

## TACTILE CODING OF OBJECT CURVATURE BY SLOWLY ADAPTING MECHANORECEPTORS

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### INTRODUCTION

While exploring a rigid object with the hand, the tactile perception of its shape remains constant despite moderate changes in orientation, velocity and direction of motion of the fingerpads, as well as variations in the contact forces exerted against the surface of the object. Based on data from electrophysiological recordings of responses from single mechanoreceptive afferent nerve fibers in monkeys, it has been hypothesized that slowly adapting mechanoreceptors (SA) in the skin encode the changes in the curvature of the skin within the regions of contact with the object (Srinivasan and LaMotte, 1991; LaMotte and Srinivasan, 1993). An implication is that the brain has direct access to the object shape as a distribution of curvatures within each contact region, and with multiple contacts we can infer the shape of the object independent of changes in the physical variables affecting contact conditions.

In this study, we have investigated the relationship between the biomechanics of primate fingertip and the responses of SAs involved in the sensing of object curvature by using mechanistic models of the primate fingertip. Although the geometry and material properties of the primate fingertip are complex, previous work has shown that simplified mechanistic models can be quite successful. A model that viewed the whole fingerpad as a linear elastic and isotropic material predicted the neurophysiological data quite well (Phillips and Johnson, 1981), but failed to predict the observed skin surface deformations. In contrast, experimental measurements of fingerpad surface deformations under line loads correlated very well with the predictions by the 'waterbed' model that viewed the fingerpad as an elastic membrane enclosing an incompressible fluid (Srinivasan, 1989). But this model failed to predict the spatial variations in neural response owing to the uniform pressure exerted by the fluid on the membrane.

### METHODS

Following our earlier work (Srinivasan and Dandekar,

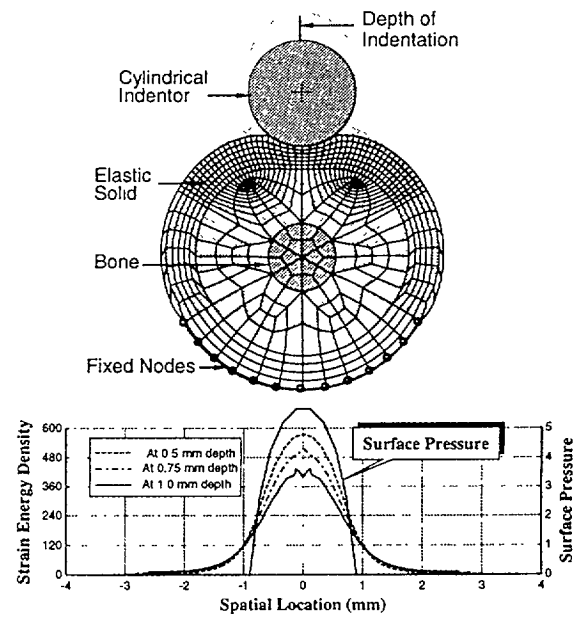


FIGURE 1

1992), we chose to analyze two plane strain models of circular cross-section (8 mm diameter). The first model consisted of a linear elastic and isotropic solid enclosing a central rigid bone of 2 mm diameter; the second model consisted of a 1 mm thick layer of the same solid enclosing an incompressible fluid. The nodes on the bottom third of the circumference, which correspond to the fingernail in the model, were constrained in all the degrees of freedom. The models were analyzed under constant force indentations by a series of cylinders whose diameters were the same as those used to record SA responses in previous neurophysiological experiments (Srinivasan and LaMotte, 1991). The contact mechanics problem was solved iteratively using the ABAQUS finite element software. For each cylinder, the pressure distribution and the width of contact region at the skin-cylinder

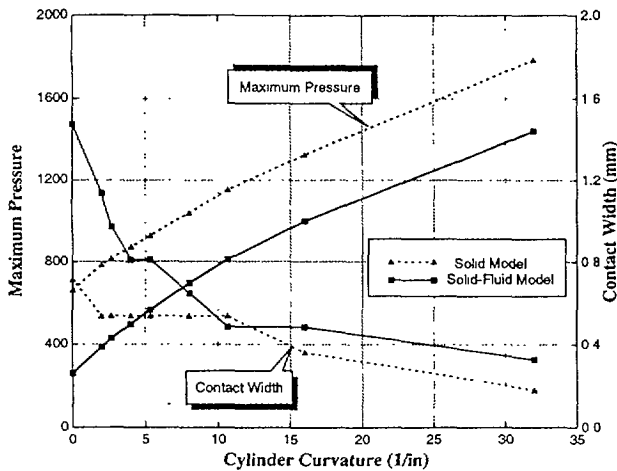


FIGURE 2

contact interface, as well as the stress and strain distributions at typical SA locations (0.5 to 1 mm below the skin surface) were calculated (Figure 1). Various calculated strain measures were then correlated with the previously recorded SA responses to infer the *relevant stimuli* for SAs, i.e., the strain measures that possibly trigger SA responses.

## RESULTS

To attain the prescribed force, each cylinder had to be indented to a higher depth in the solid-fluid model than in the solid model. The depth of indentation to achieve the prescribed force increased in proportion to the square root of the cylinder curvature for the solid model whereas there was no appreciable change for the solid-fluid model. For each cylinder, the solid model had higher maximum pressure than the solid-fluid model and consequently had smaller contact widths (Figure 2). The contact width decreased with increase in curvature, and the reduction was more rapid for the solid-fluid model. These results agree with the intuitive expectation that the solid model is much stiffer than the solid-fluid model.

In order to correlate the strain measures with the neural response data, a relation of the form  $I = a\epsilon + b$  was assumed, where  $I$  is the neural discharge rate in impulses per second, and  $\epsilon$  is the strain measure;  $a$  and  $b$  are constants across all the data points and represent, respectively, the sensitivity and response threshold of the receptor to  $\epsilon$ . Except for 1 mm depth in the solid-fluid model, all the strain measures in both the models correlated quite well with the neural discharge rate. The best matches at typical receptor locations from both models and all strain measures were absolute shear strain at 0.5 mm depth in the solid-fluid model together with strain energy density at 0.75 mm and absolute shear strain at 1.0 mm depths in the solid model (Figure 3).

Excellent correlations obtained in figure 3 and in pre-

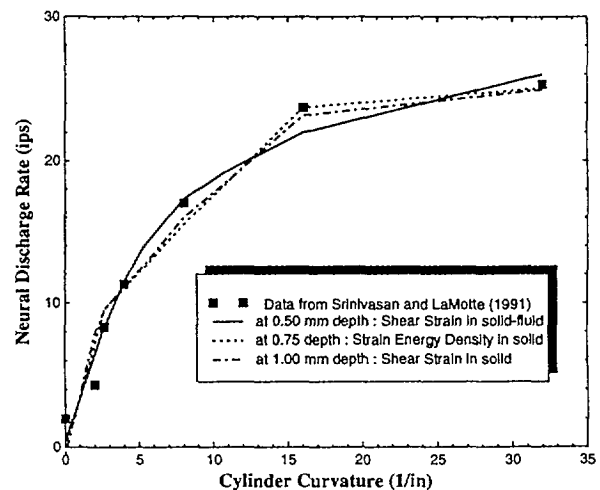


FIGURE 3

vious papers (Phillips and Johnson, 1981; Srinivasan and Dandekar, 1992) imply that (1) Use of simplified fingertip models is a fruitful approach (similar to approximating cornea, lens and vitreous body of the eye by a simple lens), and (2) mechanoreceptor electrophysiological response is directly related to strain measures at receptor locations. More biomechanical and neurophysiological experiments involving static and dynamic indentations with various shapes, as well as corresponding dynamic analysis using the finite element models are required to fully explore the role of mechanoreceptors in the tactile recognition of shapes.

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