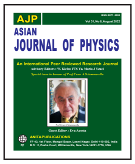

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DIC strain measurement on the full-surface of an artery analogue after stent deployment

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This article is dedicated to Professor Cesar Sciammarella

Digital Image Correlation (DIC) is a widely used optical method for measuring full-field shape, motion and deformation on the surface and within the volume of solid bodies under load. Its popularity is due to its capability of obtaining highly dense set of data for a large range of length scales and deformation levels. The contactless and full-field capabilities of DIC make it particularly suitable for studying the spatially varying material properties of natural and synthetic biological materials.

In this work, we illustrate the potentialities of DIC measurements by mapping the strain induced by the deployment of a self-expandable stent into a latex tube. A non-conventional DIC optical arrangement and data processing was adopted to cope with the cylindrical shape of the sample and with the large deformation exerted by the stent.

Experimental results show the capability of DIC to map high-resolution and seamless strain data over the full surface of the mock artery. Interestingly, although the stent was deployed into a regular cylindrical tube, the resulting deformation was inhomogeneous and asymmetric. This highlights the impact that this type of experimental data may have in the study of the stent-arterial wall interaction.

Keywords: Aortic stent, Digital image correlation, 360-deg full-surface measurement, full-field strain map.

1 Introduction

Endovascular repair (EVAR) with stent-grafts (SGs) is a well assessed minimally invasive procedure for treating aortic aneurysms. A SG is an initially collapsed fabric tube with a metal frame that is inserted through small groin incisions and guided through X-rays imaging within the aneurysm. Once accurately placed, the stent is deployed thus allowing the blood flow to bypass the weak vascular area. Since the stent needs to be anchored to the ends of the aortic segment, the interaction between the arterial walls and the stent graft plays an important role in the success and the durability of the treatment.

With respect to the large number of numerical studies on the subject (see e.g. [1] and references therein) the number of experimental *in-vitro* investigations is quite limited. This is very likely due to the challenges inherent to measurements involving soft biological tissues such as non-standard sample geometries, difficulties in reproducing the physiological loads and boundary conditions and large deformation levels.

In this paper, we demonstrate the potentialities of the Digital Image Correlation (DIC) method [2] for such application by illustrating the complete procedure for mapping the strain on the full 360-deg surface of an artery analogue after stent deployment.

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Stereo-Digital Image Correlation (stereo-DIC) is a non-contact optical method that uses two cameras for acquiring images of the test sample from two angled views during its motion and/or deformation [2,3]. For each load state, the best matches between corresponding point pairs in the stereo images are found by comparing the gray-scale distribution of pixels subsets based on a given correlation coefficient (spatial correlation). Then, stereo-photogrammetry is used to triangulate the light rays from the two calibrated cameras to get the 3D position of the measured surface points and hence the shape of the sample in each configuration of interest. If all the images of the captured sequence are correlated with a single reference image (temporal correlation) it is possible to track the same set of surface points over time and calculate the surface deformation.

In the last decades, DIC has been successfully used for a large variety of applications in both academic and industrial contests [3]. Its non-contact and full-field capabilities made DIC particularly suitable to investigate the mechanical behavior of natural and synthetic biological tissues and structures [4]. DIC has also been already used for mapping *in-vitro* the full-surface strain after the implantation of a balloon-expandable stents on a portion of an artery analogue [5], a human [6] and a porcine coronary artery [7].

In this work, we further exploit the metrological capabilities of DIC by extending the measurement area to the entire 360-deg surface of a mock artery after the implantation of a self-expandable stent. As described in the paper, a virtual multi-view DIC optical arrangement was adopted for the panoramic measurement and a SIFT-based image analysis [8] was implemented to cope with the large deformation exerted by the stent.

2 Materials and methods

In this paper, we report a DIC measurement on the entire 360-deg surface of an artery surrogate before and after the deployment of a self-expanding aortic stent. Panoramic measurements [3] can be performed either with a standard two-camera DIC system or using a polar array of cameras arranged at regular angular steps around the sample. In the former case, the multiple views can be obtained either with the aid of catadioptric components or mounting the sample on a turn-table [3]. In this work, we adopted the latter solution by using a standard stereo-DIC setup featuring two scientific graded cameras (Dalsa Falcon 4M30, 2352×1728 pixels CMOS sensor, 8 bits) equipped with 28-105 mm Nikkor zoom lenses, and two LED panels (Yongnuo YN600L, 3200-5500 K, 4800 lumen). Prior testing, the stereo-DIC system was calibrated using a closed form approach followed by a non-linear optimization routine for parameters refinement [9]. A self-expandable stent of about 20 mm diameter and 100 mm length (Fig 1a) was collapsed into a plastic cannula (Fig 1b) in which a threaded M4 rod with a plastic end adapter was further inserted (Fig 1c).

One end of a 10 mm diameter Penrose latex tube was then secured with a nylon wire to the adapter (left side on Fig 2a) while the other end was fixed onto a plastic cylindrical segment and let free to move along the axial direction. The sample was then provided with a speckle pattern manually applied with a black permanent marker (see undeformed configuration in Fig 2a). Finally, the whole assembly was fixed to a rotation stage through the threaded rod.

As shown in the schematic of Fig 3, the square bracket holding the rotation stage is fixed to the optical table such that the plane containing the camera axes is perpendicular to the axis of the cylindrical sample. Even if it could appear more effective to have the camera parallax parallel to the cylindrical sample axis, such arrangement is unpractical for measurements on slender cylinders since only the central portion of the sample would be in focus. On the contrary, the setup reported in Fig 3 allows for the sample to be in focus along its entire length (see Fig 2) even if requires a large number of views (i.e., a small angular spacing between them).

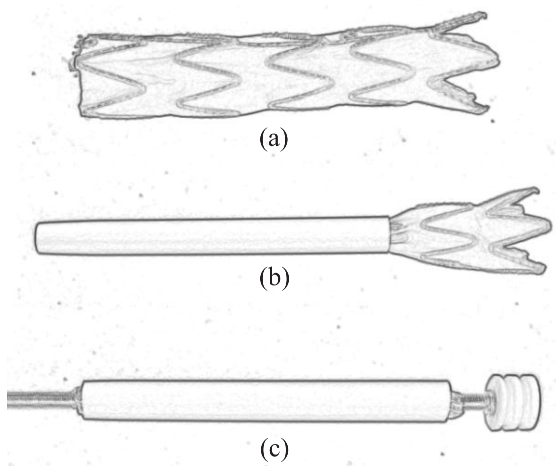

Fig 1. Schematic of the insertion of a SG (a) into the cannula used to keep the stent collapsed within the latex tube until its deployment (b). A threaded rod with a round end adapter is further inserted to allow securing the mock artery at one end and fixing the assembly to the rotation stage (c).

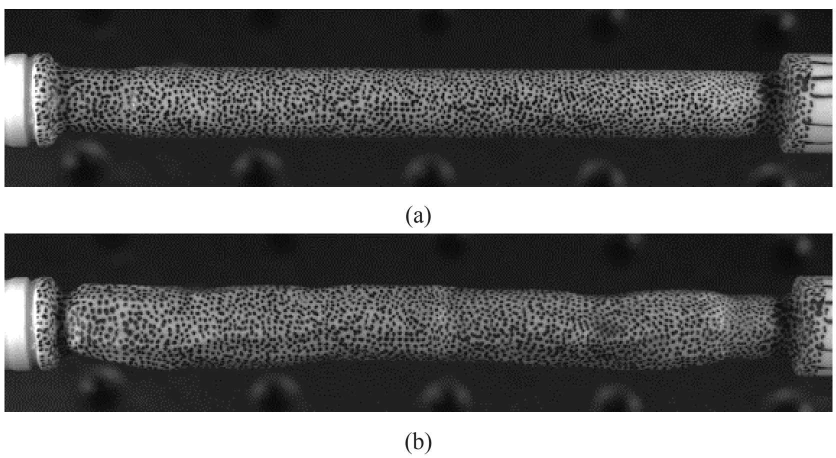

Fig 2. Images of the mock artery before (undeformed state, (a)) and after removing the cannula (deformed state, (b)).

Fourteen partially overlapping and evenly spaced angular positions were considered to collect the required image data on the entire 360-deg surface of the sample. In each position, two angled views of the sample were captured by the stereo-cameras. A first set of image pairs was captured for the undeformed configuration (see an image of the series in Fig 2a). Then, without removing the sample from the rotation stage, the cannula was gently pulled out from the open side of the sample thus causing the gradual deployment of the stent within the tube (Fig 2b). After about 10 min, a second set of image pairs were collected in the same angular positions considered for the undeformed configuration.

Each image pair was processed following standard stereo-DIC method to get the 3D position of the control points on the region of interest (ROI) common to both cameras. A 21×21 pixels subset with a 5 pixels spacing and cubic interpolation of the gray-scale distribution was used for image registration. For each angular position, a cylindrical sector of about 30° was reconstructed in the reference system attached to the cameras. A further operation was hence needed to correctly reposition the cylindrical sectors in the

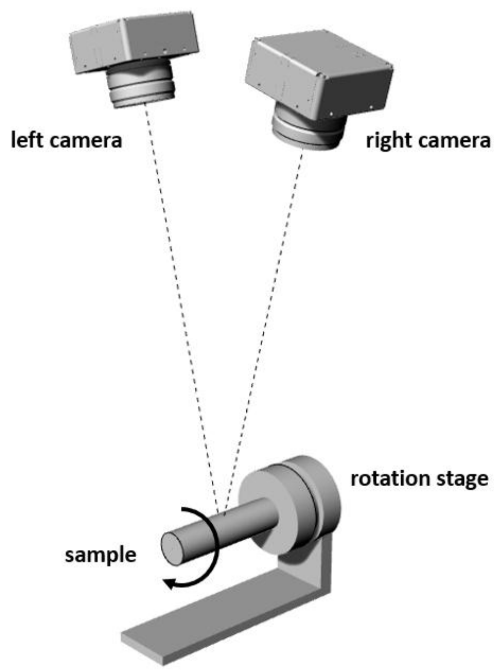

Fig 3. Schematic of the optical setup used to run the experimental tests reported in this paper.

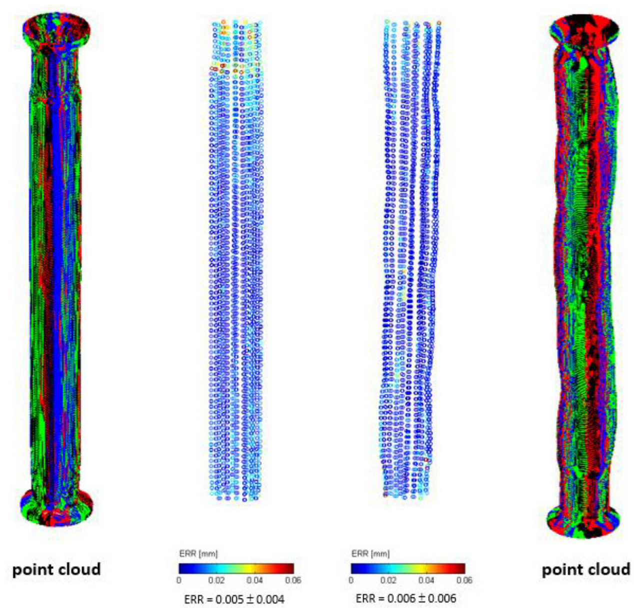

Fig 4. The point clouds reconstructed with stereo-DIC (here with different colors) were merged into a common reference frame with an optimization-based procedure. A set of control points in the overlapping region between two reconstructed sectors was repositioned in order to minimize the relative distance with the homologous set of points in the contiguous patch. The merging error between the fourteen reconstructed point clouds is plotted in the central panels for both configurations.

world reference frame and to merge them into the final shape. To this aim, starting from the first sector, an optimization-based procedure sought for the rigid body motion (RBM) that placed each pair of contiguous patches at the minimum Euclidean distance between corresponding sets of control points in the overlapping region. The results of the merging operation is reported in Fig 4. In particular, the lateral panels show the overlapped (differently colored) reconstructed point clouds while the central panels report the error for the control points selected in the overlapping regions between patches. The largest errors are very likely due to a few bright spots and deterioration areas on the speckle pattern close to the sample ends. No sensible error accumulation was found between the first and the last patches thus indicating a good level of accuracy in both DIC reconstruction and merging operation. For the deformed configuration, the seamless reconstruction guaranteed also against the presence of viscoelastic effects during the acquisition of the image sequence.

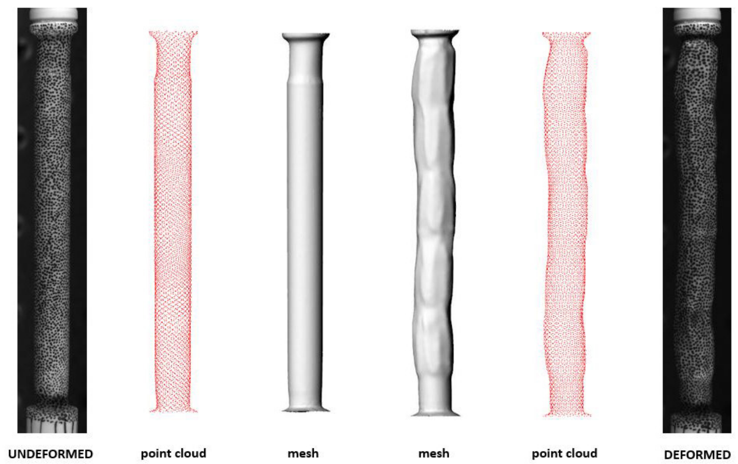

Fig 5. The selected final grids of in the two configurations and the rendered measured shapes.

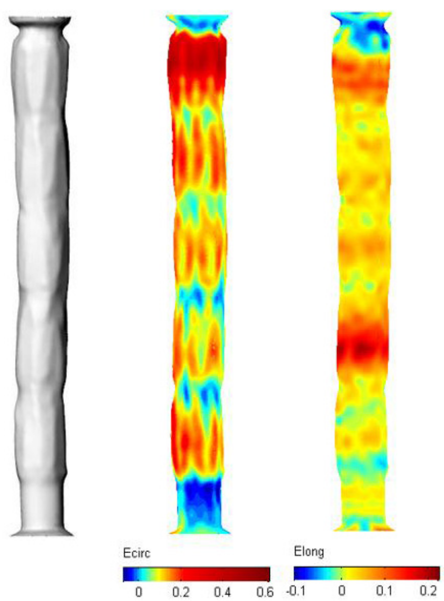

Fig 6. Full-surface maps of the circumferential and longitudinal Green strains of the mock artery after stent deployment.

A proper procedure [8] was needed to correlate the images of the undeformed configuration with their counterparts in the deformed configuration given the high level of deformation exerted by the stent deployment to the latex tube (Fig 5). Briefly, the Scale Invariant Feature Transform (SIFT) algorithm was used in a preliminary step aimed to find the rough disparities between the current (deformed) and reference (undeformed) images. The sparse and noisy point clouds obtained with SIFT were then fitted with rigid NURBS into the Rhinoceros software to give a better approximation of the disparities maps. These distributions were hence applied to the deformed image to obtain a coarse approximation of the reference image thus reducing the difference between the images to be correlated and improving the accuracy of the DIC registration [8].

Figure 6 reports the calculated full-surface distribution of the circumferential and axial Green strains on the latex tube due to stent implantation. Large strain values were measured with DIC without the need of intermediate images. The high spatial resolution of the measurement allowed the effect of the stent metal frame to be clearly visible. Notably, the uneven movements of the manual procedure for the cannula removal generated a non-uniform and asymmetric deformation.

3 Concluding remarks

This work illustrates the potentialities of the DIC method by presenting the results of strain measurement on the full-360-deg surface of a mock artery after the implantation of a self-expandable stent. We found that the resulting strain distribution was non-uniform and asymmetric even if the artery analogue was a cylindrical tube. Although only illustrative and with no clinical significance, the results put in evidence the unique features of a full-field measurement and the important contribution that it may give for a better insight into the stent-arterial wall interaction mechanism.

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