Predicting Tumor Location from Prone to Supine Breast MRI Using a Simulation of Breast Deformation

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***Abstract*—Breast cancer is one of the biggest killers to women, and early diagnosis is essential for improved prognosis. The shape of the breast varies hugely between the scenarios of magnetic resonance (MR) imaging (patient lies prone, breast hanging down under gravity) and ultrasound (patient lies supine). Matching between such pairs of images is considered essential by radiologists for more reliable diagnosis of early breast cancer. In this paper, a method to predict tumor location by simulating the breast deformation from breast in the prone position to the compressed breast in the supine position was developed, which is based on a 3-D patient-specific breast model constructed from MR images with the use of the finite-element method and nonlinear elasticity. The performance was assessed by the mean distance between corresponding lesion locations for three cases. A mean accuracy of 4.94mm in Euclidean distance was achieved by using the proposed method. Experiments using actual images show that the method gives good predictions which can be used to find exact correspondences between tumors location in prone and supine breast images.**

***Keywords*-breast deformation; finite element; MRI**

I. INTRODUCTION

Breast cancer is one of the major diseases which strictly endanger the women's health. Hence, early diagnosis is very important. Of all the soft tissue images, MRI of soft tissue will obtain excellent resolution without little radiation. At the same time, MRI could get more accurate information than any other imaging technologies such as ultrasound in actual clinical applications. And in some cases, the breast lumps cannot be found in ultrasound. So breast lumps registration between MR images and ultrasound is very useful to make some diagnoses. However the breast shape varies massively between MR images and ultrasound. The simulation of breast deformation is an effective method to predict the tumor location from breast in the prone position to the compressed breast in the supine position.

Various methods have been proposed to model breast deformation, mostly based on linear elasticity theory [1-2]. A linear method is used to make the deformation [1], which is represented by the Young's modulus. But the method is not able to express the nonlinear characteristics of the soft tissue of the breast because of the nonlinear properties of the breast. The breast deformation model based on nonphysical models was provided in [2]. However, the deformations undergone by the breast can involve large strains, so the full nonlinear theory of elasticity is required. In the software CMISS, the nonlinear model is used to simulate the soft tissue deformation and the results are effective [3-5]. But CMISS is very professional, doctors cannot easily applying it in clinical.

In this paper, a method to predict tumor location by simulating the breast deformation from breast in the prone position to the compressed breast in the supine position was developed, which is based on a 3-D patient-specific breast model constructed from MR images with the use of the finite-element method and nonlinear elasticity constitutive equation Mooney-Rivlin.

II. METHODS

The main parts of the breast deformation are the segmentation of the breast boundary, 3D breast modeling and the simulation of the breast deformation. The flow chart of breast deformation modeling is shown in Figure 1. Firstly, the skin of the breast is extracted by using the thresholding segmentation algorithm. Secondly, a 3D region growing method is used to generate the 3D breast model that is used to get the surface mesh of the breast by using the Mimics [6]. Thirdly, the meshed model is imported into the finite element software Abaqus to get the breast deformation model [7]. Finally, the Mooney-Rivlin method is applied to simulate the deformation.

A. Breast Boundary Extraction

To create the 3D model, the boundary of the breast region should be extracted, which is to locate the breast-skin and breast-chest wall. Since air produces almost zero MR signals, the background in MR images is virtually black, the breast-skin boundary is relatively clear, as shown in Figure 2 (a). So the thresholding method can be used to extract the skin region [8]. There are two steps included as the below.

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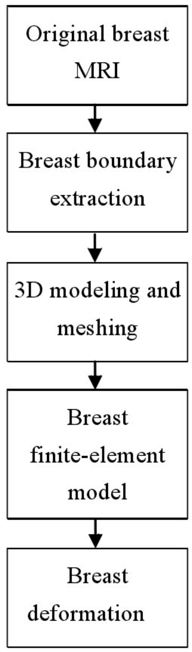


Figure 1. Flow chart of breast deformation modeling

1) Preprocessing the image: To remove the points with low pixel value, a threshold is set to filter the points. The main method is as follows, where f(x,y) is the original pixel value and F(x,y) is the value which is filtered. The preprocessing results is shown in Figure 2 (b).

$$F(x,y) = \begin{cases} 0, f(x,y) \leq \text{threshold} \\ f(x,y), \text{others} \end{cases} \tag{1}$$

2) The extraction of the skin: In order to smooth the skin boundary, the closed operation is used to process the image. After that, an improved threshold method is used to segment the skin boundary. The method is described as followed. Where the function M is to compute the sum of the pixel values around the point (x,y), see Figure 2 (c).

$$F(x,y) = \begin{cases} 0, M(f(x,y)) \leq \text{threshold} \\ M(f(x,y)), \text{others} \end{cases} \tag{2}$$

After the segmentation, the mathematical morphology operations is used to fill the holes of the images. The final segmentation result is shown in Figure 2 (d).

In the breast MR images, breast-chest wall is hardly to be distinguished, so the breast-chest is segmented manually in this paper.

B. Establishment of the 3D model

In the 3D image modeling section, a 3D thresholding method and a 3D region growing method [6] are used for 3D modeling, after the creating of the three-dimensional model, the tetrahedral meshing geometry is established, which is used in the following section.

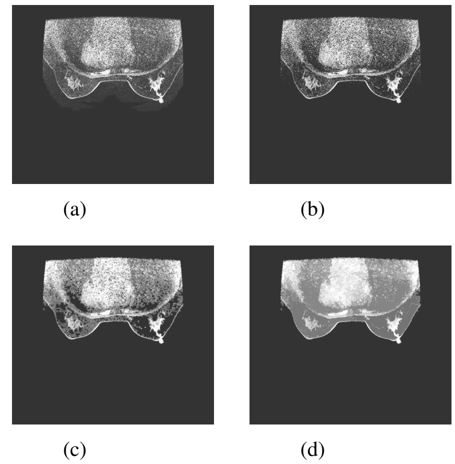


Figure 2. Extraction of breast skin ((a) original image; (b)result of preprocessing steps ;(c) segmentation results without filling the holes; (d) the final segmentation results)

After the segmentation part in the previous step, there will be several kinds of image pixels in the dicom files after the manual segmentation. One kind is represented for the soft tissue of the breast; the others are represented for nothing. Besides, some discrete points will also exist in the files because of the manual mistakes. Therefore we can use the thresholding segmentation method to segment the pixels we care about by using Mimics. Since the model to be generated should be a closed model, the discrete points cannot exist in the model. In this paper, the 3D region growing segmentation algorithm is adopted to convert the 3D model which contain some discrete points to a closed model.

Region growing algorithm makes the pixels with similar characteristics together. The principles of the region growing algorithm are as follows. Firstly, a seed point is selected from the region to be segmented. And then the algorithm will search the pixels which are near the seed point, it will add the pixels to the segmented region when the pixel meet the growth standards. Then the recently added point will be a new seed point. The procedure will continue until there is no new seed point.

C. Establishment of the finite element model

In this paper, a finite element method [4] is used to simulate the deformation by means of the Mooney-Rivlin constitutive equations. The finite element model has an increasingly wide field of applications all around the world. The method can obtain relatively high accuracy in the deformation of the soft tissue. With the help of the finite element software Abaqus [7], the deformation of the breast can be achieved. The import of the 3D grid model, the determination of material parameters, the setting of the boundary conditions and the applied gravity to the model are all included as the flowing.

1) Material parameters: Different tissues within the human body have different physiological functions, so structures of the tissues are different and material properties vary greatly from the perspective of anatomy. The complexity of the material properties of the breast soft tissue are reflected in the aspects such as creep, relaxation, nonlinear, non-uniformity, anisotropy and viscoelasticity [9]. Because of the various biological characteristics, it is hard and complex to create the all the properties of the breast tissue. The stress-strain relationships of the soft biological materials for the soft tissue are usually nonlinear [5]. In this paper, a nonlinear viscoelastic model Mooney-Rivlin [5] is applied as the constitutive relations when making the deformation, the model was used to simulate the rubber material firstly [10]. In Mooney-Rivlin, the strain energy density function W is a function of the deformation invariants I_1,I_2 and I_3.

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2 \tag{3}$$

$$I_2 = \lambda_1^2\lambda_2^2 + \lambda_2^2\lambda_3^2 + \lambda_3^2\lambda_1^2 \tag{4}$$

$$I_3 = \lambda_1\lambda_2\lambda_3 \tag{5}$$

$$W = C_1[e^{\beta(I_3-3)}] + C_2(I_2 - 3) + g(I_3) \tag{6}$$

Here, C_1, C_2 and β are the kinetic constants. λ_1, λ_2 and λ_3 is the elongation ratios of the x, y and z directions. g(I_3) is a function to describe the degree of compressed material and the value of g(I_3) is set to 0 means that the material is non-compressed. The non-linear model has better mechanical properties and has been widely used at present.

2) Boundary condition and gravity: As the state of the breast soft tissue is generated under the gravity, in this paper, a diverse gravity is applied to the finite element model. And after that the corresponding reference state of the 3D finite element model can be obtained. The so-called reference state is that the model is under no force including the gravity [11].

Secondly, because of the constraints of the breast by the pectorals, a zero displacement of the pectorals is given as the major constraint in the 3D finite element analysis. The displacement constraints could largely determine whether the finite element analysis can result in convergence. The condition was the basis of the finite element analysis.

3) Creating analysis step: There are two different ways to create the analysis step [7], one is the explicit analysis, and the other one is the standard analysis. Abaqus/Standard is suitable for the moderate non-linear problems of which the nonlinearity is smooth (for example, plastic); if it is a smooth nonlinear response, Abaqus/Standard requires less number of iterations to find the converged solution.

The standard method is suitable for the problems with a longer frequency response compared to the frequency of the vibration and it is also used to solve the nonlinear problems of which the nonlinear is smooth. Since there will be no contact problem when solving the problem under gravity, the standard analysis step is used to solve our problem.

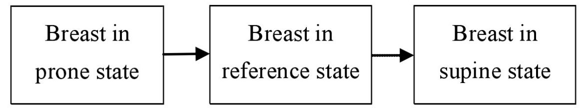
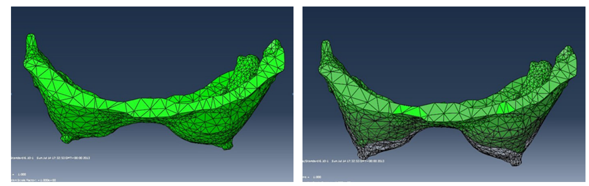


Figure 3. Process of breast deformation from prone state to supine state



(a) (b)

Figure 4. Reference state of the breast ((a) reference state; (b) comparison between reference state and prone state)

D. Deformation of the model

After the basic procedures of creating the finite model is completed, the method discussed above is used to implement converting the model of breast from prone state to reference state which is the shape of the breast without any external forces. In the same way, an inverse gravity is applied on the reference state to obtain the supine state where the displacement constraints applied on the pectoral is the same as the above. The process of breast deformation is shown in Figure 3. Details of deformation are given below.

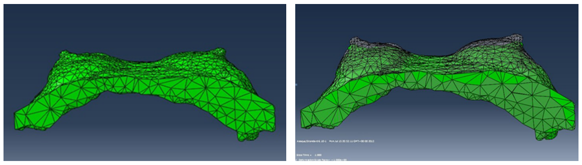
1) Get reference state: In this paper, we assume that the breast is only under gravity force in the prone state. Because of the characteristics of plastic anisotropy and viscoelastic of the breast, we cannot model all the characteristics in fact. In this paper, a compromise method Mooney-Rivlin [4] discussed above is used to model the characteristics of hyperplastic. It can be used to model the breast soft tissue. To get the reference state, an inverse gravity force is applied to the model. After applying that, the reference state of the breast is got as shown in Figure 4.

2) Get supine state: In the process above, the finite element software Abaqus is used to generate the reference state, which can be used as the basis for our future analysis. The method to get the supine state is familiar with the method used to get the reference state. We can go on imply an inverse gravity to obtain the supine state. The constitutive equation used is still the described Mooney-Rivlin model. Restraint is also the displacement constraints added on the pectorals in the previous model. After that we create the analysis step to obtain the model of the supine state. The result of the supine state is shown in Figure 5.

III. RESULT AND EVALUATIONS

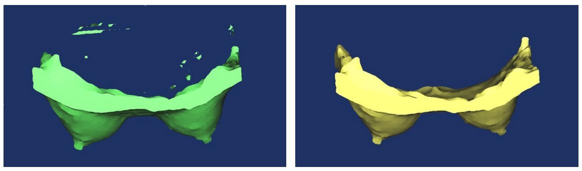
A. Results of the deformation

The breast MR images (patient lies prone) used in this paper were acquired from the Military General Hospital of Beijing PLA. Three data sets were used to evaluate the



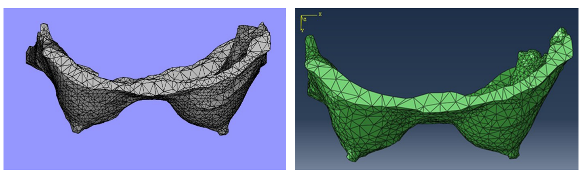
(a) (b)

Figure 5. Supine state of the breast ((a) supine state; (b) comparison between supine state and reference state)



(a) (b)

Figure 6. Results of creating the 3D model ((a) 3D model with discrete points; (b) 3D model without discrete points ;)



(a) (b)

Figure 7. Results of the meshed 3D model ((a) original meshed model; (b) optimized meshed model ;)

performance of the proposed method. Mimics software was used to build the 3D model. In the software, the simple thresholding is used to make some segmentations of the dicom files at first. Then unrelated area will be split off after that and some discrete points will still in the main region. And the region growing method was used to generate a 3D model which is closed, then the discrete point was disappear. The results of the model are shown in Figure 6.

Tetrahedral meshes was generated by using the auto meshed methodthe model is shown in Figure 7, some optimizations have been made on the meshed model.

The meshed model consists of many elements, each element is a tetrahedron and each tetrahedron has four nodes. An inp file [6-7] which can represent the relationship between nodes and the elements will do as the interface of Abaqus and Mimics. In the first part of the finite element modeling, we import the inp file which is obtained in the previous step into the Abaqus, and then a meshed 3D model can be displayed in the Abaqus.

In the part of finite element modeling, the 3D model was converted into a physical model and the constitutive equation Mooney-Rivlin was used to describe the material of the model. The constitutive equation is integrated into Abaqus, three parameters C_{01}, C_{01} and d need to be specified when using it. The parameters provided in [5] are used here. Through experiments, we finally selected the parameters C_{01} = 2kPa, C_{10} = 6kPa and d = 0.00001. The density of the breast soft tissue is set to 800 (Abaqus has no units, just unify the various parameters when using them).

After the establishment of loads and boundary conditions, we can get the breast model in the reference state. The breast model in the reference state and a comparing picture between prone state and reference state are as follows,the results and comparison can be seen in Figure 4.

Like the procedure above, we can get the supine state and the comparison between the reference state and supine state, as we can see from Figure 5.

B. *Method for results analysis*

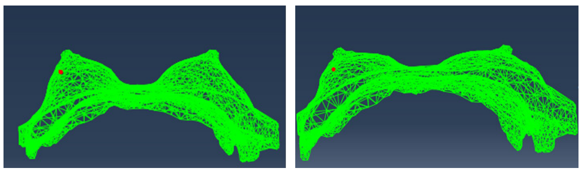
To verify the validity of the model, we need to use the position of the tumor tissue to evaluate the accuracy of the model. A breast with relatively large tumor is used to perform the corresponding experiments, and the tumor can be detected in both MRI and ultrasound. Then we can make a comparative experiment to verify whether the model is validity.

First we need to locate the tumor in the soft tissue in prone position, the coordinate of the original model is as follows: x: medial-lateral, y: anterior-posterior, and z: superior-inferior. In the dynamic enhanced graphics of the breast tissue, we can directly measure the specific location of the tumor, in this paper nipple is used as the reference position of the tumor. Because the tumor is a lump, in order to help us validate the model, we only measure the position of the tumor border relative to the position of the nipple. So we can get the coordinates of the tumor boundary by referring the coordinates of the nipple. Since the model is made up of grids, so the tumor may not be on a position corresponding to a real point, in this paper, we use an approximate method to simulate the position of the tumor. Firstly, we search the nearest coordinates closed to the tumor. Then, we pick the nearest points as the tumor approximated. And after the deformation simulation, we can obtain the corresponding coordinates of the points. By calculating the Euclidean distance of the points, the comparison results can be achieved.

In our experiments, three cases were used. The results of them are listed in Table I. As it is shown in Table I, ultrasound results are the real position of the tumor in supine state while the experiment results refer to the results of our simulation. The Euclidean distance is calculated based on the real data and the experiment data. In order to show the movement of the tumors, Figure 8,Figure 9 and Figure 10 are showed as follows where the red point is the representative of the tumor. As we can see from the table, an average of 4.94mm is achieved. Generally, this result is of great help for doctors and patients. It is of great significance especially for those patients whose tumor cannot be observed by using ultrasound.

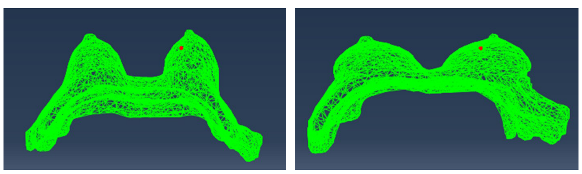
Table I
RESULTS OF THE EVALUATIONS

Case Number	Ultrasound Results(mm)	Experiment Results(mm)	Experiment Results(mm)
1	(50.42,142.07, -8.53)	(54.51,143.25, -10.46)	4.78
2	(238.62,202.89, 18.31)	(233.58,202.66, 16.91)	5.24
3	(72.09,126.57, 22.21)	(72.68,130.46, 19.44)	4.81



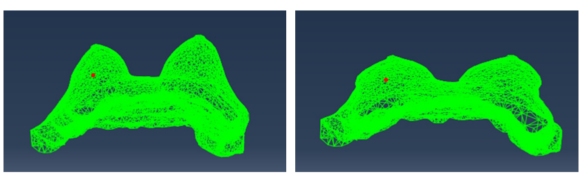
(a) (b)

Figure 8. Comparison between prone state and supine state of case 1 ((a) prone state with tumor location; (b) supine state with tumor location ;)



(a) (b)

Figure 9. Comparison between prone state and supine state of case 2 ((a) prone state with tumor location; (b) supine state with tumor location ;)



(a) (b)

Figure 10. Comparison between prone state and supine state of case3 ((a) prone state with tumor location; (b) supine state with tumor location ;)

IV. CONCLUSION

In this paper, a practical method to predict tumor location by simulating the breast deformation from prone state to supine state has been developed, which constructed 3-D patient-specific breast model from MR images with the use of the finite-element method and constitutive equation Mooney-Rivlin. An average accuracy of 4.94mm is achieved by using the proposed method. It is obviously that the method is of great significance to doctors in clinical.

Besides, we can see that there are still some shortcomings and inadequacies such as the manual segmentation process and the meshing precision. Both of them will affect the accuracy of the experimental results. All of this talked above should be considered in the future research.

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