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OCE quantification of Poisson's ratio through 2D speckle tracking

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Abstract

We describe a real-time 2D motion tracking method based on speckle analysis. We implemented this method in real-time using graphic s processing unit (GPU). The capability to track both axial and lateral motions will enable more comprehensive characterization of tissue mechanical properties including Poisson's ratio.

Keywords

Optical coherence elastography; 2D motion tracking; speckle

1. INTRODUCTION

Optical coherence elastography (OCE), a technology derived from optical coherence tomography (OCT), can be used to interrogate tissue mechanical properties in micro-scale [1, 2]. Compared to other implementations of OCE, compression OCE, similar to an indentation instrument for mechanical characterization, is simple and can be conveniently applied to an atomic site s of interest. However, accurate assessment of tissue mechanical properties through indentation is not a trivial task. Despite the complicated boundary condition, the motion at every spatial location within the sample is a vector with non-zero components in axial and lateral directions [3]. In this manuscript, we describe a real-time 2D motion tracking method based on speckle analysis. We implemented this method in real-time using graphic s processing unit (GPU). Therefore, tracking of both axial and lateral motion s will provide a more comprehensive characterization of tissue mechanical properties including Young's modulus and Poisson's ratio.

2. PRINCIPLE

We use sequentially acquired Bscan OCT data (Figure 1 (a)) for 2D motion tracking. To assess the displacement at pixel (i, j) in the k^{th} Bscan (Figure 1 (b), left), we select a region centered at pixel (i, j) (square enclosed by black solid lines in Figure 1 (b)). We will also select a region (square enclosed by black dashed lines in Figure 1 (b)) in the subsequent image centered at $(i+n_x, j+n_z)$. For each pair of regions (S_k centered at pixel (i, j) and S_{k+1} centered at pixel $(i+n_x, j+n_z)$) chosen, we calculate the cross-correlation coefficient using Eq (1), where $E(\cdot)$ indicates to take the expectation value; μ_{S_k} and $\mu_{S_{k+1}}$ indicate the mean

value of the chosen sub-images; σ_{S_k} and $\sigma_{S_{k+1}}$ indicate the standard deviation of the chosen sub-images [4].

$$\rho_{n_x, n_z} = \frac{E[(S_k - \mu_{S_k})(S_{k+1} - \mu_{S_{k+1}})]}{\sigma_{S_k} \sigma_{S_{k+1}}}. \quad (1)$$

By varying the values of n_x and n_z , cross-correlation coefficient is evaluated for $n_x=0, \pm 1, \pm 2, \dots, \pm N$ and $n_z=0, \pm 1, \pm 2, \dots, \pm N$. We will identify the maximum cross-correlation coefficient and the corresponding values of n_x and n_z . Therefore, the lateral displacement is estimated to be $\delta L_x = n_x d_x$ and the axial displacement is estimated to be $\delta L_z = n_z d_z$, where d_x and d_z indicate the physical pixel width for a digitized pixel in OCT image. The same process is applied to every pixel within the image.

The above described algorithm was implemented in real-time using GPU, and the flow chart of the algorithm is shown in Figure 2.

3. EXPERIMENTAL SETUP

A spectral-domain OCT engine at 1310 nm with a 7.4 μm axial resolution and a 91 kHz A-scan rate (Figure 3) was used to acquire experimental data [5]. In the sample arm, the collimated light beam was steered by a galvo mirror, and further relayed by a 0.23 pitch GRIN lens (Newport, LGI1300-1) with 1.8 mm diameter. The distal facet of the GRIN lens was in contact with the surface of the sample placed on a rigid surface. The GRIN lens allowed optical access of the sample up to several millimeters in depth, and also compressed the sample as a cylindrical indenter. A vertical translation stage was actuated by a linear motor to perform the axial compression. Due to the small size of the indenter compared to the sample, the displacement field established within the sample is varied in both lateral and axial dimensions within the OCT system's field of view.

4. RESULTS

Using the setup shown in Figure 3, we performed motion tracking based on OCT imaging, during sample compression. The algorithm in Figure 2 was implemented using GPU in real-time to track both axial and lateral motions within the sample. The resultant motion fields are shown in Figure 4 (a) and (b). In addition, we simulated the axial displacement field (u_z) and lateral displacement field (u_x) (Eqs. (2) and (3) where i is the imaginary unit, a is the radius of the indenter, z is the axial coordinate, x is the lateral coordinate, and h is the indentation depth), based on an analytical solution for a rigid flat ended cylindrical punch [6]. Simulation results shown in Figure 5 (a) and (b) are consistent with experimental data shown in Figure 4, which validates the effectiveness of our method for 2D motion tracking. To extract the Poisson's ratio using axial and lateral motion fields, we considered a function $\mathbf{R}$ defined as the ratio between u_z and u_x (Eq (4)). $\mathbf{R}$ is independent of the indentation depth, and can be used to robustly assess Poisson's ratio (ν) despite the unknown value of indentation depth h . Using different values of Poisson's ratio ($\nu=0.4, 0.45$ and 0.5), we simulated displacement fields with random noise, established the function $\mathbf{R}$, extracted

Poisson's ratio through least square curve fitting, and show the results in Figure 5 (c). We were able to accurately extract Poisson's ratio at different indentation depths.

$$u_z = \frac{h}{\pi(1-\nu)} \operatorname{Im} \left[2(1-\nu) \log \left(\sqrt{x^2 + (z+ia)^2} + z + ia \right) - \frac{z}{\sqrt{x^2 + (z+ia)^2}} \right] \quad (2)$$

$$u_x = \frac{h}{\pi(1-\nu)} \operatorname{Im} \left[\frac{x}{\sqrt{x^2 + (z+ia)^2} + z + ia} \left(1 - 2\nu - \frac{z}{\sqrt{x^2 + (z+ia)^2}} \right) \right] \quad (3)$$

$$R = \frac{\operatorname{Im} \left[\frac{x}{\sqrt{x^2 + (z+ia)^2} + z + ia} \left(1 - 2\nu - \frac{z}{\sqrt{x^2 + (z+ia)^2}} \right) \right]}{\operatorname{Im} \left[2(1-\nu) \log \left(\sqrt{x^2 + (z+ia)^2} + z + ia \right) - \frac{z}{\sqrt{x^2 + (z+ia)^2}} \right]} \quad (4)$$

5. CONCLUSION

In this paper, we described a method for 2D motion tracking and demonstrated our capability of real-time 2D motion tracking. We further validated our methods by comparing experimental data with simulation results, and assessed the feasibility of quantifying material's Poisson's ratio using displacement fields.

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Figure.1.

(a) Sequentially acquired Bscan OCT data used for 2D motion tracking; (b) regions of interest selected in adjacent Bscan frames for speckle analysis.

Figure.2.
Flow chart for 2D motion tracking

Figure.3.

Configuration of OCT system to acquire experimental data for 2D motion tracking. Here, BS stands for broadband source.

Figure.4. Experimental results of real-time motion tracking based on OCT imaging: (a) axial and (b) lateral displacements within the sample under compression.

Figure. 5.

Simulated displacement fields in (a) axial and (b) lateral directions; (c) results of Poisson's ratio extracting using 2D displacement fields.