Biomechanical modelling of the behaviour of the human breast under the effect of gravity for tumor detection

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Abstract

Magnetic Resonance Imaging (MRI) has been used as an effective tool for breast cancer evaluation due to its high sensitiveness to detect breast tumors. However, these MRIs are performed with the patient lying prone, while the tumor resection surgery is performed with the patient lying in supine position. The breast undergoes large deformations due to the change in the direction of gravity, and nonpalpable breast lesions must be localized before surgery for their removal. Modelling the breast deformation under gravity loading (from prone to supine position) could allow for the localization of the tumor and help the planning of breast cancer treatment. This study presents biomechanical simulations by the Finite Element (FE) method using ABAQUS software. Patient-specific breast geometries of two patients with different breast sizes were obtained from prone MR images and used in the simulations. Computed Tomography (CT) images in the supine position were also available for the same patients and used for evaluation purposes. The evaluation of the methodology has been carried out by considering the distance between the nipple and the tumor centroid identified in both images. Furthermore, the mean Euclidean distance between the estimated deformed breast surface and the supine surface extracted from CT image was calculated and finally, the percentage overlap between the deformed breast mask and the CT breast mask was obtained. The proposed method achieves an average localization error for the tumor of 4.27 mm.

1. Introduction

Breast cancer is a disease with a major global impact. In fact, it is one of the most prevalent pathologies in women. Almost 2.3 million new cases are diagnosed every year worldwide [1] and produce about 500,000 deaths per year, making it one of the leading causes of cancer death among women [2]. The breast of an adult female is mainly composed of adipose tissue, fibro glandular tissue, and skin. The breast is posteriorly attached to the chest by the pectoralis fascia over the pectoral muscle, while the skin and supporting Cooper's ligaments define and maintain its shape. [3].

The main treatment for breast cancer is surgery. For years, mastectomy has been chosen as the treatment for breast cancer. Lately, improved mammography screening led to the diagnosis of nonpalpable tumors. In these cases, the preferred treatment is breast conserving therapy or lumpectomy, whose goal is the complete resection of the tumor and the preservation of the shape of the breast. It is used for early-stage breast cancer and requires localization of the tumor prior to surgery. This necessary pre-localization is done since the diagnostic imaging, in this case MR imaging, is performed in the prone position, whereas surgery is performed in the supine position, so the breast undergoes a large deformation from one position to the other. One of the most popular techniques for preoperative localization is Wire Guided Localization: this procedure it is performed by a radiologist on the same day as the patient's planned surgery and consists in the insertion of a hooked wire to tag the location of the lesion under radiological guidance.

Biomechanical modelling and simulation of the breast is a promising area of research with potential uses in healthcare applications, specifically in the diagnosis and treatment planning of breast cancer. In recent years, several research groups have made important improvements in the field of biomechanics, modelling the breast with the FE method.

Previous works have modelled the breast as an isotropic and incompressible material [4,5,6,7,8,9,10]. All of them have considered a homogeneous tissue, except [5,6], which have considered a heterogeneous tissue differentiating between adipose tissue and fibroglandular tissue. Moreover, all these works have used non-linear elastic (hyperelastic) models, specifically, the Neo-Hookean form, and in [4] the 5-parameter Mooney-Rivlin form was also used.

Despite these advances, there are still several issues limiting the clinical application of biomechanical models, such as the automation of patient-specific model generation, robust image segmentation and mesh generation, and the accuracy of biomechanical models [11].

In this work, a biomechanical model of the breast has been designed by applying the gravity load that exists between the prone position (MR image) and the supine position (surgery). In addition, the viscoelasticity of the breast tissue has been explored and the breast has been modelled as a visco-hyperelastic material.

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2. Methods

2.1. Data

Taking into account the burden of the simulation (long simulation set up time and running time) the proposed methodology has been applied in this work to two cases provided by the Hospital General Universitario Gregorio Marañón (HGUGM) in Madrid. Two cases with different breast volume were chosen: Case 1, a patient with a large breast and Case 2, a patient with a small breast.

Each case included a prone MR image, from which the 3D volume model of the breast was obtained and a supine CT image, that has been considered as our reference of the surgical position for evaluation purposes, an example of the two positions is shown in Figure 1.

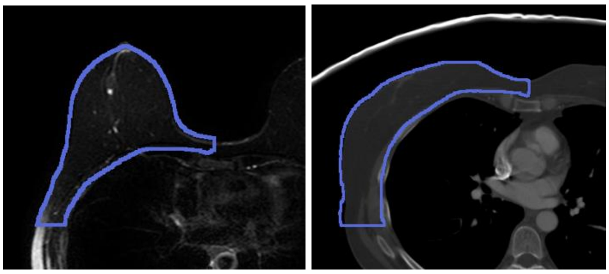

Figure 1. *Left: prone MR image. Right: supine CT image.*

2.2. Segmentation and Meshing

The patient-specific imaging data were segmented using Slicer 3D software [12]. In this procedure, the breast is delineated from the background and the border with the chest wall as a homogeneous tissue.

After the first phase, the segmentation was exported as a triangular mesh (STL format). The mesh obtained was postprocessed using the Iso2mesh library in MATLAB to generate a more suitable mesh for the solver.

The surface meshes were then imported into ABAQUS and converted into a tetrahedral mesh. Specifically, a linear 4-node tetrahedron element (C3D4 in ABAQUS nomenclature) was employed. The size of the for each case was:

- *Case 1:* 53,323 elements; 10,596 nodes.
- *Case 2:* 36,939 elements; 7,457 nodes.

2.3. Finite Element Model

2.3.1. Formulation and Constitutive model

A literature review of previous work was carried out to find the best biomechanical model to be used in this work.

The breast was modelled as a homogeneous and isotropic tissue with a density of 1000 kg/m^3. Like most biological tissues, breast tissue exhibits hyperelastic characteristics under deformation. Therefore, we used a Neo-Hookean hyperelastic constitutive model to describe the stress-strain relationship of breast tissues. The neo-Hookean first potential strain energy potential is defined as:

$$U = \frac{\mu_0}{2}(\bar{I}_1 - 3) + \frac{2}{K_0}(J^{el} - 1)^2$$

where μ_0 is the initial shear modulus and K_0 is the initial bulk modulus:

$$\mu_0 = 2C_{10} \qquad K_0 = \frac{2}{D_1}$$

C_{10} is the neo-Hookean parameter; D_1 is an incompressible parameter; $\bar{I}_1$ is the first invariant of deviatoric deformation and J^{el} the determinant of the deformation gradient.

In this work, we assumed that the parameter C_{10} ranges from [40, 80] Pa [8,9].

In addition, the viscoelastic properties of the tissue have been explored in this work. To calculate the viscoelastic behaviour, the Prony series is used to describe the transient response of the material. The parameters of the Prony series are defined as:

$$g_i = \frac{G_i}{G_0}$$

where g_i^P is the i-th value of the ratio of the modulus of relaxation at one shear stress of the material; G_i is the value of the modulus of stiffness of the i-th element, G_0 is the value of the instantaneous modulus of stiffness. Similarly,

$$k_i = \frac{K_i}{K_0}$$

k_i^P is the i-th value of the ratio of the volumetric modulus of the material; K_i is the value of the volumetric modulus of the i-th element and K_0 is the value of the instantaneous volumetric modulus.

Taylor et al. [13] suggested that visco-hyperelastic models could describe the behaviour of soft tissues subjected to large deformations. However, no reference was found for the adjustment of the viscoelastic parameters. Thus, an exhaustive calibration of the parameters was carried out to obtain a range of plausible values.

2.3.2. Finite Element Simulation in ABAQUS

- *Parts*: Two parts were created: a rigid internal surface simulating the chest wall and the breast as a deformable part (Figure 2).

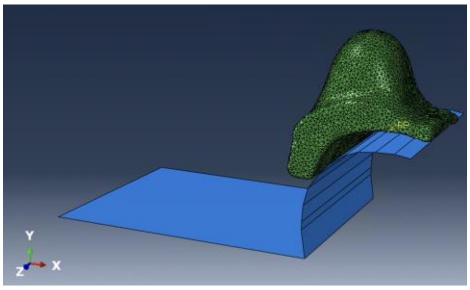

Figure 2. *Rigid internal surface (blue) and breast volumetric mesh (green).*

- *Material*: Visco-Hyperelastic.
- *Step*: Dynamic-explicit (period 0.35s, Δt=0.01)
- *Interaction*: The breast tissue was observed to slide on the chest wall under the effect of gravity. Hence, the interaction was modelled as a surface-to-surface contact between the internal rigid surface and the contact surface of the breast with a friction coefficient of 0.8.

- *Load*: a gravity load was applied.
- *Boundary Conditions*:

  - *Internal surface*: Fixed in all directions.

  - *Breast*: A medial symmetry boundary condition was applied to simulate the junction with the contralateral breast (Figure 3). Furthermore, the medial area of the breast was restricted in movement in the y-direction (Figure 4) a previously proposed inVavourakis et al. [14].

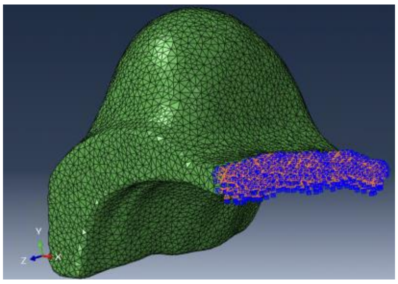

Figure 3. *Medial Symmetry Boundary Condition.*

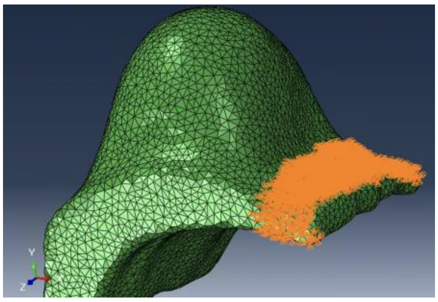

Figure 4. *Medial Area Boundary Condition.*

3. Results

3.1. Viscoelastic Parameter Range

As mentioned above, the optimal range of the viscoelastic parameters was obtained by an exhaustive calibration using as reference the distance between the estimated position of the nipple in the surgical position and the reference supine position of the tumor in the CT used for evaluation. The optimal range identified for the viscoelastic parameter was between (0.65-0.85), neglecting those that provide values higher than 15 mm, as we can see in Figure 5.

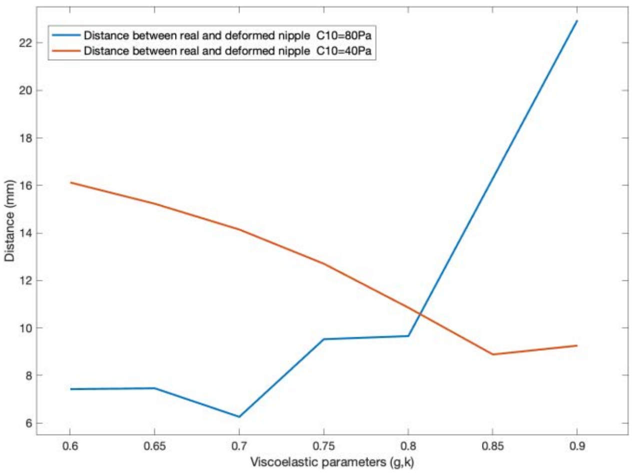

Figure 5. *Viscoelastic parameters vs Nipple distance.*

3.2. Landmarks Distance

Two landmarks were identified in the prone and supine images: the position of the nipple and the centroid of the tumor extracted from the lesion segmentation. The Euclidean distance between the position of the supine landmarks in the CT and the position estimated by the simulation was calculated.

3.3. Mean Distance Between Surfaces

The mean distance between surfaces has been calculated as the average value of the minimum distance between each node on the frontal surface portion of the breast in supine position and the frontal surface of the simulation mesh.

3.4. Breast Overlapping

The percentage of overlapping was calculated between the supine breast mask from the CT and the deformed mask obtained from the simulation mesh.

Table 1 and Table 2 present the results obtained for the two cases. Visual results are shown in Figure 6 and Figure 7.

- **Case 1**

C_{10} (Pa)	g;k	Nipple distance (mm)	Tumor distance (mm)	Surface distance (mm)	Overla-pping (%)
80	0.7	6.26	8.83	11.47	75.82
40	0.85	8.89	10.11	10.48	75.61
40	0.8	10.86	3.13	10.85	77.65

Table 1. *Results Case 1.*

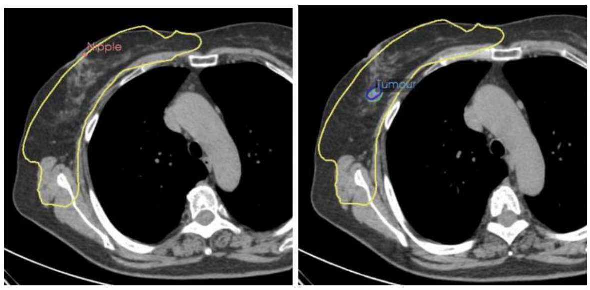

Figure 6. *Results of simulation for Case 1 with C_{10}=40Pa and g=k=0.8. Left: supine CT image, estimated nipple position and deformed mesh (yellow). Right: Supine CT image, supine tumor (light blue), estimated tumor (blue) and deformed mesh (yellow).*

- **Case 2**

C_{10} (Pa)	g;k	Nipple distance (mm)	Tumor distance (mm)	Surface distance (mm)	Overla-pping (%)
80	0.7	18.17	10.49	7.99	71.51
40	0.85	15.74	7.48	6.86	74.58
40	0.8	15.21	5.40	6.30	74.83

Table 2. *Results Case 2.*

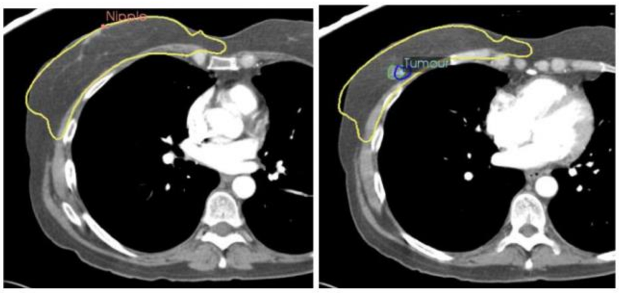

Figure 7. *Results of simulation for Case 2 with C_{10}=40Pa and g=k=0.8. Left: supine CT image, estimated nipple position, and deformed mesh (yellow). Right: Supine CT image, supine tumor (green), estimated tumor (blue) and deformed mesh (yellow).*

4. Discussion and Conclusions

This work proposes and validates a visco-hyperlastic biomechanical model to support preoperative localization of breast lesions. The patient-specific breast models were obtained from a preoperative MR image acquired in the prone position. A supine CT image has been used as reference in surgical position for the validation of the proposed method.

The analysis has been carried out in two cases: Case 1, a patient with large breast and Case 2, a patient with small breast. For both patients, better results in terms of distance between the predicted location of the tumor and the one segmented in the supine configuration have been obtained for a hyperelastic parameter c_{10}=40 and viscoelastic parameter g=0.8 with a mean value of 4.27 mm.

The results, obtained with a simplified model of the breast that does not consider its heterogeneous structure, are considered very promising. Similar results have been achieved with other proposals in the literature that also involve an image intensity-based registration step [10].

5. Future work

The skin covering the breast provides some anatomical support to the breast. Therefore, future work could obtain the relationship between the skin and the breast and get the most appropriate model of the skin.

It could also be studied the breast tissue as a heterogeneous tissue consisting of adipose and fibroglandular tissue, being able to estimate the proportion of both tissues when segmenting them and thus, defining a specific biomechanical model that considers material properties for each patient.

It should also be noted that the proportion of breast tissue varies according to the woman, her age, size of the breast, whether she is premenopausal or postmenopausal, and, in general, the specific constitution of the patient, which is why the results vary from patient to patient. An important breakthrough would be to optimize the model parameters to create patient-specific models.

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