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Technical note

Full-field strain distribution in multi-vertebra spine segments: An *in vitro* application of digital image correlation

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ABSTRACT

The biomechanics of the spine is experimentally assessed in terms of range of motion and overall stiffness. Quantification of the surface strain distribution is currently limited either to the vertebrae or the discs, whereas a full-field approach to measure the strain distribution in a multi-vertebra segment is currently missing. The aim of this work was to explore the feasibility of using Digital Image Correlation (DIC) to measure the strain distribution simultaneously on the vertebral bodies and the intervertebral discs of spine segments in different loading configurations.

Three porcine spine segments were tested. A white-on-black speckle pattern was prepared which covered the hard and soft tissues. Two different loading configurations (flexion and lateral bending) were reproduced, while two sides of the spine were analyzed with DIC.

Measurements were successfully performed on the entire region of interest of all specimens, in both configurations. The DIC analysis highlighted the strain gradients present on the spine segments including tension and compression associated with bending, the direction of principal strains in the different regions, as well as bulging of the discs under compression. Strains of tens of thousands microstrain were measured in the discs, and below 2000 microstrain in the bone.

This work showed the feasibility of applying DIC on spine segments including hard and soft tissues. It also highlights the need for a full-field investigation, because of the strain inhomogeneity in the vertebrae and discs.

1. Introduction

The spine consists in a sequence of hard (vertebrae) and soft tissue (intervertebral discs), stabilized by ligaments. Spine characterization is a fundamental challenge in biomechanics because it could help engineers and clinicians to better understand physiological/pathological conditions, and to design better implants [1, 2].

Spine segments have often been investigated *in vitro* [3–7]. In such experiments either known motions are imposed to measure the structural stiffness [8–10], or known loads are applied to measure the range of motion [11–13]. From these tests, structural properties and behaviour of the spine segment as a whole is assessed. Only in few cases the local strain distribution has been measured. However, such experiments focused separately either on the vertebra or on the intervertebral disc. Strain in the vertebra has been measured by means of strain gauges [14–17] this provided accurate measurements, but was limited to the area of application of the strain gauges. The reinforcement effect of strain gauges can be significant (up to 9%) [14,18,19]. Measuring the local strain in the intervertebral disc is even more difficult, due to the intrinsic nature of the disc itself (low stiffness). One of the first measurements of the strain on the outer part of the disc (*Annulus fibrosus*) was based on stereo-photogrammetry and covered a limited portion of the disc [20]. More recently, the entire disc surface was investigated (excluding the adjacent vertebrae), using digital image correlation (DIC) [21]. A method to explore the strain field on spine segments with large in-plane and out-of-plane deformations is missing.

The aim of this work was to explore the feasibility of using DIC to measure the full-field strain distribution simultaneously on the vertebral bodies and intervertebral discs of thoracolumbar

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spine segments in different loading configurations. Specifically, the following research questions were addressed:

- The feasibility of applying a speckle pattern with sufficient contrast for the correlation algorithm, that should not become damaged when the specimen was kept hydrated;
- The robustness of the pattern to withstand the large deformations expected in the soft tissue (up to 100,000 microstrain) for up to 50 cycles;
- The procedure must allow measuring the small deformations expected in bone (of the order of 2000 microstrain) with acceptable errors (not exceeding 200 microstrain);
- The possibility of measuring strains in specimens undergoing relatively large in-plane (up to 3 mm) and out-of-plane (7 mm) displacements, while correlating at least 90% of the region of interest.

2. Material and methods

2.1. Specimen and pattern preparation

For ethical reasons, in this methodological work porcine spine segments from the slaughterhouse were preferred. The three animals were female, of the same breed, approximately 9 months old and approximately 100 kg at sacrifice. The segments consisted of four thoracolumbar vertebrae (T7-T10/T11-T14/L2-L5) selected for resemblance in terms of ranges of motion and dimensions [22–24]. The specimens were kept hydrated, and stored at −28 °C to avoid alteration of the mechanical properties.

The ribs, the muscles, the anterior longitudinal ligament, and the periosteum were carefully removed using surgical tools. The interspinous, supraspinous and posterior longitudinal ligaments, and the capsules were left intact in order to preserve the natural kinematics. The specimens were aligned so that the middle disc of each segment was aligned horizontally in the frontal and lateral views [25]. In this configuration, two pots of poly-methyl-methacrylate were created parallel to one another, where the upper half of the most cranial vertebra and the lower half of the most caudal vertebra, were embedded (Fig. 1).

In order to use DIC to make measurement on the spine segments (both the vertebrae and the intervertebral discs), a high-contrast white-on-black speckle pattern [26,27] was prepared. The spine segments were first stained with a dark background (a solution of 4 g of methylene-blue per 100 ml of water) [28,29]. Two applications were required for the intervertebral discs and three for the vertebrae to obtain a uniform background. Dying was preferred, rather than surface painting, as a layer of paint would crumble and crack due to the large deformations of the soft tissues.

The speckle pattern was applied with paint instead of using a powder, as was done previously [26]. This allows avoiding artifacts as the dots can strain during the test (unlike powder grains). Furthermore, paint dots resist to saline solution without damage, allowing specimen hydration and storage. A white water-based paint (Q250201 Bianco Opaco, Chrèon, Italy) was diluted at 40% with water and sprayed using an airbrush-airgun (AZ3 HTE 2, nozzle 1.8 mm, Antes Iwata, Italy) to prepare a white speckle pattern with the qualitative and quantitative requirements described in [30]. The spraying distance (300 mm) and the pressure (1000 kPa) were optimized to obtain the desired dot size, and minimize the scatter of dot dimension [35]. The actual size of the speckle dots was measured in the 2D digital images (acquired by DIC system) of the ROI through a custom script developed for this work. The speckles had a dimension of 6 pixels (average 0.18 mm with a standard deviation of 0.18 mm), larger than the minimum recommended size while the facet were sufficiently large compared to the speckle size [30].

The specimens were soaked in saline solution before the tests.

2.2. Mechanical testing

The specimens were loaded using a uniaxial servo-hydraulic testing machine (8032, Instron, UK) in displacement control. In order to avoid transmission of any undesired component of load, free rotation of the loading plate was allowed by means of a ball joint, while free horizontal translations were granted by means of two low-friction orthogonal linear bearings.

In order to assess the feasibility of measuring strains on such complex specimens, two different loading configurations were simulated, which are frequently investigated in the literature [31] (Fig. 2):

- Flexion: the vertical force had an anterior offset equal to the 20% of the antero-posterior depth of the central intervertebral disc;
- Lateral bending: the vertical force had a lateral offset (both towards right and left) equal to the 20% of the coronal width of the central intervertebral disc.

Ten preconditioning cycles were applied between 0 and 1.0 mm of compression, at 0.5 Hz. A compression of 3.0 mm was applied for each loading configuration in 0.1 mm steps, while DIC images were acquired at each step (see below). This value of compression was based on preliminary tests to reach typical strains associate to physiological loads [32,33] to prevent damage of the specimens. These loading configurations did not aim to mimic any specific motor task.

2.3. Digital image correlation

A commercial 3D-DIC system (Q400, Dantec Dynamics, Denmark) with directional custom designed arrays of LEDs (10,000 lm in total) was used. Images were acquired by two cameras (5 MegaPixels, 2440 × 2050 pixels, 8-bit) equipped with high-quality metrology-standard 35 mm lens (Apo-Xenoplan 1.8/35, Schneider−Kreuznach, Germany; 135 mm equivalent) for a stereoscopic view. Due to the curvature of the vertebral bodies and discs, the cameras were positioned at a distance of 260 mm from the specimen and vertically to maximize the area framed by both cameras (Fig. 2).

The field of view was set to 70 mm by 60 mm (resulting in a pixel size of 28 micrometers), with depth of field of 20 mm (lens aperture f/16). The field of view was wide enough to frame the entire region of interest (ROI): the central intervertebral disc and the two adjacent vertebrae.

To explore the possibility of assessing the different sides of the spine, two different acquisitions were performed for each loading configuration and each specimen:

- Frontal view: the cameras pointed the anterior wall of the spine segment;
- Lateral view: the cameras pointed the lateral side (either right or left) of the spine segment.

During the mechanical tests, series of images were acquired starting from the unloaded condition (reference step) and every 0.1 mm step of compression.

The correlation was performed with Istra-4D (v.4.3.1, Dantec Dynamics, Denmark) using the following parameters (Fig. 1):

(a) Facet size: 33 pixels;
(b) Grid spacing: 19 pixels;
(c) Contour smoothing: local regression with a kernel size of 5 × 5;

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