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Full-surface deformation measurement of anisotropic tissues under indentation

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ABSTRACT

Inverse finite element-based analysis of soft biological tissues is an important tool to investigate their complex mechanical behavior and to develop physical models for medical simulations. Although there have recently been advances in dealing with the computational complexities of modeling biological materials, the collection of a sufficiently dense set of experimental data to properly capture their typically regionally varying properties still remains a critical issue.

The aim of this work was to develop and test an optical system that combines 2D-Digital Image Correlation (DIC) and a novel Fringe Projection method with radial sensitivity (RFP) to test soft biological tissues under *in vitro* indentation. This system has the distinctive capability of using a single camera to retrieve the shape and 3D deformation of the whole upper surface of the indented sample without any blind measurement areas (with exception of the area under the indenter), with nominal depth and in-plane resolution of 0.05 mm and 0.004 mm, respectively. To test and illustrate the capabilities of the developed DIC/RFP system, the *in vitro* response to indentation of a homogeneous and isotropic latex foam is presented against the response of a slab of porcine ventricular myocardium, a highly in-homogeneous and anisotropic tissue. Our results illustrate the enhanced capabilities of the developed method to capture asymmetry in deformation with respect to standard indentation tests. This feature, together with the possibility of miniaturizing the system into a hand-held probe, makes this method potentially extendable to *in vivo* settings, alone or in combination with ultrasound measurements.

1. Introduction

Indentation tests have been extensively used to investigate the bulk mechanical response of soft biological tissues undergoing large deformation *in vitro* and *in vivo* [1–14]. Collected experimental data, mainly in the form of single-point load/indentation depth curves, have often been used with inverse Finite Element (FE) based algorithms for material characterization.

It is well known that a well-conceived and high-fidelity inverse material characterization procedure relies on an appropriate model of the experiment i.e. in a faithful representation of the geometry, boundary and loading conditions as well as on a sufficiently dense and accurate set of experimental data. The latter requirement becomes particularly critical when the material properties are location and direction dependent such as for most of biological tissues that are strongly in-homogeneous and anisotropic materials [15]. In this case, many more material parameters must be measured and so it is essential to extract more information from the experiment than can be gained from a single load-displacement curve.

Most inverse analyses that implement indentation experiments into FE models assume that the biological tissue is a continuous, isotropic, homogeneous and nearly incompressible solid (see summary of literature in Table 1). Moreover, since during indentation, deformations are induced under an axisymmetric condition, the model is usually modelled in 2D using axisymmetric elements under the assumption that the deformed profile is identical for all the coaxial sections of the sample. This latter scheme has been used even when dense sets of data from large portions of the sample were available through 3D Digital Image Correlation measurements [1,16]. Although the cylindrical symmetry assumption holds true for silicone rubber phantoms [16] and has been demonstrated to be reasonably acceptable for porcine liver [1], it is expected that it cannot be considered valid for strongly anisotropic tissues such as the heart ventricular wall considered in this study. It is well known, in fact, that

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Table 1
Literature review of works implementing the indentation test for material characterization of soft biological tissues.

Tissue	Experimental data	Material model	List of publications
Porcine liver	3D DIC displacement, force	Hyperelastic Neo-Hookean	Ahn et al. [1]
Rabbit eardrum	Single-point force, FP displacement	Exponential Fung	Buytaert et al. [2]
Porcine liver, spleen and human liver	Single-point force, displacement	Exponential Fung	Carter et al. [3]
Engineered cardiovascular tissue	2D DIC displacement, force	Fiber-reinforced composite	Cox et al. [4]
Human tongue and cheek	Single-point force, displacement	Hyperelastic Yeoh	Gerard et al. [5]
Human liver stomach	Single-point force, displacement, time	Quasi-linear viscoelastic Fung	Lim et al. [9]
Porcine brain	Single-point force, displacement, time	Hyper-viscoelastic	Miller et al. [10]
Silicone gel	3D DIC displacement, force	Hyperelastic Neo-Hookean	Moerman et al. [16]
Porcine liver, spleen	Single-point force, displacement, time	Linear viscoelastic	Ottensmeyer [11]
Human skin	Single-point force, displacement	Linear elastic	Pailler-Mattei et al. [12]
Porcine liver	Single-point force, displacement, time	Hyper-viscoelastic	Samur et al. [13]
Porcine liver and esophagus	Single-point force, displacement, time	–	Tay et al. [14]

myocardium (composing 70% of the ventricular wall) possesses a profoundly anisotropic behavior due to its complex three-dimensional muscle fiber architecture [17].

The arguments above motivated our study that aimed to: (i) develop a non-invasive optical system able to collect the full-field shape and deformation of the entire upper surface of soft tissues undergoing indentation (except underneath the indenter), (ii) illustrate the enhanced performance of such a measurement, taking advantage of the possibility to capture the whole inhomogeneous deformation field of anisotropic materials.

To this scope, a novel Fringe Projection system with radial layout and sensitivity (Radial Fringe Projection, RFP) was developed and tested. RFP, combined with 2D-Digital Image Correlation (DIC), was then used to perform three-dimensional measurements of shape and deformation using a single camera. This feature is not of secondary importance since it could eventually allow the building of compact systems suited to be miniaturized into hand-held probes for *in vivo* measurements, potentially for clinical applications.

The paper is organized as follows: firstly, the rationale behind the novel RFP method is described and the optical set-up combining RFP and DIC for *in vitro* indentation experiments on soft biological tissues is presented and illustrated. Then, experimental results from tests performed on a homogeneous and isotropic latex foam and a porcine left ventricular (LV) wall are compared and discussed. Finally, ongoing research and possible future development of the novel experimental system are presented with a view to implementation as part of an inverse FEA approach for mechanical characterization of anisotropic tissues undergoing large deformation.

2. Materials and methods

2.1. Radial fringe projection (RFP)

Fringe Projection [18,19] is a well-established optical technique able to provide non-contact, high-resolution, full-field (i.e. on a pixel-by-pixel basis) reconstruction of object shapes at video frame rates.

A standard Fringe Projection (FP) profilometry system consists of a projection unit (typically a commercial liquid crystal display (LCD) projector), an image acquisition unit and a data processing unit. When a computer-generated sinusoidal fringe pattern is projected onto the object surface at a given angle θ with respect to the viewing direction (Fig. 1a), the appearance of the fringes is modulated by the object shape and, under the hypothesis of collimated projection and observation from infinity (i.e. use of telecentric lens or of a large distances between camera and object), it is possible to relate the height $h(x, y)$ of a given object point $P(x, y, z)$ with respect to a reference plane (here the xy plane, with the z axis coincident with the camera axis, i.e. $h = z$) and the phase $\phi(x, y)$ through the equation

$$h(x, y) = \frac{\phi(x, y)}{2\pi f \sin\theta} = k\phi(x, y) \tag{1}$$

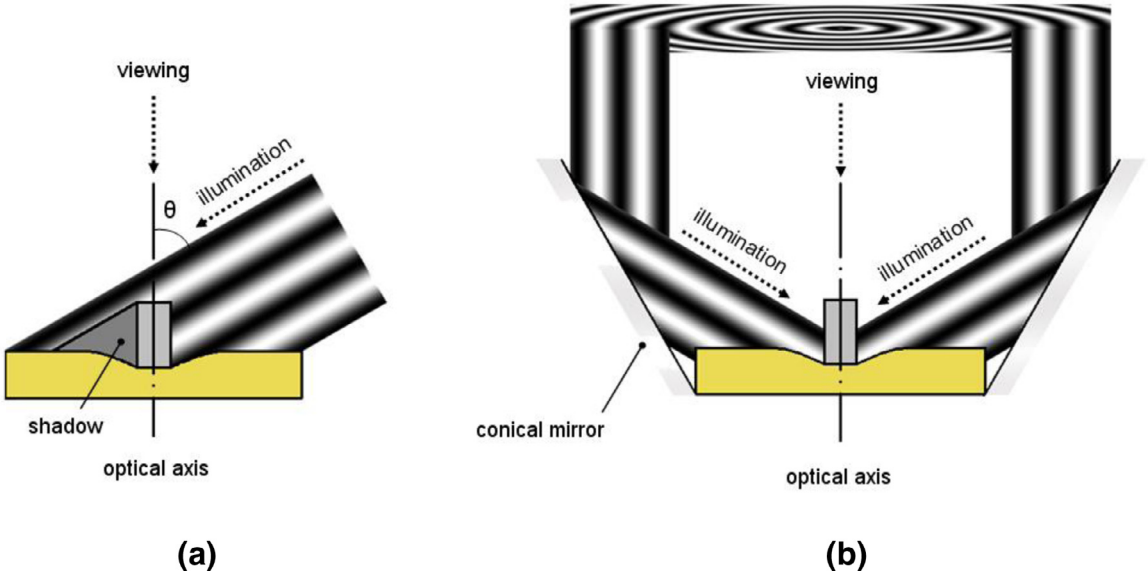

Fig. 1. Schematic of a standard Fringe Projection system (a) and a Radial Fringe Projection system (b) applied to indentation test.