VALIDATION OF HOMOGENIZED FINITE ELEMENT MODELS OF HUMAN METASTATIC VERTEBRAE USING DIGITAL VOLUME CORRELATION

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Introduction

Fragile vertebral fractures in patients with spinal metastases have an incidence of around 15% and significantly decrease patients' quality of life [1]. Although prevention of these fractures would be of paramount importance, the currently adopted tools are not accurate (below 50% of specificity and sensitivity) enough [2]. Homogenized subject-specific finite elements (FE) models of the vertebrae, once properly validated, could be employed to predict fracture. Digital Volume Correlation (DVC) is a full-field technique that enables the measurement of the full 3D deformation within the bone [3]. These data can be used to evaluate FE models' ability to predict local displacements and deformations into vertebral structure. Hence, the goal of this study is to present a validation framework where full-field numerical (from FE models) and experimental (from DVC) displacements are compared on multiple vertebrae, some of which with metastatic lesions.

Methods

Two thoracic four-vertebrae human spine segments with metastasis (one metastatic, one control and the two externally adjacent vertebrae) were obtained from an ethically approved donation program. Posterior arcs were removed, and external vertebrae were embedded in PMMA. Specimens were scanned in unloaded and loaded conditions inside a μCT system (Scanco VivaCT80, voxel size 39 μm) and were loaded in axial-compression up to physiological strains in the control (healthy) vertebra [4]. Displacements were measured by DVC with a nodal spacing equal to 50 voxels (DVC uncertainty was in the ranges 3-17 μm for displacements and 91-1030 με for strains). Homogenized linear elastic FE models of the middle vertebrae were generated from the unloaded scan. After computing tissue mineral density from voxels grey values, material properties of the bone were mapped on each element (Bonemat, Istituto Ortopedico Rizzoli) using a density-elasticity equation. The boundary conditions replicated the experimental test: displacements measured by the DVC were trilinearly interpolated and applied on the top and bottom nodes of the models. Numerical displacements predicted by FE model were compared to experimental displacements within a volume of interest selected in the middle third of the models. By differentiating the displacements using the same algorithm for experimental and computational values (Ansys APDL) also principal strain values were compared.

Results

FE- and DVC-derived displacements show a good agreement (Fig.1), especially in the cranio-caudal direction ($R^2 > 0.66$, RMSE < 36 μm), with lower accordance for the metastatic vertebrae than for the healthy ones. The FE strain fields instead, although of the same order of magnitude, were poorly correlated ($R^2 < 0.5$) with the experimental ones.

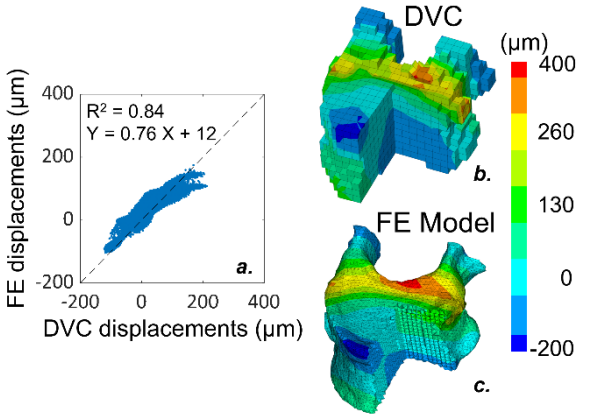

Fig.1: Scatter plot (a) between experimental (b) and numerical (c) displacements in the cranio-caudal direction for one of the control vertebrae analysed.

Discussion

The aim of this study was to assess the predictive accuracy of homogenized FE models of vertebrae with and without metastases taking advantage from experimental data. Loading the structure through the intervertebral disc allows to analyse larger displacements, keeping away from the uncertainty of the measurement data. The homogenized FE models could predict sufficiently well the experimental displacements, despite the presence of the lesions.

References

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