Elastic full-field strain analysis and microdamage progression in the vertebral body from digital volume correlation

G. Tozzi¹, V. Danesi², M. Palanca² and L. Cristofolini²

¹School of Engineering, University of Portsmouth, UK
²School of Engineering and Architecture, Alma Mater Studiorum - Università di Bologna, Italy

Abstract. The digital volume correlation (DVC) method has been exploited over the past decade to measure complex deformation fields within biological tissues, including vertebrae. However, damage progression in the vertebral body under applied load is still poorly understood. The aim of this paper was to couple microdamage evolution with full-field volumetric strain maps along the three main physiological directions, as well as identifying the most vulnerable area along caudal-cranial direction.

Introduction

Bone injuries, as well as pathologies such as osteoporosis and bone cancer, are among the major causes of vertebral fractures. For this reason, knowledge of the failure mechanism in the vertebra is of fundamental importance to understand vertebral biomechanics and improve diagnosis and surgical treatment. In vitro testing of the vertebral body has been extensively carried out in the past, but mainly focusing on fracture, where the strain distribution and progression from the elastic (and more physiological) regime was not investigated [1]. Recently, non-contact measurement techniques such digital image correlation were successfully employed to obtain full-field strains on the cortical shell of vertebrae as well as minimize the ‘contact artifacts’ due to the application of strain gauges. However, the main limitation of these experimental techniques is represented by their inability to capture and quantify the internal strain distribution, and the internal microdamage evolution under load. In this perspective, digital volume correlation (DVC) is ideal to investigate the local internal damage in vertebrae. In this study, full-field strain from DVC was obtained for vertebral bodies under compressive load. Specifically, the main aims were: 1) to evaluate the local strain progression/distribution in axial as well as antero-posterior and lateral-lateral directions along the caudal-cranial direction for each specimen, 2) to identify microdamage accumulation/progression during the loading regime and to associate this with strain distribution in the three main directions).

Methods

Three thoracic vertebrae (T1, T2, T3) were harvested from three fresh porcine thoracic spines. Step-wise compression testing of the vertebral body in combination with time-lapsed micro-CT imaging was performed. In situ testing was conducted by means of a loading device (CT5000, Deben Ltd, UK), equipped with a 5kN load cell and custom-designed environmental chamber, which was filled with physiological saline solution. To measure the strain distribution in the elastic range, and the subsequent microdamage progression, the specimens were compressed axially in a step-wise fashion up to 15% apparent strain (0% with 50N preload, 5%, 10% and 15%). Micro-CT imaging (XTH225, Nikon Metrology, UK) was carried out at each step with isotropic voxel size of 38.6-39 micrometers. The micro-CT scanner was set to a voltage of 88-89 kV, a current of 115-116 microA, and exposure time of 2 seconds. The image acquisition was performed at a rotational step of 0.23° over 360° for a total scanning time of 90 min approximately. DaVis DVC software (v8.3, LaVision, Germany) was used to compute the full-field strains in the vertebra along the axial, antero-posterior and lateral-lateral directions, respectively. The micro-CT images were masked in order to remove the background areas (saline solution) with no useful information in the correlation, which would cause strain uncertainties and artifacts in the DVC analysis [2, 3]. DVC computation produced final sub-volumes of 48×48×48 voxels, reached after successive (predictor) passes using sub-volumes of 128×128×128 voxels, 112×112×112 voxels, 96×96×96 voxels, 80×80×80 voxels and 64×64×64 voxels, with a 0% overlap. This multipass sequence was found to produce the lowest strain error in DaVis-DV for such type of samples, with the same imaging and environmental settings [2, 3].

Results

The axial, antero-posterior and lateral-lateral strain distributions for the three loading steps (5%, 10% and 15%) on the sagittal section of the three specimens (T1, T2, T3) were evaluated. T1 showed a main microdamage accumulation in the trabecular bone (caudal direction), which started to be evident from the 10% compressive step and degenerated into a trabecular collapse at 15% (Fig. 1). Such collapse gradually led to a weakening of the vertebral body in the transverse plane, with damage of the cortical bone anteriorly.
The strain maps for the three directions well described the damage events, with high strain magnitudes distributed along the damaged regions. The strain accumulation pattern with load differed in T2 and T3 in terms of highest magnitude and caudal-cranial location within the vertebral body.

![Strain Maps](image)

**Figure 1.** Strain distribution (axial, antero-posterior and lateral-lateral components, in microstrain) under axial load and corresponding microdamage progression for one specimen (T1). A-P indicates the Antero-Posterior direction on the image.

**Conclusions**

The results obtained in this study clearly show how different vertebral bodies may be subjected to different stress/strain distribution. Thus, consequent microdamage can develop and progress in different ways towards the final failure of the vertebra. Interestingly, DVC has the ability to predict high-strain concentration and therefore damage way before this occurs. This has the potential to be implemented in clinical CT assessment of vertebrae, given controlled loading conditions during imaging.

**References**

