meeting, 1992

[8] Sussman, T. and Bathe, K J, "A finite element formulation for nonlinear incompressible elastic and inelastic analysis", *J Computers and Structures*, Vol 26, No 1/2, pp 357-409, 1987