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Toward Biomimic Breast Deformable Model for Robotic Breast Biopsy Navigation Development

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Abstract—**Breast cancer is the most common cancer in female. Accuracy of breast biopsy intervention is necessary for the certain breast cancer diagnosis. Many breast navigation systems have been developed in the past time to cope with this uncertainty, however, the worthwhile accuracy could not yet reach due to the breast deformation during the intervention. The concept of breast mathematical model to simulate breast deformation and guide the breast biopsy intervention is proposed in this paper. The real-time and the accuracy of the model are the critical requirements to use the model with the breast biopsy navigation. The breast model is constructed by simplify the continuous breast tissues into finite point-masses system with specific stiffness and damp on linkages between masses. The mesh alignments are arbitrary base on evidence of the tissue's microstructure. The mass-spring method is used for implementation the point-masses and their linkages. The experimental system simulation for using model with real-time breast biopsy navigation was setup on a constructed mass-spring system of 2D breast phantom. The experiment was performed to proof the core concept of the proposed breast model to be use as a key component for our full-robotic breast biopsy navigation.**

I. INTRODUCTION

BREAST cancer has been the most commonly diagnosed cancer among women worldwide. Most early breast cancer detections are from the signs of breast abnormalities seen on screening mammogram while the definite breast cancer diagnosis could be made with histological examination of the abnormal tissue. The reliable of breast cancer diagnosis depends on whether the tissue samples were truly collected from the suspicious site of detected abnormality. Breast biopsy is the procedure to collect tissue samples from breast. Biopsy needle is inserted though breast skin and sampling tissue out of the target lesion using some image modalities such as ultrasound, x-ray, or magnetic resonance imaging to monitor direction and position of the biopsy needle toward the target tissue's location.

Breast biopsy can be performed only by the expertise radiologists. The limitation and confuse perspective of the guided image modalities could cause the difficulties of controlling biopsy needle insertion. Moreover, breasts could be deformed by breath motion, posture change, or external force applied on breasts during breast biopsy. The position of target tissue settle inside breast can suddenly shift with the breast's motion thus result in target missing.

Navigation the breast biopsy intervention with the tracked biopsy needle and the calibrated imaging equipments could solve the problem of dimensional limitations of image guidance [1] but not the problem causes by the deformation. The mathematical model of how the breast tissue deform under specific conditions might be the most practical way to deal with deformation. The term 'deformable model' was first proposed by Terzopoulos in 1987 [2] and since then the deformable models have been widely used in various types of applications.

Deformable models have been used in many applications, especially simulation, animation and product design. In medical application, the model is well-known for surgical simulation [3], medical image analyses [4], and is used for analysis of developed medical devices [5]. The heuristic approaches such as Deformable Splines or Mass-Spring Model are favorable for surgical simulation since only the natural-like look or sensing is the requirement for the simulations [6]. Accuracy is not critically need. The same goes with image analyses which model-driving algorithms deform features in the static image toward the deformed image [7], no physical-based deformation needed to be known. Deformable models in medical devices analyses are different. The accuracy and the realistic is required evaluate an object deform characteristics under specific stress-strain conditions. Model bases on Continuum Mechanics [8] with Finite Element Method (FEM) implementation is widely used. However, this method can only be used offline due to the large amount of time for the computation.

Deformable models for the guidance of surgery or intervention are quite uncommon and none of the existing was well-established for integrating to the navigation system. In this paper, the concept of deformable model for surgical/intervention is proposed focusing on assisting breast biopsy intervention. The simulation and analysis are performed to proof the concept is practical to be integrated to the system.

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II. DESIGN CONCEPT

The core of this paper is the concept of deformable model for surgical/interventional navigation: breast biopsy. The key concerns of our application are

1) Accuracy: The model should be built upon constitute law of motion to retain the realistic of deformation and subsequently predict the characteristic of breast deformation during biopsy.

2) Capability of reaching real-time computation: Since both the deformation and the navigation in surgery or intervention are time-dependent, the model suites for this application should provide accurate navigation result at accurate time to accomplish the true accuracy of the system.

This concepts of utilize deformable model in navigation application are rarely found. Most applications of deformable model in medicine could be categorized in to three main application; image analysis, surgical simulation, and offline analysis, as mentioned above. None of these require accuracy together with the properties of real-time computation in the same method. The issue blocking accurate models from real-time computation is the complexity of solving governing partial differential equation of dynamic elastic material,

$$\rho \ddot{x} = \nabla \cdot \sigma + f \tag{1}$$

Which is in accord with Newton's second law. ρ is material density, f is the external force, and σ is the stress tensor. Equation (1) is the mathematical model of continuous materials according to continuum mechanics. Numerical method such as FEM is commonly used for discretizing the model into linear model and iterately solving for the model's equilibrium. However, the method is far too complex to yield real-time performance. Wouldn't it be better to have mathematical model which already be the simplified form of the material's physical properties which easier to solve?

Continuous material can be discretized into system of finite point-masses, on molecular perspective. The interaction between point-mass depends upon bonding or linkage between two adjacent point-mass, thus, result in the overall materials' mechanical and chemical properties. This explains why diamond and charcoal have different characters with different carbon stack. Focusing on the soft tissue which is the compound organic material, microstructure also play the important role on the tissue stiffness and characteristic how each soft tissue deform under specific conditions. One of the good example is the epithelial tissues with different cell shape, arrangement, and cell stack influence the large-scale mechanical properties of tissue through cellular tension and intercellular adhesion force between adjacent cells as well [9, 10].

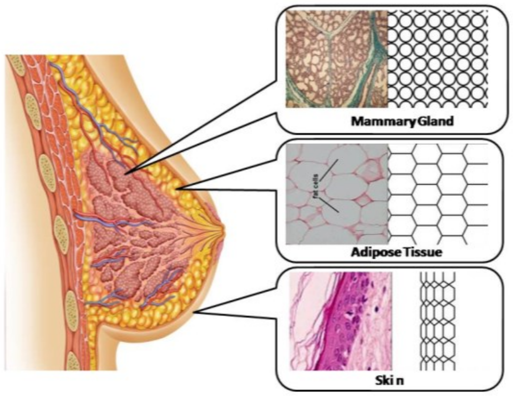

Fig. 1. Breast anatomy, its tissue components, and the mimic mesh shape corresponding to microscopic structures (the sources of images used in this diagram are from [11-13])

Breast composes of number of different soft tissue; squamous epithelium (skin, alveolar, and nipple), adipose tissue (supporting fat), glandular tissue, and fibrous connective tissue. The neighbor tissues are the chest muscle and its fascia sheet. Corresponding tissues' properties could be modeled mimic to their cytostructure and distribution of stiffness around one discretize point-mass. The breast anatomy and the ideas how the tissue can be modeled are shown in Fig. 1.

The linkage between point-masses works as the stiffness as the two masses move closer or apart from each other. The common relation of stiff is according to position (x) and velocity ($\dot{x}$) between the two adjacent points. Therefore the equation of motion of the system consist of N point-masses is

$$M\ddot{x} = -C\dot{x} - Kx + f \tag{2}$$

where M, C, K are the mass, damping, and stiffness matrices of dimension 3Nx3, respectively. Hence the PDE in Equation 1 become the system of second order ordinary differential equation when simplify the continuous material into finite point-mass system. The system could be solved by integrating the system over time which is numerically performed by multiplying the finite step of Δt to the equation over time.

III. MODEL SIMULATION AND ANALYSIS

A. System Simulation

The overview of integrating the deformable model in the breast biopsy navigation system is designed base on traditional breast biopsy protocol and necessaries.

The based breast biopsy navigation system is developed by Taniutchawoot and Bantita [14, 15] in our research group.

This system could be integrated with ultrasound imaging modality, MR, or other modalities of interest for breast biopsy guidance. The deformable model would be integrated into this system to definitely work with breast; the most deformable organ.

Breast biopsy navigation is simulated working with the deformable model. The design of model-integrated breast biopsy navigation is depicted in Fig. 2 which consists of tracking camera to track biopsy needle and imaging devices and surface camera to track breast surface deformation. The deformable model would deform itself according to the input surface deformation to localize the target site inside deformed breast. The system then navigates the tracked needle insertion to the target site with the confirming of calibrated guided image.

Parts of the design system which involve with the deformable model are separated from the overall system as in Fig. 2 (b) and are simulated in this section to proof the concept of developing the breast model for breast biopsy navigation.

In the system simulation, we mapped a 2D video of our constructed breast mass-spring system to the simulated model mimicking that mass-spring system. Fig. 2 (c) shows the setup of the simulation which consist of a web camera, a breast phantom, and a notebook computer. The camera captured the real-time motion of the feature points in the phantom during the author performed instant pushing on the individual place to deform the system. The captured motions of the features were sent to the computer as inputs of the model to predict the innermost feature in the breast phantom. The setup of system simulation imitates the diagram of the designed system in Fig.2 (b).

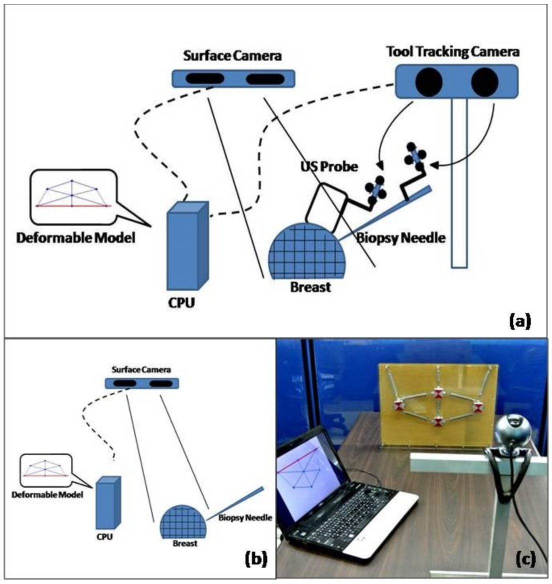

Fig. 2. The diagram shows component of the system, (a) the design of the robotic breast biopsy navigation system, (b) part of system which mainly involve with the deformable model, and (c) photo of the setup of the system simulation experiment.

breast was constructed with known springs' coefficients as depicted in Fig. 3 for the breast phantom. Parallel acrylic planes which assumed slightly friction are the 2D motion constraint. Spring connections between masses are equipped with our design accessory to make the theoretical springs out of the compression springs; the springs can be either stretch or compressed under the same spring's coefficient.

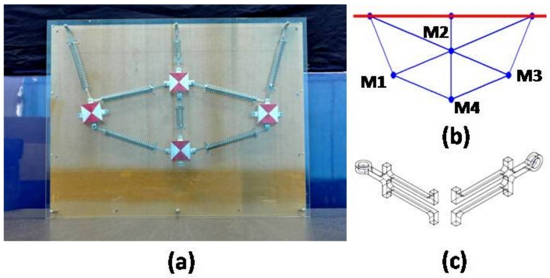

Fig.3. (a) Constructed breast mass-spring system, (b) 2D animation of the system with point-masses labeled M1, M2, M3, and M4 (c) the spring accessory

The position of the outer nodes; M1,M3, and M4 masses (Fig. 3 (b)), in the model is mapped to the corresponding feature points in real-time captured image. M2's position is evaluated in comparison between in the capture images and the model. The sharp rod punches in one of the three outer nodes to interfere the system time to time.

Offline camera calibration is pre-processed using Camera Calibration Toolbox for MATLAB [16] to find exact pixel dimension in millimeter. The system was set up so (Fig. 4 (a)) the camera plane and the front plane of our mass-spring system are parallel. The red marks were drawn on every masses in order to detect positions of the centers. Our in-house feature detection base on Hue channel (Fig. 4 (b-c)) is developed to detect the position of four massed. Temporal calibration is unnecessary in this simulation since only one camera systemic used to capture both motion of masses and motion of needle tool without the need of the tracking system.

Coefficients of the springs and the masses in the model is set to equal to the spring coefficient and mass weight used in the construction. Equation of motion for each discrete mass is according to Lagrange's Mechanics,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\frac{\partial L}{\partial q_i}+\frac{\partial P}{\partial \dot{q}_i}=Q_i \tag{3}$$

According to equation (3), here we have

$$K=\sum_{i=1}^{4}\frac{1}{2}m_i\,\vec{\dot{X}}m_i\cdot\vec{\dot{X}}m_i \tag{4}$$

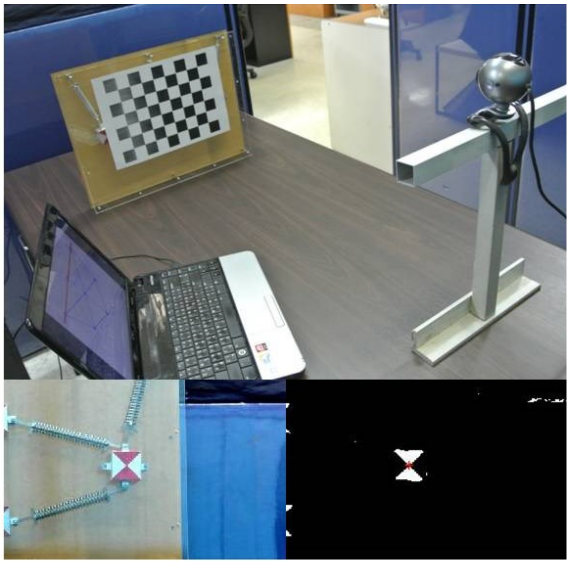

Fig. 4. The diagram shows component of the system, (a) the design of the robotic breast biopsy navigation system, (b) part of system which mainly involve with the deformable model, and (c) photo of the setup of the system simulation experiment.

$$V=\frac{1}{2}k_{ij}\left(\vec{X}m_i-\vec{X}m_j\right)\cdot\left(\vec{X}m_i-\vec{X}m_j\right)+\frac{1}{2}k_{ij}{l_{ij}}^2 -k_{ij}l_{ij}\left[\left(\vec{X}m_i-\vec{X}m_j\right)\cdot\left(\vec{X}m_i-\vec{X}m_j\right)\right]^{\frac{1}{2}}-m_i g\vec{X}m_i\cdot\vec{e}_j \tag{5}$$

Therefore, the equation of motion for mass i is

$$m_i\ddot{\vec{X}}{m_i}^T-k_{ij}\left(\vec{X}m_i-\vec{X}m_j\right)^T+\frac{k_{ij}l_{ij}\left(\vec{X}m_i-\vec{X}m_j\right)^T}{\sqrt{\left(\vec{X}m_i-\vec{X}m_j\right)\cdot\left(\vec{X}m_i-\vec{X}m_j\right)}}+m_i g=Q_i \tag{6}$$

Simulink Diagram (Fig. 5) is implemented for the simulation and understandable systemic workflow. The diagram shows the interaction between masses.

The central block which implements the equation of motion for mass M2 (center mass) includes second-order integration and subtraction block of its own position and surrounding nodes for each spring displacement. On the contrary, boundary nodes' block (M1, M3, M4) contain acquisition block of actual masses' position which is the input from captured images. Additional second-order integration and subtraction block as in central node are options for a boundary block in case of losing of data acquisition at some boundary nodes.

Adaptive step size for 4th-orderRunge-Kutta Method is used in the integration scheme. Online implementing is tested starting with image acquisition, feature extraction, pixel to millimeter conversion and integration scheme. Time counting for interval, right after image acquisition, though output acquisition is collected as well as positions of center node in images and corresponding simulated positions.

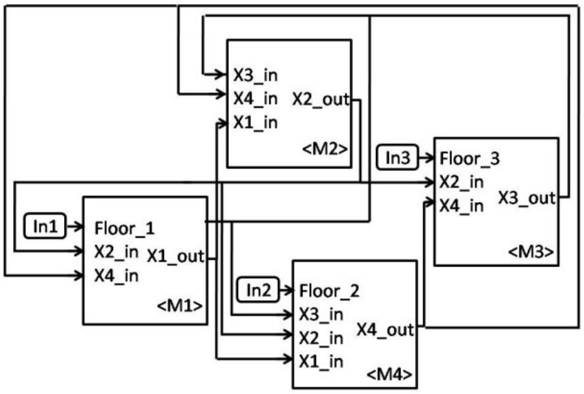

Fig. 5. Simulink Diagram of simple breast simulation. <M1>, <M2>,<M3>, and <M4> label the block of mass corresponding to Fig.3 (b). The names follow with _in indicate input to that block from other node. The names follow with _out indicate output from that block to the other node. In1, In2, and In3 indicate constant locations of floor attachment.

IV. RESULT

The result of the system setup and the simulation are presented in this section.

The calibration result of the experiment setup was 4.24 mm and 4.56 mm for a pixel's width and height. The accuracy of the in-house developed feature detection was 4.14±1.47 mm in all the captured images compare to the manually positioning the center of masses in every images. The average time for one loop of process count from image acquisition, feature extraction, pixel to millimeter conversion and integration scheme is 1.09 ±0.21 seconds.

The system simulation results are separate according to two different scenarios; system without interference and system after interference until the system reach equilibrium position again. The scenarios were categorized by the judgment of the author to differentiate the image series from series of captured images. Without interference, the system has the mean absolute error (MSE) of 15.93±9.28 mm. The MSE while the system has been interfered is 18.29±12.31 mm.

V. CONCLUSION AND DISCUSSION

The breast biopsy is an intervention to sampling abnormal breast tissue to examine whether the tissue is cancerous. The accuracy of the sampling process is critically required in order to have the correct breast cancer diagnosis. The use of navigation system with breast biopsy could improve the efficiency of the performance. However, the breast deformation remains the main problem in the inaccuracy of the biopsy intervention.

This paper focuses on developing breast mathematical model to simulate the breast deformation during the biopsy intervention. The overview of the computer-integrated breast biopsy system which includes the navigation system and the breast deformable model is also described and designed to understand the role of the purpose model in the whole system. The model would be assigned deformable properties according to the breast anatomical components and virtually deform according to an actual breast and calculate where the lesion is in any deformed configuration. Then the biopsy needle could be navigated to the breast tissue target during the breast deformation.

The concept of the breast deformable model for breast biopsy navigation is proposed and proof in the two main requirements of the concept; the accuracy and the real-time capability.

The result of our system simulation represents the accuracy of the simple model to perform the prediction of the target inside the breast. The result while the system is not interfere indicated the baseline accuracy of the model to predict the system without dynamic while the interfere system is very dynamic to mimic the real-time deformation due to biopsy needle insertion. The accuracy result depends on many factors, the model accuracy itself, the time mismatch between the model and the system, the accuracy of our in house feature detection algorithm, and also the camera calibration algorithm. The range of standard deviation of the none interfere system would indicate the error of the feature detection algorithm while the MSE itself represent the baseline difference between the model and the construction. The MSE during the construction is dynamic is higher than the other as predictable because it include the integration error and the time mismatch. However, the result is promising and challenges the more complex tissue model.

In any object, the gross structure is the shape we see, but plenty of deeper structure levels can be observed within, range from the macrostructure, microstructure until the molecular structure. Breast, for example, is on organ with deeper levels composed of different tissue types. Each individual tissue also includes different types of cells and noncell components. The mass-spring (damper) method with mesh shapes mimicking microstructures is used to simplify the way to model the influence of underlining structures in soft tissue which evidently is associated with remodeling phenomenon.

The mass-spring technique is one of the most famous methods to model dynamic object because spring and dashpot displacements over time are calculated via integration of known differential equations over time rather than iterative solving of the systemic equation. However, problems that a mass-spring technique's user might experience would be computational overload and system instability. The first is related with computational complexity and integration time-step variable chosen in implementation. Second, system instability is mostly due to poor mesh topology. To reduce too much computation, most previous works simplify their implementations in several ways, i.e. surface implementing of 3D object instead of 3D implementing itself and set proper time-step for each system. With inappropriate system simplification, deformation time-lag is easily experienced visually and, consequently, inaccuracy of the model response. Poor mesh design leads to system collapse with shear forces. Many recent mass-spring-damper models tend to add some additional altitude connection between each particle or particle to virtual plane in each unit shape. However, in-creasing the number of spring connection leads to more complex implementation.

To avoid such situations, future studies would include characteristics of a system response over a boundary condition. This might solve the issue of computational overload due to incredibly small time step during integration. Moreover, boundary values prohibit components from causing system collapse.

Deriving a breast model leads to further advantage for biopsy path planning based on deformable prediction.

Design of a systemic workflow is also interesting. Deforming model to actual breast contour using grid projection camera or soft marker is the initial idea to operate in real-time during breast intervention. However, system workflow might be considered to avoid obstructing the clinical intervention. Furthermore, robotic needle insertion with specified insertion velocity is an important part to make the performance of biopsy steady and predictable.

In the future, further applications that can be expected from the breast model are central platforms for breast diagnosis; planning, intervention guiding, follow-up assessment, or breast reconstruction outcome prediction. With the central platform, intervention on breast can be easier, using the new way of interpreting medical information.

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