Constrained Non-linear Elasticity Reconstruction Technique for Breast MRI Elastography

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Synopsis To increase the displacement SNR in breast MR elastography, tissues are compressed significantly. As a result, breast tissues undergo large deformations. This leads to significant geometric and material nonlinearities. In this study, methods for treating these nonlinearities are presented and their impact on elasticity reconstruction is investigated. For elasticity reconstruction, a constrained elastography method is used where tissues are treated as hyperelastic materials. The tissue hyperelastic parameters are calculated using inversion techniques with a nonlinear finite element (FE) model for forward modeling. Simulations indicate the feasibility of reconstructing the tissue hyperelastic parameters using displacement data with moderate SNR.

Introduction Tissue elasticity alteration is well known to be associated with the presence of cancer. This has led to the development of elastography techniques for imaging tissue elasticity over the past decade. There are two MR elastography (MRE) methods: harmonic and quasi-static. In harmonic elastography, small amplitude harmonic actuation with frequencies ranging from 50-500 Hz is applied to deform the tissue whereas in quasi-static elastograpy, the tissue undergoes relatively large deformations with very low frequency. Large deformations increase the SNR of displacement, which lead to better quality of elasticity reconstruction. However, under large deformations, soft tissues become nonlinear. Beside geometric nonlinearity, breast tissues exhibit significant material nonlinearity under strains greater than 0.02 [1]. In our previous work, we have introduced a constrained reconstruction technique for breast MR elastography [2]. In that work, tissues are assumed to be linear elastic. The aim of this work is to extend our previous model by adding material and geometric nonlinearities. The purpose is two folds: to investigate the impact of these nonlinear effects on the reconstruction, and to explore ways of improving specificity based on the nonlinear parameters.

Methods As in [2], the breast elastography experiment is preceded by a contrast enhanced MRI imaging to obtain the geometry of each tissue type. Thus, a quasi-static sinusoidal compression is applied to the breast while resulting displacement data of the breast tissues are acquired using a stimulated echo (STEAM) pulse sequence [3]. The forward model in this reconstruction technique is a nonlinear Finite Element (FE) model of the breast, where breast tissues are assumed to be hyperelastic undergoing finite deformations. To obtain a constitutive model for hyperelastic materials, a strain energy function with a set of coefficients called the hyperelastic parameters is defined. The following expression represents a polynomial form widely used to represent strain energy functions:

$$U = \sum_{i+j=1}^{n} C_{ij}(I_1 - 3)^i (I_2 - 3)^j \qquad (1)$$

where C_{ij} represents the hyperelastic parameters and I_1 and I_2 are the strain invariants. With n=2, the above represents the Mooney Rivlin form widely used with incompressible materials. Following the principle in the constrained reconstruction [2], it is assumed that the C_{ij} parameters are uniform throughout the volume of each tissue type. Two methods are proposed to reconstruct the hyperelastic parameters. The first uses nonlinear optimization to calculate the set of C_{ij} parameters that minimizes the difference between the measured displacements and displacements calculated using the FE model. The other calculates C_{ij} using an iterative procedure where each iteration involves stress calculation using the FE model followed by C_{ij} parameters updating. For updating, the C_{ij} parameters are calculated for each finite element by solving a nonlinear constitutive equation derived from (1). The average of C_{ij} over the set of finite elements within each tissue will represent the updated hyperelastic parameters of the tissue.

Results For breast MRE, we used a volunteer's breast MRI image to create a 3D FE mesh. A sagittal slice of this mesh, where a simulated tumor is added, is depicted in Figure 1. Normal tissues are assumed to be Mooney Rivlin hyperelastic materials with C_{ij} parameters obtained in our lab [1]. The tumor is assumed to be linear elastic with a Young's modulus of 12.0 kPa which corresponds to an invasive carcinoma. The tumor's linear elasticity was assumed because of the relatively low strains the tumor undergoes as a result of its higher stiffness. According to these assumptions, displacements resulting from 5 mm compression normal to the breast's sagittal plane were calculated using a nonlinear contact FE model. The displacement component in the compression direction was contaminated by normally distributed noise to simulate an SNR value of 30. This displacement component was used with the optimization technique for tissue elasticity reconstruction. Starting with an arbitrary initial guess of C_{ij} parameters and a Young's modulus of 4.0 kPa, the hyperelastic parameters of the normal tissues and the tumor's Young's modulus were reconstructed. Figure 1 depicts the stress-strain curves of the true and reconstructed parameters, which indicate a very good agreement.

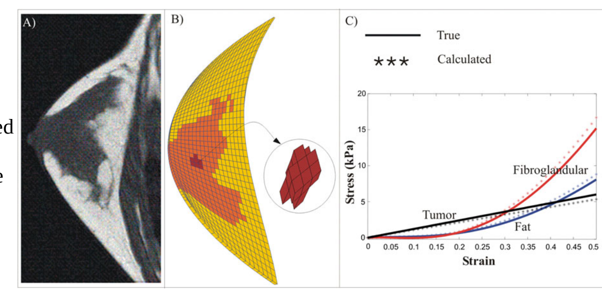

Figure 1: a) A magnitude image of central slice through the breast. b) FE mesh of the slice shown in (a) with a simulated tumor. c) true and reconstructed stress-strain curves of the fat, fibroglandular and tumor tissues.

Conclusions This article presents a constrained MRE technique, that can be potentially used to detect breast cancer. In this technique, quasi-static finite compression is assumed to be used for actuation. As such, large tissue deformation is expected which leads to significant material and geometric nonlinearities. To account for these nonlinearities, two inversion methods were proposed. The purpose of this work is two folds: to investigate the impact of these nonlinear effects on the elasticity reconstruction and to explore ways of improving specificity based on the nonlinear parameters. Due to the fact that breast tissues are highly nonlinear, conventional elastography methods, which assume linear elasticity, lead to elastograms that are dependent on the amount of applied compression. One advantage of hyperelastic parameter reconstruction is eliminating this dependence. The latter paves the way for reading elastograms in a consistent way. The presented breast elastography example, indicate that hyperelastic parameter reconstruction is possible with moderate SNR values. Further studies will be conducted using experimental displacement data.

References

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