3D REZONING FOR FINITE ELEMENT MODELLING OF LARGE BREAST DEFORMATIONS

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ABSTRACT

Fine-meshed finite element models, employing finite strain formulations, are often unable to simulate very large deformations due to the large distortions of individual elements. Rezoning, where the deformed mesh is improved and simulation results are remapped onto the new mesh, has been proposed as a remedy. However, rezoning is currently not readily available for tetrahedral elements. Therefore we have developed a 3D rezoning method for tetrahedral elements. The 3D rezoning achieved a mean displacement accuracy of 99% for homogenous material and 97% for heterogenous material in comparison to a finite strain formulation for a 30% compression example. Its applicability to our problem, the simulation of large breast deformations as occurring during X-ray mammography, was demonstrated.

KEYWORDS: Rezoning, Finite Element Method, Mammography, Simulation

INTRODUCTION

A validation method for the registration of X-ray mammograms has been proposed [Hipwell *et al.*, 2006]. It is based on building biomechanical breast models from magnetic resonance (MR) mammograms, simulating plausible breast deformations as occurring during X-ray mammography, applying the resulting transformation to the MR mammograms, and generating pseudo X-ray mammograms from the transformed MR mammograms. This method enables the quantitative assessment of the registration performance since the 3D transformation, and hence the projected 2D displacement field between the two pseudo X-ray mammograms, is known.

In this work we are concerned with improving our biomechanical breast models based on finite element (FE) methods such that very large deformations can be accurately simulated. Previously we have shown that for in-vivo compressions of 20% and accurate displacement boundary conditions linear models (linear material and small strain assumption) can predict the displacement of internal landmarks with a mean error of 2.1mm and that nonlinear models (hyperelastic material and finite strain formulation) were not more accurate [Tanner *et al.*, 2006]. This will not hold when simulating the very large compressions ($\geq$50%) occurring during X-ray mammography.

Several groups have employed FE methods to simulate breast deformations [Azar *et al.*, 2002; Samani *et al.*, 2001; Yin *et al.*, 2004; Pathmanathan *et al.*, 2004; Ruiter, 2003; Schnabel *et al.*, 2003]. In comparison, we [Schnabel *et al.*, 2003; Tanner *et al.*, 2006] employed very fine meshes of 10-noded tetrahedral elements in order to account for the heterogeneous distribution of fibroglandular tissue and the irregular breast shape. However, fine-meshed FE models employing a finite strain formulation and small elements often fail to solve for very large deformations due to excessive mesh distortion. Rezoning, where an intermediate deformed mesh is improved and the solution is then remapped onto the new mesh, has been proposed as a remedy. ANSYS [ANSYS Inc., 2006], the commercial FE package we use, supports manual rezoning only for a sub-set of 2D elements and material properties. The Arbitrary Lagrangian Eulerian (ALE) framework from ANSYS LS-DYNA, which can be thought of as an automatic rezoning, is currently only available for hexahedral elements. Yet the generation of unstructured hexahedral meshes directly from volumetric data remains a challenge while this is not a problem for tetrahedral elements. Furthermore, convergence problems were also experienced with LS-DYNA and the ALE framework for very fine hexahedral meshes when simulating a 70% compression of a hemisphere. We therefore developed a 3D rezoning algorithm. This paper reports the achieved accuracy and demonstrates that this method can be applied to simulate a breast compression of 70%.

METHOD

An automatic 3D rezoning algorithm was implemented using the ANSYS parametric design language. The procedure is as follows:

1) solve first load step,
2) update mesh geometry with solution,
3) extract deformed surface,
4) remesh deformed surface,
5) map stress and material type onto new mesh,
6) apply boundary conditions,
7) solve current load step,
8) keep track of cumulative displacements,
9) go to 2) until last load step.

The accuracy of the 3D rezoning was assessed with respect to the results provided by a finite strain formulation. A cube with 60 mm long sides (0 mm $< x_1, x_2, x_3 <$ -60 mm) was compressed in the x_3-direction, see Figure 1. The compression was modelled using a plate and frictionless contact for models without rezoning, while displacement boundary conditions in the x_3-direction were employed at each rezoning step. The model was fixed by zero displacements on the zero planes, i.e. $dx_i = 0$ for $x_i \in [-0.1, 0.1], i = 1, 2, 3$. The cube was meshed with an element size of 8 mm resulting initially in 4404 10-noded tetrahedral elements.

Heterogeneous breast tissue, consisting of fat, fibroglandular and tumour, was modelled by assigning the tissue type to the elements in accordance with a cubical region of a segmented MR mammogram. Two material models were tested called M1 and M2. M1 was an isotropic, linear, elastic material model where all tissue types had a Young's modulus E of 1 kPa. M2 modelled breast tissue in accordance with the results reported in [Krouskop *et al.*, 1998; Wellman, 1999] with $E =$ 18.5 kPa for fatty tissue, $E = 1001.3e^2 - 272.7e + 86.1$ kPa for fibroglandular tissue and $E = 37.9 \exp(19.9e)$ kPa for tumorous tissue, where e represents the strain. All models used a Poisson's ratio of 0.495.

The rezoning performance was assessed for a compression of 30% since the finite strain formulation failed to converge for larger compressions of M2. Rezoning was performed at every 2% or 5% compression step. Errors were uniformly sampled at 1 mm intervals.

Rezoning was applied to a breast model constructed from a MR image acquired at the Guy's and St. Thomas' Hospital Trust, London. The image had a voxel dimensions of 1.37 × 1.37 × 4.2 mm and an axial slice orientation. The resulting 10-noded tetrahedral mesh consisted of 40246 elements.

RESULTS

The undeformed cube and results for 30% and 70% compressions are shown in Figure 1. The results of assessing the accuracy of the automatic 3D rezoning are summarised in Table 1. The 30% compression introduced a mean displacement of 10.42 mm to 11.37 mm for the finite strain formulation. Most similar results were achieved with rezoning employing a finite strain formulation or with small strain rezoning at every 2% compression step. As expected, the heterogeneous material model M2 caused an increase in the interpolation errors for rezoning. Assuming small strains and performing no rezoning introduced a volume shrinkage of more than 7% and a mean error of 2 mm for the 30% compression and a volume shrinkage of 46% for the 70% compression. Some convergence problems were experienced with finite strain rezoning at larger compressions. The 2% (5%) small strain rezoning resulted in volume changes of -4.5% (-8.8%) for the 70% compression.

Figure 2 demonstrates the application of the 3D rezoning method to the simulation of a breast compression using the heterogeneous material model (M2). Rezoning introduced a volume change of -2.75%.

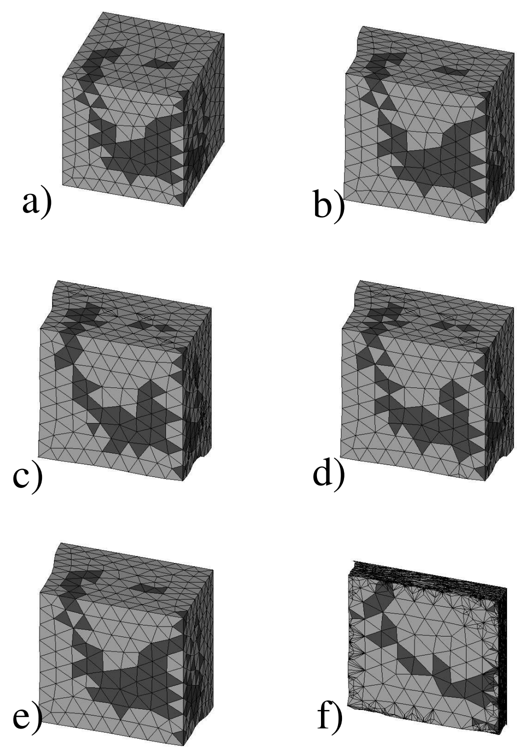

Fig. 1. Cube mesh surfaces with tissue types in different shades of grey (light: fat, dark: fibroglandular tissue). a) undeformed cube, (b-e) simulation results of compressing the cube by 30% for material model M2 using b) finite strain formulation, c) 2% finite strain rezoning, d) 2% small strain rezoning or e) small strain formulation. f) 70% compression result for 2% small strain rezoning.

Method	Volume change (%)	Mean error (mm)	95% error (mm)
	Material model M1		
Finite strain	-0.37	-	-
2% rezoning, finite strain	-0.36	0.09	0.13
5% rezoning, finite strain	-0.36	0.09	0.13
2% rezoning, small strain	-0.98	0.10	0.15
5% rezoning, small strain	-1.86	0.34	0.53
Small strain	-7.59	2.01	3.14
No transformation	-	11.37	9.83
	Material model M2		
Finite strain	-0.49	-	-
2% rezoning, finite strain	-0.50	0.33	0.59
5% rezoning, finite strain	-0.49	0.30	0.52
2% rezoning, small strain	-1.11	0.28	0.56
5% rezoning, small strain	-1.95	0.33	0.76
Small strain	-7.78	1.96	3.12
No transformation	-	10.42	16.85

Table 1. Accuracy of rezoning and small strain formulation with respect to the results from the finite strain formulation for a 30% compression.

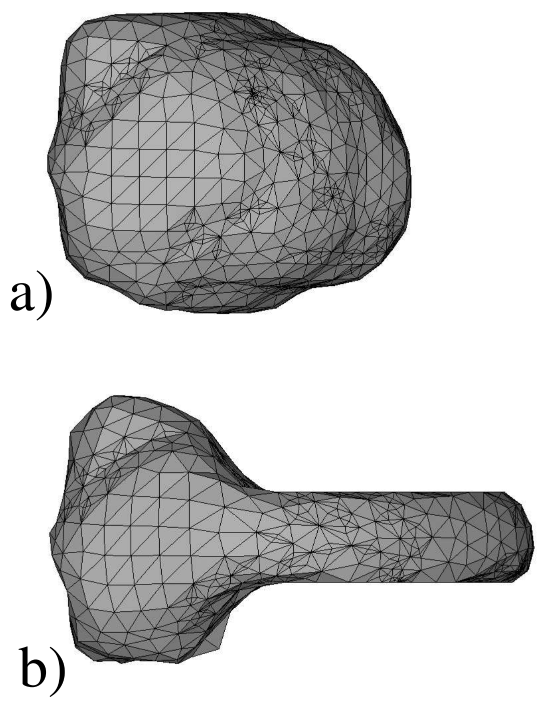

Fig. 2. Mesh surface a) before and b) after simulating a cranio-caudal compression of a breast by 70% using 3D small strain rezoning at each 2% compression step.

CONCLUSION

We have showed that the mean inaccuracy introduced by 3D rezoning for 2% steps is less than 1% for a homogenous material and about 3% for a heterogenous material for a compression of 30%. Note that the finite strain formulation will also have discretisation errors for heterogeneous materials. Assuming small strains without rezoning led to mean errors of more than 17% and caused substantial volume shrinkage. Rezoning errors for 2% steps remained at 1% for a 40% compression of the homogeneous material and volume changes remained below 5% for a 70% compression. Given the other uncertainties when modelling breast compressions, we believe that the interpolation errors introduced by 3D rezoning are acceptable.

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