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MATERIAL MODELING OF HUMAN BREAST FOR FINITE ELEMENT BASED APPROACHES IN BIOMECHANICS

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SUMMARY

Finite Element Analysis (FEA) showed reliability of computational mechanics for the estimation of organ motion. However, there are still open questions about material modeling. The importance of the adoption of appropriate material models to investigate human breast biomechanics is underestimated. The goal of this work is to demonstrate the importance of material constitutive laws approximations in human breast Finite Element (FE) based models. Linear elastic material models are inappropriate to predict breast displacement. In this work, material models employed in a simple FE model of human breast, undergoing large deformations due to gravity effect, are analyzed. An hemispherical geometry with a spherical inclusion is used to model the human breast shape. Different material models are investigated to accurately model changes in terms of displacement, stress, reaction forces magnitude and distribution. Results clearly show that material modeling influences strongly the accuracy of FE models simulating large deformations of human breast.

INTRODUCTION

Finite Element Methods (FEMs) are employed to determine deformations or stresses in human structures such as bones, tendons, and breasts [1,2,3]. Authors have employed different material models in their attempt to model the human breast biomechanics [4,5,6,7]. Reviewing data given by studies aiming to characterize human breast material behavior using identical constitutive laws [4,8], discrepancies are evident. Moreover, different conclusions have been drawn about the accuracy of linear elastic material models modeling large deformations of human breast. Tanner et a. [9] evaluated the factors that influence the breast model accuracy in a controlled clinical situation where the organ boundaries are reasonably accurately known but some uncertainty exists about the tissue's mechanical properties. Whiteley et al. [10] compared linear elastic and pseudo-nonlinear modeling approaches for a full nonlinear elastic tissue problem that has an exponential stress-strain relationship. Both studies dealt with FE modeling of human breast tissue but the conclusion drawn are largely different. Tanner et al. [9] stated that material properties do not affect the accuracy of a biomechanical, FE based, human breast model. Contrarily, Whiteley et al. [10] assessed that simple material models are not appropriate even in the case of modeling deformations of the human breast under gravity. These studies are not conclusive. Indeed, ambiguity remains about the correct weighting factor influencing the accuracy of a FE model of an organ characterized by a soft tissue such as the human breast. The aim of this study is to clarify the role of material properties in FE modeling of human breast undergoing large deformations.

METHODS

In this study, linear, pseudo-nonlinear, and nonlinear (neo-Hookean and Mooney-Rivlin) material models are investigated. The material models are supposed to be: homogeneous, isotropic, and incompressible.

Linear Elastic Material Model – It is written according to the Cauchy generalized Hooke's law [11]:

$$\sigma = C \cdot \varepsilon \quad (1)$$

where, σ is the Cauchy stress tensor, C is the stiffness or elastic tensor, and ε is the strain tensor.

Pseudo-nonlinear Material Model – It is in the form:

$$E_Y = \frac{\partial \sigma}{\partial \varepsilon} = \sum_{i=0}^{n} c_i \varepsilon^i \quad (2)$$

where, the Young's modulus E_Y is defined as the gradient of the stress-strain (σ-ε) curve for uniaxial tension, and an exponential relationship is assumed where c_i are constants, and n is the order of the polynomial.

Nonlinear Matarial Models – Hyperelastic models are modeled according to Neo-Hoolean and Mooney-Rivlin (5 parameters) constitutive laws, respectively defined, according to the strain energy density function:

$$\psi = c_1(\overline{I}_1 - 3) \qquad \text{(Neo-Hookean)} \quad (3)$$

$$\psi = \sum_{i+j=1}^{N} c_{ij}(\overline{I}_1 - 3)^i(\overline{I}_2 - 3)^j \qquad \text{(Mooney-Rivlin, N=2)} \quad (4)$$

where, Ψ is the strain energy density function, $\bar{I}_1$ and $\bar{I}_2$ are the first and the second invariants of the deviatoric component of the left-Cauchy-Green deformation tensor [7], and c_{ij} are material constants.

As the complexity of the above mentioned mathematical formulations influences the accuracy of a FE breast model has not been completely investigated yet. In this study. hyperelastic material models and their linear and pseudo-nonlinear approximation are evaluated.

The geometric model employed has been proposed by [10]. It is characterized by an outer hemispherical part representing the fat ti ssue and an inner spherical part modeling the fibroglandular tissue. The hemisphere is fixed at its basis.

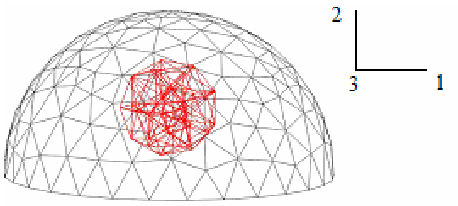

Figure I: Geometric representation of the human breast: a spherical inclusion (fibroglandular tissues) is encompassed in a hemisphere (fat tissue).

The employed material models are that ones used by [9]. Three different typologies have been analyzed: linear elastic L1 Eq.(1), pseudo-nonlinear NL1, NL2 Eq.(2), and hyperelastic nH1, nH2, and nH3 defined by Eq.(3) and MR1, and MR2 r eferring to Eq.(4). The proposed FE model is validated by comparing results provided by the model proposed by [10] based on Veronda & Westmann's strain energy density function material constitutive law:

$$\psi = a(e^{b(\bar{I}_1 - 3)} - 1) \qquad (5)$$

where, Ψ is the strain energy function, $\bar{I}_I$ is the first deviatoric strain invariant, and a and b are material constants. The maximum error obtained, comparing the model with the same provided by [10] is 7.7%.

RESULTS AND DISCUSSION

The differences between the Neo-Hookean model nH1 Eq.(3) and its elastic linear model approximation L1 Eq.(1), and the pseudo-nonlinear models NL1, NL2 Eq.(2) and their Neo-Hookean nH2, nH3 Eq.(3) and Mooney Rivlin, MR2 and MR3 Eq.(4), approximations, applying a gravity load, in the three directions $U_1(1,0,0)$, $U_2(0,1,0)$ and $U_2(0,-1,0)$ are calculated. One can notice the differences between the Neo-Hookean model nH1 and the elastic linear model L1 only for the application of the gravity load in the direction $U_2(0,-1,0)$. For the direction $U_1(1,0,0)$ and $U_2(0,1,0)$ the numerical solver do not converge, the model being unstable due to the excessive distortion of the mesh. Taking into account the cases for which the simulations converged, it is possible to notice that approximating a Neo-Hookean model with its linear expression leads to changes in displacements at leas t of 20.0%, much more than 0.5% as stated by Tanner et al. in [9]. Larger changes may be highlighted between the pseudo-nonlinear model NL2 and the Neo-Hookean model nH3. For the material models NL2 and MR2 the differences may be more than 40.0%. The most critical situation occur for the directions $U_1(1,0,0)$ and $U_2(0,-1,0)$. For the latter, the discrepancy between the models L1 and nH1 is evident. Only for the d irection $U_2(0,-1,0)$ there seems to be a good approximation. The explanation could be linked to the boundary conditions. In fact, for the case $U_2(0,-1,0)$ the gravity load is applied in the direction of t he geometrical constraint, which means that the displacement of the geometry is more limited. Assuming the hemisphere basis as directly matched with the pectoralis fascia, it is interesting to evaluate the magnitude of the reaction forces in that area. The distribution of the reaction forces values are calculated. Applying a gravity load in direction $U_2(0,-1,0)$ the maximum reaction force value employing a Neo-Hookean material model (nH1) is 865.956E-3 (MPa). Using its linear elastic approximation (L1), the maximum value for the linear model is 523.624E-3 (MPa) (less than 65%).
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CONCLUSIONS

This study evaluated the impact of different material models on the FE modeling of a simplified 3D geometric representation of the human breast shape (Figure I). The geometrical model refers to the study c onducted by Whiteley et al. [10] while the implemented material models refer to the work of Tanner et al. [9]. The u se of the material models of Tanner et al. [9] allowed the understanding of the impact of the errors in FE analysis due to material modeling of soft biological tissues. The results confirmed the assumption made by Whiteley et al. [10] that material models are very important for human breast FE material modeling. The approximation of nonlinear material models, such as Neo-Hookean and Mooney-Rivlin hyperelastic models, with their linear or pseudo-nonlinear approximation is not a suitable solution. The lack of accuracy is very high. Moreover, hyperelastic material models showed differences between them approximating a pseudo-nonlinear one. In con clusion, this study showed that the use of m aterial models is o f primary importance for FE models of organs, such as the breast. Hence, innovative techniques for the characterization of b iological materials, particularly, soft tissues, should be investigated.

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