Can OCT Imaging and FE Simulations Help Us Tackling Fingertip Micromechanics?

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Abstract. Despite advancements in imaging techniques, it remains challenging to interpret OCT observations of deeper skin layers under the fingertip surface, even more so when digital image correlation (DIC) aims to analyze deformations near tactile mechanoreceptors. In this work, a novel approach is adopted allowing us to connect OCT imagery to 2D finite element (FE) simulations of the deformation of the fingertip cutaneous tissues under tangential loading scenarios. Numerical predictions help deduce local stresses in the stratum corneum and viable epidermis from the experimental measurements of the average in-plane strain. Questions remain however about deformations in the direction perpendicular to OCT scans, which motivate ongoing efforts to collect 3D OCT data. Ultimately, this interdisciplinary approach holds the potential for unraveling the complexities of tactile perception and enhancing our understanding of touch at the micro-scale.

Keywords: OCT, DIC, FEM, Touch, Micro.

1 Introduction

Touch originates from subcutaneous sensory units called mechanoreceptors [1]. These units, whose density is highest at the fingertip, detect skin deformation when touching objects. Although the macroscopic deformation of the fingertip has already been extensively studied [2], less is known about deformation at the scale of the mechanoreceptors. Optical coherence tomography (OCT), an optical imaging technique relying on low-coherence interferometry, allows in-vivo observation of the micro-scale layered structure of the fingertip cutaneous tissues [3]. Nevertheless, the strains developing in the vicinity of biological sensors remain unclear. Indeed, although OCT generates high image quality of the outermost skin layer (i.e., the stratum corneum), the image's noise level increases rapidly when probing deeper layers, where the mechanoreceptors are located. This complicates the estimation of the strain field by digital image correlation (DIC).

The finite element (FE) method has enabled realistic reproduction of the behavior of the fingertip under normal load [4]. Hence, the interpretation of OCT images of the fingertip could be eased based on the prediction of local stresses using FE modeling of the micro-structure of the fingertip.

This study proposes an original strategy to couple OCT imaging and 2D FE modeling of the fingertip during tangential loading.

2 Description of the approach

OCT images of a fingertip in contact with a flat glass plate under ~0.5N normal load were re-analyzed from [3] (Fig. 1(a)). During contact, the plate moved in the distal/proximal direction until full slip occurred, before a similar motion was imposed in the reverse direction. Due to the limitations of OCT, segmentation of the viable epidermis (VED) was achieved only for selected frames, whereas the stratum corneum segmentation was always successful. Consequently, only the SC innermost and outermost boundaries, defined by two sets of points $p_i = (x_i, y_i)$, were tracked between successive frames using a linear mapping (Fig. 1 (b)). The mapping allowed us to characterize the average deformation of the whole image and is described by the following equation:

$$\begin{aligned} \hat{x}_{i,t+1} &= F_{11} x_{i,t} + F_{12} y_{i,t} + \Delta x \\ \hat{y}_{i,t+1} &= F_{21} x_{i,t} + F_{22} y_{i,t} + \Delta y \end{aligned} \tag{1}$$

Where $(\Delta x, \Delta y)$ are variables introduced to account for the displacement of the origin of the coordinate system in successive frames. This shift and the components of the deformation gradient $(F_{11}, F_{12}, F_{21}, F_{22})$ are determined by least square fitting.

A 2D FE model was built, replicating the segmented geometry. The skin was modeled as an incompressible hyperelastic material comprising three layers with different stiffness. The mesh was subjected to generalized plane strain and the displacement of the edges was prescribed affinely, using the average deformation deduced from the experimental observations.

3 Preliminary results and conclusions

Fig. 1(c) shows the evolution of the average deformation gradient throughout the loading for the SC. The results are promising as the two phases of the tangential loading (i.e. the right-to-left and left-to-right motions of the plate) can be seen in the evolution of the shear parameter F_{12}. Preliminary predictions of the 2D FE model can be seen in Fig. 1(d). Important stress heterogeneity was developed within the tissue. Further analysis of the OCT images will be performed to determine the best assumption for the out-of-plane behavior.

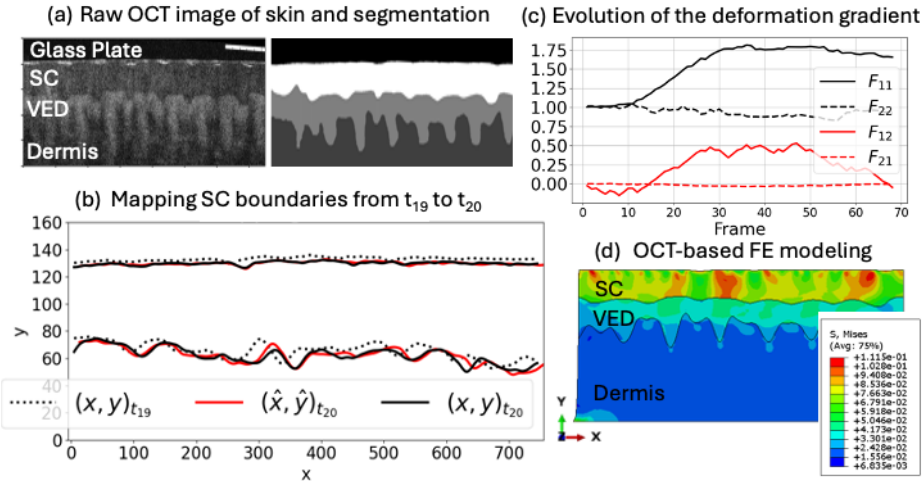

Fig. 1. (a) OCT image of a fingertip's skin loaded against a flat plate and its segmentation; (b) Linear mapping between successive frames; (c) Evolution of the deformation gradient throughout the tangential loading; (d) FE prediction of the heterogeneity of von Mises stress.

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