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Research Paper

An improved panoramic digital image correlation method for vascular strain analysis and material characterization

K. Genovese[a], Y-U. Lee[b], A.Y. Lee[b], J.D. Humphrey[b,*]

[a]Dipartimento di Ingegneria e Fisica dell'Ambiente, Universita' degli Studi della Basilicata, Potenza 85100, Italy
[b]Department of Biomedical Engineering, Yale University, New Haven, CT 06520, USA

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ABSTRACT

The full potential of computational models of arterial wall mechanics has yet to be realized primarily because of a lack of data sufficient to quantify regional mechanical properties, especially in genetic, pharmacological, and surgical mouse models that can provide significant new information on the time course of adaptive or maladaptive changes as well as disease progression. The goal of this work is twofold: first, to present modifications to a recently developed panoramic-digital image correlation (*p*-DIC) system that significantly increase the rate of data acquisition, overall accuracy in specimen reconstruction, and thus full-field strain analysis, and the axial measurement domain for *in vitro* mechanical tests on excised mouse arteries and, second, to present a new method of data analysis that similarly increases the accuracy in image reconstruction while reducing the associated computational time. The utility of these advances is illustrated by presenting the first full-field strain measurements at multiple distending pressures and axial elongations for a suprarenal mouse aorta before and after exposure to elastase. Such data promise to enable improved inverse characterization of regional material properties using established computational methods.

1. Introduction

Advances in computational mechanics and computer technology have enabled sophisticated finite element analyses in vascular biomechanics, including solutions of initial and boundary value problems having complex, subject-specific geometries. Nevertheless, a common limitation to most such analyses is the continued prescription of uniform material properties (cf. Humphrey and Holzapfel, 2012). This situation results not from computational or theoretical limitations, but rather from the lack of experimental quantification of actual regional variations in material properties. The existence and potential importance of non-uniform properties is supported by advances in vascular mechanobiology (cf. Humphrey, 2008), which imply that cells should be expected to build in regional variations in material properties to offset complexities in geometry or applied loads that would otherwise result in non-uniform stress fields that are sub-optimal for biological function. Computational results based on both traditional finite element analyses (e.g., Ryan and Humphrey, 1999) and newer growth and remodeling simulations (e.g., Wilson et al., 2012) further support this expectation.

To begin to address the need for new methods of quantification of regional material properties in blood vessels having complex geometry, we introduced a panoramic-digital image

*Corresponding author. Tel.: +1 203 432 6428.
E-mail address: jay.humphrey@yale.edu (J.D. Humphrey).

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correlation (*p*-DIC) method (Genovese et al., 2011a, b). Although the basic method can be implemented to study various soft tissues having different overall sizes and shapes, we built and tested a system having a spatial resolution targeted specifically for studying the mechanics of mouse arteries, which typically are 500 to 1000 μm in diameter. This system and general approach have proven very useful in this regard (e.g., Genovese et al., 2012), but an inherent limitation restricted the rate at which data could be collected. The purpose of this paper, therefore, is to present both a novel modification to our *p*-DIC system, which increased significantly the rate of data collection while increasing the axial domain of measurement and overall reconstruction accuracy, and a new method of data analysis, which similarly improved the reconstruction accuracy while decreasing the computational time. To illustrate the utility of these two advances, we present new data on short-term, elastase-induced changes in regional material behaviors in the mouse abdominal aorta during *in vitro* experiments. Such data can contribute to the interpretation of this well used method to study the pathogenesis of abdominal aortic aneurysms.

2. Material and methods

2.1. *Improved p-DIC approach*

Briefly, our original *p*-DIC concept and experimental system allows geometric reconstruction and tracking of surface displacements, and thus calculation of strains, along much of the length and around the entire circumference of an excised mouse artery. To accomplish this full-field measurement, the specimen is placed co-axially within a 45° concave conical mirror. Because the resulting peculiar optical scheme of image formation requires a small stereo angle (~1°), our original *p*-DIC system uses a single camera rather than the multiple cameras that are used in standard stereo-DIC (cf. Sutton et al., 2009) or related methods of soft tissue strain analysis (Hsu et al., 1995; Everett et al., 2005). A "pseudo" stereo-capability is thus achieved by generating four polar-symmetric views of the specimen (namely Right and Left, Up and Down) by sequentially reflecting the image of the sample to the single fixed camera. This sequence of views is achieved by manually tilting a flat mirror four times about two perpendicular axes through a gimbal mount. Each set of four tiltings of the mirror requires about 3 min, however, and consequently the data cannot be collected continuously and the deformed state must remain unaltered during this measurement period. In addition to this primary limitation, minor drawbacks to our original system include a reduced sample gauge length (about 4 mm) due to the presence of a fixed calibration pattern on the uppermost inner surface of the conical mirror and a circumferentially uneven illumination of the sample achieved via four gooseneck-pipe fiber optic illuminators. See the original papers for a schema of the overall experimental set-up and the method of stereo-image generation.

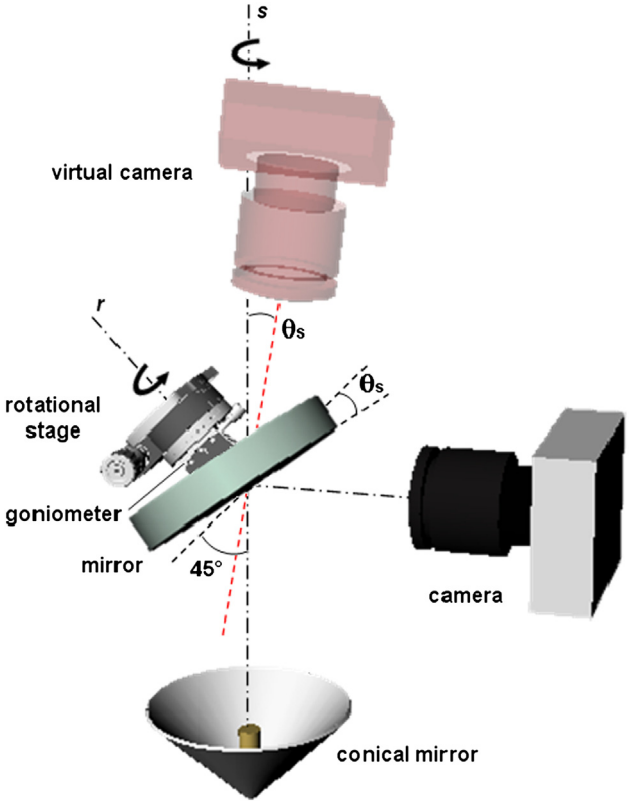

Fig. 1 – Schema motivating a multi-view panoramic-Digital Image Correlation (*p*-DIC) method. A full rotation of the goniometer-mounted flat mirror about the *r* axis yields a full rotation of the viewpoint (i.e., virtual camera) around the axis *s* of the specimen that is placed co-axially within the conical mirror. The stereo angle θ_s is exaggerated for clarity of representation, but is typically about 1 degree.