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Mechanical model of the breast for the prediction of deformation during imaging

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ABSTRACT

To predict changes in the shape of the breast in different imaging devices, a Coupled Eulerian–Lagrangian (CEL) mechanical model is developed. The CEL method allows for a more adequate representation of the very large deformations experienced by the soft and incompressible tissues of the breast. The mechanical response of the tissues is based on advanced mathematical formulations and experimental data from the literature. Realistic geometries generated from Magnetic Resonance (MR) images are used as study cases. Furthermore, specific boundary conditions are applied to the model to predict the shape of the breast and the location of the internal tissues in a prototype microwave breast imaging system, where an immersion medium is used. The accuracy of the model was assessed by comparing the numerical results with a laser scan of the same subject in the microwave breast imaging system.

1. Introduction

Breast imaging is essential for screening and early diagnosis of lesions. As discussed in Kopans [1], several imaging modalities are used in clinical settings and the breast orientation and positioning procedures differ between the various modalities. This makes comparison across modalities a challenging task, which occurs clinically when patient care involves imaging with several techniques. When new methods are introduced, validation and comparison with gold standard approaches is also challenging due to variations in breast position. For example, X-ray mammography involves compressing the breast between two parallel plates and collecting 2D images at two different acquisition angles. Another example is Magnetic Resonance Imaging (MRI), where the patient lies prone with her breasts extending into a specifically designed coil. The shape of the breasts is therefore dictated by the gravity load and by any contact between the breast and the coil. At the University of Calgary, a microwave breast imaging system, termed Tissue Sensing Adaptive Radar (TSAR) is under development [2]. As shown in Fig. 1, the patient lies prone on the examination table with one breast extending through a hole and into a tank containing canola oil. An initial patient study has been completed with TSAR, and correlation of TSAR images with MRI images collected from the same patient has proven to be challenging due to the differences in breast shape in the MR and TSAR scanners. Patient-specific models that may be numerically simulated to reflect different imaging procedures are of interest to interpret information from this new imaging modality.

The deformations of the breast during procedures involving imaging have been previously investigated using Finite Element analysis. Modelling breast deformations is a challenging problem due to the anatomical complexity, and uncertainties regarding reliability of biomechanical breast models have been discussed [3]. Several studies have reported development of breast models with simplifications such as a homogeneous interior [4–6], while relatively few report models including details of the breast interior. Azar et al. [7] built a realistic breast model from MR data to track lesions during biopsy. The MR scan was segmented semi-manually and included fibro-glandular tissues, adipose tissues and a lesion. The mechanical properties of the tissues were formulated as non-linear stress–strain curves. To mimic biopsy, the imposed displacements were dictated by the contact of two rigid plates compressing the breast model. To validate the model, two vitamin E pills were placed on the skin of the breast and used as landmarks to track their displacements during the compression procedure. The results indicated that lower compression lead to more

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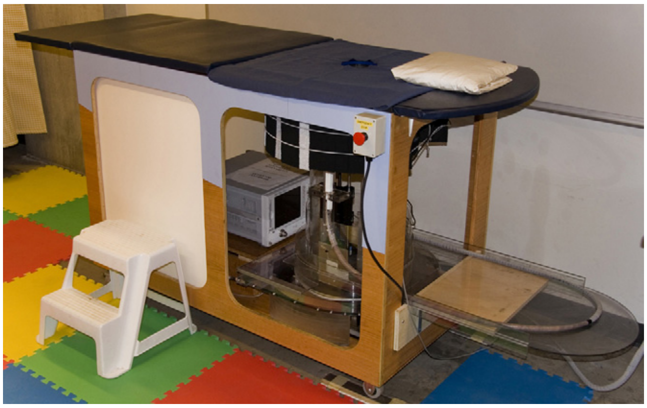

Fig. 1. The TSAR system prototype. The breast extends through the hole in the table top. A tank under the table (covered in black material) contains canola oil and the sensors of interest.

Figure adapted from [2].

accurate results, as fewer errors were induced by the collapse of the elements representing fat. Samani et al. [8] also reported a realistic model and generated the meshes from MR images. Mechanical properties were assigned using non-linear finite-strain formulations for fat and fibro-glandular tissues. On the other hand, a linear elastic model was used for the skin. A displacement of 8 mm was then applied to one of the compression plates. Although the results were promising, the authors mentioned that more reliable material properties have to be defined to increase the accuracy of the model. Ruiter et al. [9] investigated mammographic compression based on geometries obtained from MR data and the same mechanical properties as Samani et al. [8]. The accuracy of the models was evaluated by applying a compression of 21% and using multiple landmarks to track the displacements. More recently, Pathmanathan et al. [10] developed a comprehensive Finite Element model including the major breast tissue categories and realistic geometry generated from medical images. The aim of this research was to understand the tracking of lesions and tissues during deformation; however, comparison with experimentally deformed specimens was not considered. The mechanical formulations used to define the behaviour of the tissues were based on non-linear models and parameters from literature. The authors explain that lesions do not significantly affect the overall shape of the breast and their position changes only slightly after deformation.

These models suffer from the difficulty to represent extremely soft materials such as fat with the conventional Finite Element Method (FEM) due to the mathematical limitation of a purely Lagrangian approach. Since the deformations that are usually applied to breast tissues are considerable, the excessive distortion of the elements may lead to inaccurate results and numerical instabilities. Furthermore, the assumed incompressibility of biological tissues can produce results that are far stiffer than expected, an occurrence known as locking. Hence, the literature indicates that there is a need for a sophisticated breast model to aid in accurately predicting large deformations. This breast model is required:

- to represent the mechanical behaviour and deformations of a breast in clinically relevant conditions, such as biopsy procedures and mammographic compression;
- to be capable of predicting deformations of the breast in new imaging settings;
- to be applicable to patient-specific cases;
- to include the internal structure of the breast, to allow the tracking of lesions and glandular tissues.

In this paper, we explore the suitability of the Coupled Eulerian–Lagrangian (CEL) method for modelling breast deformations.

The CEL approach (e.g. [11]) exploits both the Lagrangian and the Eulerian pictures of Mechanics. The Lagrangian framework, in which one follows the path of each material particle, is most suitable for the description of solids and indeed it is the approach normally employed for the case of the breast tissue as well. In contrast, the Eulerian framework, in which one looks at a region in space (the control volume) and sees the continuum body “flow” within it, is suited for fluids.

The CEL method is based on the use of a mesh that is fixed in space (the Eulerian mesh), and through which the continuum flows, occupying at each instant of time a certain subset of elements. This method allows for the combination of several different materials within the same Eulerian mesh, including solids modelled with the traditional Lagrangian approach, allowing large deformations and no limitations in the complexity of the geometry.

We propose to represent each of the internal tissues of the breast as an Eulerian material, and to enclose all of these inside the skin, modelled as a Lagrangian membrane that defines the boundary of the body. We hypothesize that this approach will permit accurate prediction of the deformation of the breast tissues in a range of clinically relevant scenarios.

Section 2 is devoted to a brief description of the Coupled Eulerian–Lagrangian method. Section 3 describes the geometry, material properties, boundary conditions, interactions, and details of the Finite Element implementation. Section 4 describes the procedure for preliminary validation of the model, by means of the comparison of the deformed shape of a breast in the TSAR scanner prototype as predicted by the model with experimental results; moreover, the capability of the model to represent clinically relevant deformations is demonstrated with a test case based on mammography.

2. Theoretical background

In Continuum Mechanics, there are two different, but intimately connected formulations. In the approach due to Lagrange, one tracks the motion of each material particle in the body B, and labels it by means of its referential position X; the set of the referential positions of all particles in B is called reference configuration B_R. In the approach developed by Euler, one looks at a point x in the physical space $S \equiv \mathbb{R}^3$, which at each instant of time $t \in \mathbb{R}_0^+$ could be either empty or occupied by some material particle of the body B; in this approach, one is not interested in the “identity” of this particle, which changes at every instant of time, but rather in evaluating physical quantities at that particular spatial point. These two alternative pictures of Mechanics are related by the configuration map

$$\chi : B \times \mathbb{R}_0^+ \to S : (X, t) \mapsto x = \chi(X, t) \tag{1}$$

Any field f, be it scalar, vector, or tensor, can be written in the Lagrangian form ${}^{\ell}f$ or the Eulerian form ${}^{e}f$, which are related by means of the configuration map χ, i.e.

$${}^{\ell}f(X, t) = {}^{e}f(\chi(X, t), t) = {}^{e}f(x, t) \tag{2}$$

(the superscripts ℓ or e will be omitted when there is no danger of confusion, for the sake of a lighter notation).

2.1. The Coupled Eulerian–Lagrangian method

The Coupled Eulerian–Lagrangian Eulerian method (CEL) (see, e.g. [11]) could be seen as a particular case of the Arbitrary Lagrangian–Eulerian method (ALE). Indeed, in the ALE method,