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DEFORMATION MODELING OF BREAST BASED ON MRI AND FEM.

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ABSTRACT

Breast tissue deformation has recently gained interest in various medical applications. The recovery of large deformation caused by various loads and image registration is non-trivial task. The need arise to estimate large breast deformation, which can mimic natural body movement caused by examinations or surgery. Finite element methods (FEM) have been widely applied in this field. In this work we present fundamentals for FEM based one breast image transformation. The exemplary results are presented. The model uses the simplest constitutive tissue description, which makes it easily applicable and fast.

INTRODUCTION

Breast cancer is the most frequent women's cancer around the world. Its early diagnosis is crucial for the prognosis of patient survival and results of treatment [1]. One of the most informative and at the same time non-evasive diagnostic techniques is based on Magnetic Resonance Imaging (MRI) [3]. Unfortunately, for many reasons both technical and medical, it is performed in prone patient position. On the other hand other imaging techniques (e.g. Computer Tomography (CT) and Positron Emission Tomography (PET)) and what is the most important surgery are performed in supine position [2]. Since changing position from prone to supine leads to breast deformation [5], we propose an algorithm based on finite element method (FEM) to model it.

MRI BREAST DATA

Magnetic Resonance Imaging is one of the most popular diagnostic examination, in case of breast cancer diagnosis. It is safe technique because the MRI does not use the ionizing radiation. The possibility of multiple contrasts acquisitions, both anatomical and functional, plays a key role in MRI breast cancer detection. Exemplary MR image is presented in Figure 1. The obtained MRI data constitute basis for FEM construction. This method requires domain (image) discretisation, tissue parameters estimation, transformation equation definition, boundary condition setting (see next section) [4].

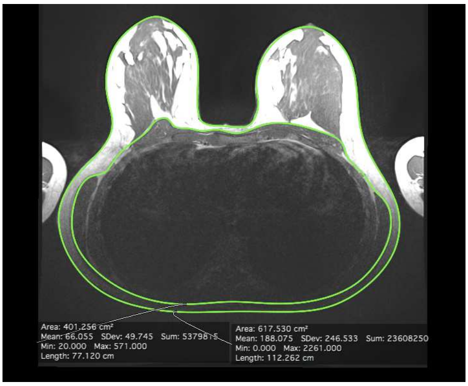


Figure 1. Exemplary breast MR image (internal green contour is a chestwall boundary, external green contour is a body boundary).

DISCRETIZATION OF THE DOMAIN

Basic element

First step in the finite element analysis is the object domain discretisation - division into smaller domain elements. It replaces the body with infinite degrees of freedom by a finite number of elements with finite and strictly defined degrees of freedom.

For two dimensional analysis one can discriminate two main element types: three node triangular element (T3) and four node rectangular element (Q4). In this paper we focus on Q4 bilinear quadrilateral element, which is a generalization of four node rectangular element. The bilinear quadrilateral element has Young Modulus E, Poission's ratio ν, thickness t and is described with two linear functions (1). The bilinear quadrilateral element can be described in both global (x, y) coordinates (Figure 2), and local coordinates (ζ, η) (Figure 3).

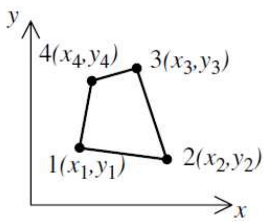


Figure 2. Bilinear quadrilateral element in global coordinates.

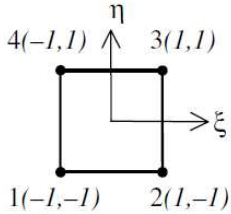


Figure 3. Bilinear quadrilateral element in local coordinates.

Mesh generation and Boundary condition

Mesh generation is a process where the coordinates of object domain nodes are set. In case of breast MRI transformation the mesh generation is performed in two steps: (1) - generating equidistant mesh for whole image, (2) - choosing nodes, which overlap a segmented image mask. The resulting mesh is presented in Figure 4.

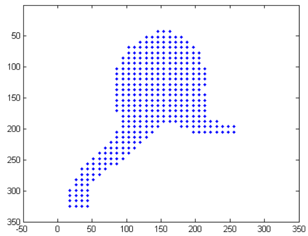


Figure 4. Resulting mesh for one segmented image (one point represents one mesh node).

The boundary nodes between chestwall and breast tissues (Figure 5) were set as stationary. However, before deformation, the chestwall nodes are moved down to the sternum level. This is the simplest way to represent muscle movement during body position changing. The skin boundary nodes (Figure 5) are constrained with collision detection and reaction (see next section).

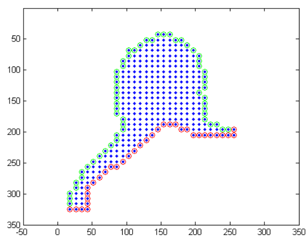


Figure 5. Boundary conditions for mesh, chestwall nodes (red), skin nodes (green).

BASIC EQUATIONS IN FEM ELASTIC DEFORMATION

The bilinear quadrilateral element is described by four shape functions listed as follows in terms of local ζ and η coordinates:

$$\begin{aligned} N_1 &= \tfrac{1}{4}(1-\zeta)(1-\eta), \\ N_2 &= \tfrac{1}{4}(1+\zeta)(1-\eta), \\ N_3 &= \tfrac{1}{4}(1+\zeta)(1+\eta), \\ N_4 &= \tfrac{1}{4}(1-\zeta)(1+\eta). \end{aligned} \tag{1}$$

The strain displacement matrix is described as follows:

$$B = \tfrac{1}{|J|}[B_1 B_2 B_3 B_4], \tag{2}$$

where J is the Jacobian determinant and the nodal B_i matrix is given by:

$$B_i = \begin{bmatrix} \frac{\partial N_i}{\partial x} & 0 \\ 0 & \frac{\partial N_i}{\partial y} \\ \frac{\partial N_i}{\partial y} & \frac{\partial N_i}{\partial x} \end{bmatrix}. \tag{3}$$

Element plane strain matrix is given as follows:

$$D = \frac{E}{(1+\nu)(1-\nu)} \begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix}. \tag{4}$$

The element stiffness matrix is given by:

$$k = t \int_{-1}^{1} \int_{-1}^{1} B^T DBJ d\zeta d\eta. \tag{5}$$

Two points Gauss-Legendre quadrature is used for practical evaluation of integrals (5) over the element area. The point coordinates and weights are presented in Table 1.

Table 1. Point coordinates and weights for two points Gauss-Legendre quadrature.

n	$\zeta_i = \eta_i$	W_i
2	$\zeta_1 = \zeta_2 = \pm 0.577350269189626$	$W_1 = W_2 = 1$

To calculate nodal displacement the following structural equation is used:

$$U = FK^{-1}, \tag{6}$$

where U is node displacement matrix, F is nodal forces matrix and K is global stiffness matrix. Once the boundary conditions are set, the matrix U is solved by partitioning and Gaussian elimination.

The following boundary condition limitations should be taken into account:

- The chestwall displacement is calculated using Eq. (6). For known displacement of the chestwall nodes, internal forces, induced by the displacement and working on other object nodes are calculated. Based on the calculated forces the object nodal displacement is estimated.
- Chestwall nodes during deformation are set as stationary. However material parameters are set, to simulate breast tissues sliding along muscles.
- The collision detection and reaction for skin nodes is performed by detection of other skin nodes in surroundings $\varepsilon_x < dx$ or $\varepsilon_y < dy$ where dx and dy are one node dimensions. If another node is detected the nodal forces in F matrix (see Eq. (6)) are changed according to deformation directions.

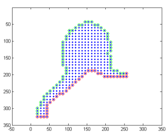
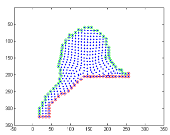
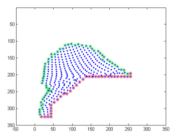
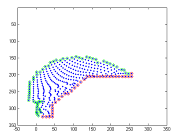
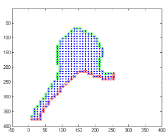
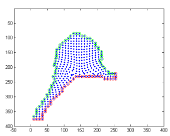
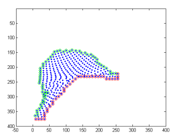
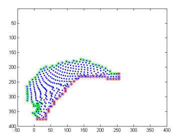
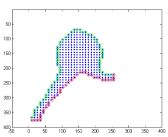
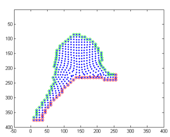
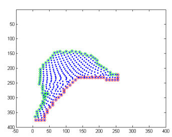
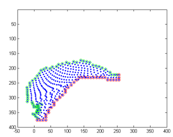
EXEMPLARY RESULTS OF THE SIMULATIONS

The transformation algorithm is performed in three steps: (1) - chestwall deformation, (2) - removal of load from gravitational force from object, (3) - use of gravitational force in opposite direction. For model parameters [6], [7] given in Table 2, results of the transformation for three patients are presented below.

Table 2. Model parameters.

Node type	Young Modulus	Poission's ratio
Skin	101 kPa	0.4995
Chestwall	5 kPa	0.25
Other	50 kPa	0.48

Table 3. Patient resulting meshes.

Patient	Original mesh	Chestwall deformation	Unloaded model	Loaded model
P1				
P2				
P3				

The analyzed images show the efficiency of our methodology. The breasts shape is preserved, and results correspond with the real breast shape in supine position.

CONCLUSIONS

In this paper we have presented fundamentals for FEM based one breast image transformation. The presented model uses the simplest constitutive tissue description (isotropic, linear elastic, homogeneous), which gives acceptable results. However to represent real prone to supine body deformation, dataset should be processed as one 3D object instead of one by one image. Tabular parameters works only for small and medium breast size. For bigger breasts, parameter tuning is needed. Also, the computation time optimization should be taken into account. The full, 3D model extension will be a subject of our future studies.

Deformed Medical Resonance Images need to be fused with Positron Emission Tomography (PET) Images, which are obtained in patient supine position, while MRI is performed in patient prone position. MRI-PET fusion is crucial step in precise and patient specific breast cancer treatment planning.

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