

Study on Three-dimensional Configuration of Dermal Papillae: Effects on Meissner Corpuscles

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Abstract— Finite Element Method (FEM) analysis is widely used for micro-scale studies on mechanoreceptors. Previous studies primarily used two-dimensional (2D) models of the fingertip cross-sections vertical to fingerprint ridges including dermal papillae. Their results suggested that the 2D configuration of dermal papillae largely affects the stress concentration at the base of them where Merkel cells distribute. Oppositely, they barely affect Meissner corpuscles which are located at the tip of dermal papillae. Although these 2D models assume that the structure of dermal papillae is even in the third direction along fingerprint ridges, it is uneven in reality. This paper focuses on the effect of this unevenness of dermal papillae. Two types of 3D models are used. One is a model that is even along fingerprint ridges as is the case with 2D models, and the other is uneven as is the case with the real skin. This uneven model demonstrates the concentration of stress at the tip of dermal papillae. This result indicates that dermal papillae possibly enhance the response of FA-I, which is associated with Meissner corpuscles.

I. INTRODUCTION

The relationship between mechanoreceptors (i.e. Merkel cells, Meissner corpuscles, Pacini corpuscles, and Ruffini endings) and surrounding environment is still one of open issues in haptics research. Maeno et.al [1] used a 2D FEM model of cross-sectioned fingertip involving both fingerprint ridges and dermal papillae. Dermal papillae are the concavo-convex structure between epidermis and dermis, which is adjacent to both Merkel cells and Meissner corpuscles. With this structure, stress is focused at the positions of Merkel cells [2]. Even though Merkel cells and Meissner corpuscles share the common environment, Maeno's result indicates that this environment barely affects Meissner corpuscles while it largely affects Merkel cells.

It is worthwhile to point out that this 2D FEM model does not precisely duplicate the real skin microstructure because of an assumption that the structure of dermal papillae is even in the third direction along fingerprint ridges. Unlike this, the real structure of dermal papillae is also concavo-convex, i.e. uneven, in the third direction. Cauna [3] observed this structure by microscopy. This uneven structure may also affect mechanoreceptors.

In this study, we examine whether this unevenness has any function. We use two of 3D FEM models. One model has an even structure of dermal papillae and the other has an

uneven structure (hereafter, “2D” and “3D” models, respectively).

II. 3D FEM MODELS

Both of “2D” and “3D” models are multi-layered including epidermis, dermis, and subcutaneous tissue (Fig. 1). The Young's moduli are 0.136 MPa, 0.08 MPa, and 0.034 MPa, respectively. Poisson's ratio is 0.48 for all the layers. These material parameters are based on [1]. The size parameters are same for both models as shown in Fig. 1. Each model contains 6 fingerprint ridges and 12 dermal papillae. The “2D” model is a representation of the assumption of 2D FEM model in a 3D space. Its dermal papillae are designed as trapezoid apexes in the front cross-section and even in the side cross-section (Fig. 2 (a)). The “3D” model has an additional concave-convex structure in the side cross-section (Fig. 2 (b)). Its height is 0.15mm, which is equivalent to the average length of Meissner corpuscles in human skins.

A square plate indenter ($0.88 \times 0.88 \text{ mm}^2$) is applied to the surface of the FEM models without friction. This indenter is a rigid body. Its vertical displacement is a control parameter.

III. RESULTS AND DISCUSSION

Figure 3 shows typical examples of the distribution of Von-Mises stress at the apexes of dermal papillae (top view). The displacement of the indenter is 1 mm. The white dashed square represents the indenter. While the colors from blue to red in the scale bar represent the stress up to 0.008 MPa, gray means the stress over that value. In the “2D” model, the stress concentrates at the corners of the indenter and also diffuses outside of the area of the indenter. On the other hand, in the “3D” model, the gray area is decreased inside the indenter and less stress is observed outside the indenter, which means that the stress is more evenly distributed within the area of the indenter. The peak stress values are along the fingerprint ridges at the edges of the indenter.

Figure 4 shows the stress distributions sensed by Meissner corpuscles. The stress values are sampled at the apexes of the dermal papillae in the “3D” model and the same positions are assumed in the “2D” model. The vertical axis presents the Von-Mises stress. The horizontal axes present the spatial coordinates parallel to the skin surface. While four local maximum points are observed in the “2D” model, two local maximum lines are observed in the “3D” model. These points and lines imply the shape of the indenter. The ratio of the minimum to the maximum within the area of the indenter is lower in the “3D” model (32%) than that of the “2D” model (47%).

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In short, the 3D configuration of dermal papillae effectively distributes stress among the apices. The peak stress points shape a relatively continuous line that is along the edges of the indenter. On the other hand, the “2D” model shows that the stress is focused at the corners of the indenter and blurred around the area of the indenter. These characteristics of the 3D configuration of dermal papillae may (1) increase the FA-I population response and (2) possibly shape discrimination ability. In future work, we examine other conditions such as different relative positions/orientations of the indenter.

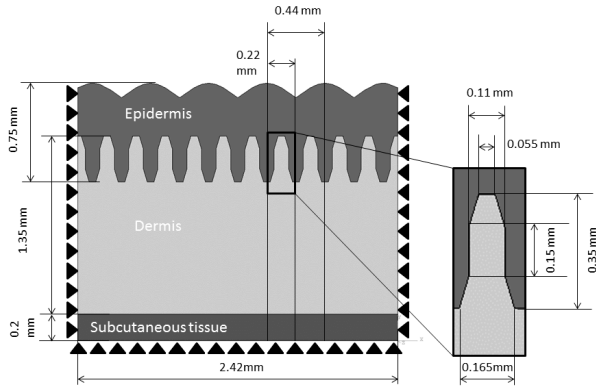


Figure 1 Exterior measurement of models. Inset: measurement of one unit of dermal papilla. The black triangles present that the normal displacement is constrained. This constraint is also applied in depth dimension.

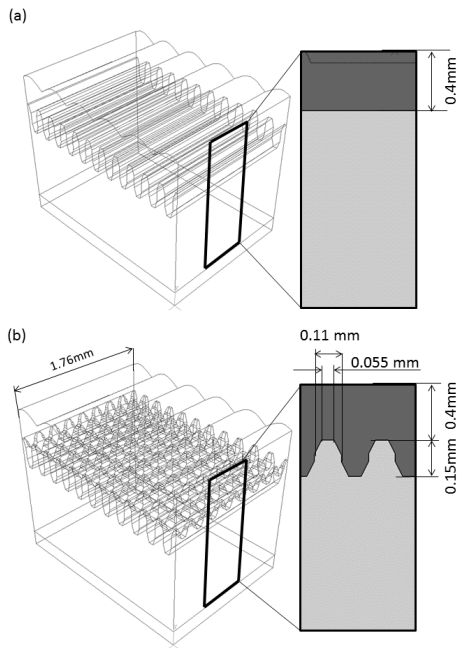
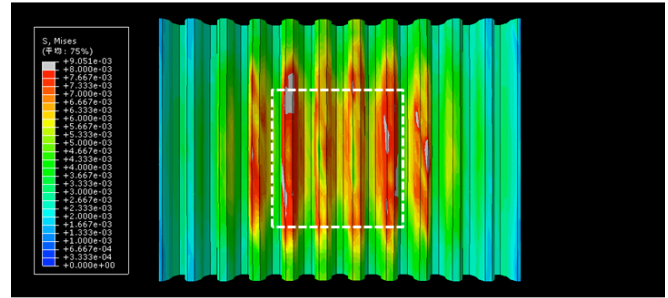


Figure 2 Configuration in the side cross-section of (a) the “2D” model and (b) the “3D” model. The apices of dermal papillae have the same trapezoid structure as the front cross-section.

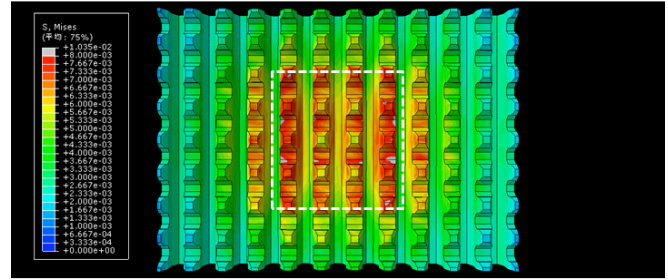
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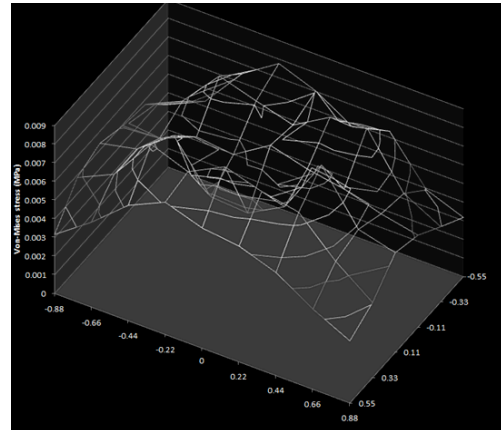


(a)

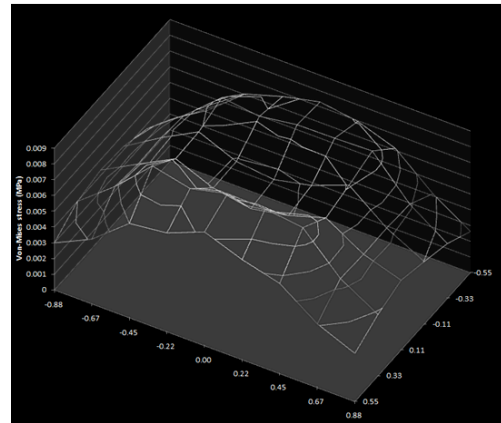


(b)

Figure 3 Distribution map of Von-Mises stress at apices of dermal papillae in (a) the “2D” model and (b) the “3D” model. The white square represents the area of the indenter.



(a)



(b)

Figure 4 The stress-distribution plots of (a) the “2D” model and (b) the “3D” model.