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A Surface Vibration-based Method for Tumor Detection of Women Breast in a DIET System

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Abstract

This paper presents a hysteresis loop analysis (HLA) method based on dynamic force-displacement relationship to detect and localize cancerous tumors that exhibit significantly higher stiffness than soft healthy tissues in women breast. Steady state sinusoid displacements induced by mechanical actuation for 2 silicone phantoms (1 homogeneous "healthy"; 1 with 20mm stiffer inclusion "tumor") are captured using a non-invasive Digital Image Elasto Tomography (DIET) system. Hysteresis loops for each measured reference point across the phantom surface are reconstructed using the measured displacement and a calculated mass normalized restoring force. The distribution of the elastic nominal stiffness over the breast surface is estimated using an F-type hypothesis test and regression analysis. The sensitivity of the method to measurement errors from the DIET system is evaluated using a homogeneous healthy phantom with different camera angles. Results show displacement reconstruction errors from very small motion can be eliminated by using a threshold Δd to significantly reduce errors in identified nominal elastance. The stiffer inclusion induced a greater number of reference points with higher stiffness in the inclusion segment than other segments in the x and y directions, while a consistent distribution of stiffness for the homogeneous control phantom was identified. The overall results show the capability of the method to accurately detect and locate the inclusion in typical, representative silicone breast phantoms without misidentifying other regions or a healthy no-inclusion phantom.

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Keywords: Steady state actuation; force-displacment relationship; hysteresis loop; statistical analysis; tumor detection; stiffness identification.

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1. Introduction

Breast cancer is diagnosed in over one million women annually and causes over 400,000 mortalities [1]. Successful early detection provides a means to reduce mortality, where a tumor size of 10-14mm at first detection has been shown to lead to 15-year survival rates of over 85% [2]. The current standard screening technique is X-ray mammography. Mammography causes patient discomfort due to breast compression reducing screening compliance, requires radiation exposure limiting the applicable age group, and is less available in remote areas [3]. In addition, mammography can have low sensitivity as the radio-density of cancerous tissue varies only 5%-10% from healthy tissue, which can lead to false-positive rates up to 24% [4]. However, cancerous breast tissue is 400-1000% stiffer than healthy breast tissue [5], which is a far greater than the radio-density contrast in standard X-ray mammography for breast cancer screening.

Successful approaches based on elastography have been developed to image and characterize the elastic properties of normal and abnormal human tissues. Many of these techniques rely on full volume measurements of actuated tissue displacements using magnetic resonance [6] and ultrasound [7] imaging. These methods require expensive imaging equipment, and use computationally expensive and difficult inverse problems to find tumors in the 3D volume [8], and can also suffer identifiability issues [9]. Both techniques have yielded comparable results to direct mechanical measurement of tissue [10], but, as noted, are extremely expensive in computation and equipment.

Digital Image Elasto-tomography (DIET) is a novel elastographic approach to quantify elastic properties of human tissue [10-13]. In the DIET system, steady-state, low amplitude sinusoidal mechanical motion is induced in the breast volume. Cameras arranged in a ring capture 2D images of the breast surface at 10 points in the sinewave (every 36 degrees) over a full vibration cycle. A reconstruction algorithm uses consecutive sets of 2D images to generate a 3D model to measure surface displacement of each reference point [14, 15].

In the search for rapid, effective and computationally light solutions, this study develops a practical hysteresis loop analysis based method to identify the nominal elastic stiffness across the surface of the breast. The identification method is applied to 2 silicone breast phantoms with comparable properties to human tissues [16] to experimentally demonstrate and validate the feasibility of this approach. The sensitivity of the method to measurement or displacement construction errors is investigated using a homogeneous healthy phantom with different camera angles, although a similar method has previously shown good robustness to a wide range of measurement noise and model uncertainty in very different dynamic applications [17-19]. Finally, the detection and localization of stiffer inclusions in the breast phantom is achieved by identifying significant changes of nominal stiffness in the region of inclusion, along with consistent, lower stiffness values in the remainder of the phantom mimicking healthy tissues.

2. Method

The dynamic hysteretic behavior of each reference point at the breast surface can be represented using a single-degree-of-freedom (SDOF) nonlinear mathematical model:

$$f_s(v(t), \dot{v}(t)) = -m \cdot \ddot{v}(t) \tag{1}$$

where m is the mass attributed to the selected point, $f_s(v(t), \dot{v}(t))$ is the restoring force, and $\ddot{v}(t)$ is the relative acceleration of the reference point to the fixed base in the DIET system. Gravity and input actuation forces are ignored, as they are vertical forces and the equation only assesses stiffness in the horizontal direction. Thus, Equation (1) can be rewritten:

$$f_s(v(t), \dot{v}(t)) / m = k_e \cdot v(t) = -\ddot{v}(t) \tag{2}$$

where $f_s(v(t), \dot{v}(t)) / m$ is a mass normalized, generalized restoring force approximated by a nominal or effective stiffness, k_e, and relative actuated tissue displacement $v(t)$.