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A 3 DIMENSIONAL FINITE ELEMENT MODEL OF THE MONKEY FINGERTIP FOR PREDICTING RESPONSES OF SLOWLY ADAPTING MECHANORECEPTORS

Kiran Dandekar
Mandayam A. Srinivasan
Department of Mechanical Engineering and
Research Laboratory of Electronics
Massachusetts Institute of Technology
Cambridge, Massachusetts

1 INTRODUCTION

The primary source of information in tactile sensing is the train of neural impulses emitted by the mechanoreceptors embedded in the skin. The impulse discharge rate in a nerve fiber is known to be related to the stress state around the corresponding receptors located at the nerve terminal. In order to better understand the mechanics of touch, it is necessary to establish a quantitative relationship between the stress state at a mechanoreceptor location and the neural response of the receptor to a given mechanical stimulus. Due to the subsurface location of the receptors and the opacity of the fingerpad, the stress state and deformations in the close vicinity of a receptor cannot be observed experimentally. Therefore, we have developed a 3 dimensional finite element model of the monkey fingerpad which can be used to predict the stress state at the receptor location for a variety of loadings applied on the surface of the fingerpad. In this paper, we demonstrate its ability to predict biomechanical and neurophysiological experimental data.

2 METHODS

The external geometry of the monkey fingertips was obtained from precise epoxy casts made using dental cement molds. These casts were extremely accurate in reproducing the finger print ridges, details of the nail and wrinkles on the skin. A videomicroscopy setup consisting of a monochrome CCD camera with zoom lenses, a frame grabber, and a 486 PC was used to acquire images of the casts in different orientations. A stepper motor was used to rotate the fingertip about an axis parallel to the bone axis in 1° steps, and an image was grabbed at each step. The boundary of the fingertip in an image frame essentially represented the orthographic projection of the fingertip for that particular orientation. These 2D sections were imported into a solid modeler software (PATRAN) and a 3D model of the fingertip with realistic external geometry was generated. The relative thickness of the bone in the distal phalanx was determined from X-ray images and a concentric bone was generated inside the fingertip. To account for the several layers of skin and the adipose tissue underneath (Darian-Smith, 1984), the mesh was generated in layers such that each layer could be assigned a distinct material property and mechanistic constitutive behavior. The material of each layer was treated as linear isotropic and the innermost layer was made several orders of magnitude stiffer than all the other layers to simulate the rigid behavior of the bone. Two models with 8 and 20 noded isoparametric elements were generated and the number of nodes in the two models were 8500 and 17,000 respectively. The typical diameter of the fingertips was approximately 8 mm and element size in the region of contact with indentors was approximately 500 microns and 250 microns respectively.

3 RESULTS

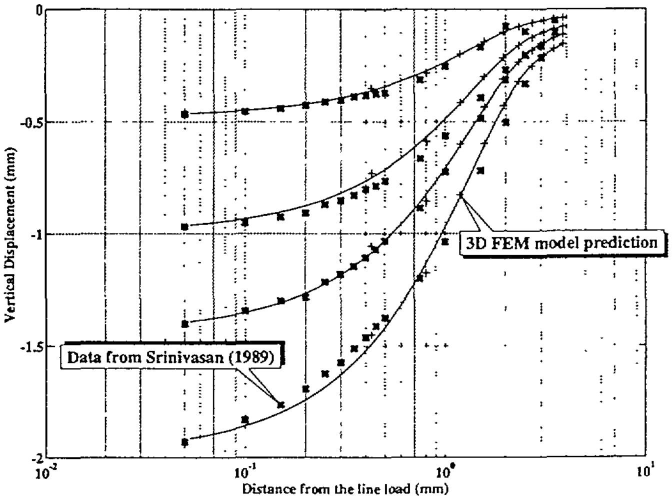

FIGURE 1

Our previous attempts at modeling the primate fingertip consisted of using 2D models to simulate an axial crosssection of the fingertip (Srinivasan and Dandekar, 1994). These models were fairly accurate in predicting the spatial neural response of the mechanoreceptors to indentations by aperiodic gratings, but failed to match the experimentally observed surface deflection profile of the fingertip under a line load. All the 2D models showed a very local deformation pattern characteristic of an elastic material, which was in sharp contrast with the experimentally observed deformation profiles which were wider. Figure 1 shows the predictions of the 3D model compared with the experimentally observed data from Srinivasan (1989). The model used had three distinct layers and the outer layer simulating the skin, was an order of magnitude stiffer than the middle layer simulating adipose tissues and three orders of magnitude less stiff than the innermost layer that simulated the bone. It should be noted that only the *ratio* of the stiffnesses among the layers governs the displacement profile in a finite element problem with prescribed displacements (Srinivasan and Dandekar, 1994).

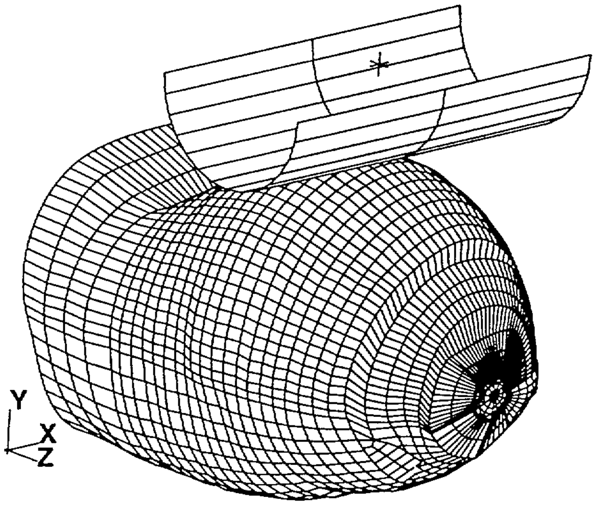

FIGURE 2

Srinivasan and LaMotte (1991) have shown that slowly adapting mechanoreceptors respond to the curvature of the object contacting the fingerpad. In one of their experiments, monkey fingertips, with the fingernail glued to the table, were indented with cylinders of varying curvatures and the responses of single afferent neural fibers to a constant force of indentation were recorded. Figure 2 shows the simulation of the same experiment performed using the three dimensional model of the monkey fingerpad. The boundary conditions in the finite element analyisis were modeled by fixing all the degrees of freedom on the nail. The indentor was treated as a rigid surface and the overall force was controlled and maintained constant in indentations by all the cylinders. Each indentation consisted of a sequence of incremental steps and the contact problem was solved using finite deformation formulation for every step using the ABAQUS finite element software.

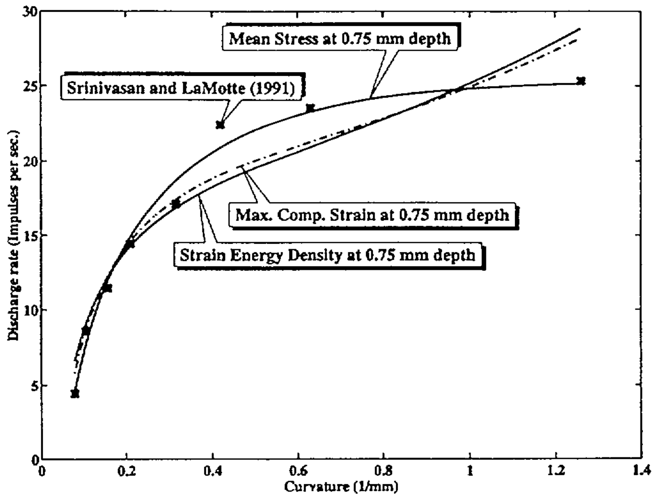

FIGURE 3

Various stress and strain measures calculated at the receptor locations were compared with the recorded SA neural discharge rate from LaMotte and Srinivasan (1991). Our previous work (Srinivasan and Dandekar, 1994) has shown that strain energy density and maximum compressive strain are the strain measures are linearly related to the SA responses, and therefore, are the leading contenders to be the *relevant stimulus* of the SA receptors. Figure 3 shows the comparison of the experimentally recorded steady state SA discharge rate and three measures of calculated stress state at a typical receptor location, 0.75 mm below the skin surface. The excellent fit between the experimental and calculated data supports the validity of the model. Although the mean stress provided the best fit, similar comparisons over a larger set of diverse stimuli are necessary for further verification of the model and the relevant stimulus.

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