Finite Element strain prediction in intact and lesion-affected vertebral bodies: a new validation experiment

FINITE ELEMENT STRAIN PREDICTION IN INTACT AND LESION-AFFECTED VERTEBRAL BODIES: A NEW VALIDATION EXPERIMENT

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Introduction

Accurate estimates of strain in human vertebrae would be important to quantify physiological deformations, and their modification by metastatic lesions, but a single study reported strain validation (R^2 = 0.70) [1]. To replicate damage mechanisms [2], vertebral endplate deformation should be permitted, while most existing studies either included endplates in endcaps [3] or removed them [4]. Only displacements could be accurately predicted when permitting endplate deformation by leaving in place intervertebral disks [5]. FE models of metastatic vertebral bodies could predict failure but using an endplate-removal setup [6].

This study aims to: (i) validate an experimental procedure that permits endplate deformation; (ii) test the procedure in intact and lesion-affected human vertebral bodies, measuring surface displacements and strain with Digital Image Correlation (DIC); (iii) determine the prediction accuracy of a FE model of the vertebral body.

Methods

Homogeneous distribution of the contact pressure was attempted by pressurizing a low viscosity gel acting on a thin deformable membrane covering the proximal endplate. Three human lumbar vertebrae (L3-L5, single donor) and three pseudo-vertebrae machined from bulk polyethylene underwent compressive testing in load control up to 2 kN, after removal of the distal endplate (flat caudal plane). Simulated lesions were obtained on human vertebrae by drilling hemispherical domes of increasing diameter (from 10 to 25 mm in steps of 5 mm) starting from the center of the flat caudal plane, with no involvement of the cortical wall. Displacement and strain fields were measured on three aspects (left/right anterolateral and posterior) by DIC, performing five repetitions per side. Endplate deflection was measured by an LVDT in specimens with lesions.

CT-based FE models of intact and lesion-affected vertebrae, including cortical bone mapping [7] were built, and inhomogeneous [8] and transversely isotropic material properties [9] were assigned.

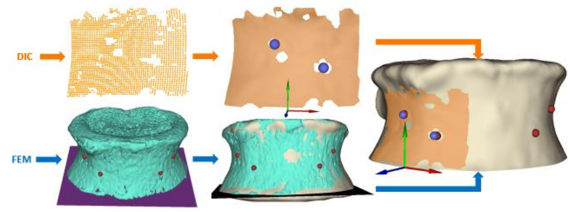

Figure 1: Matching of DIC (top) and FE (bottom) data.

Load was distributed on the proximal endplate. Caudal plane was vertically fixed and circumferentially free to expand. FE and DIC were spatially registered (Figure 1).

Results

Accuracy vs. theoretical calculations in pseudovertebrae (3–8 % longitudinal strain underestimation) and precision in anterior aspects of human vertebrae (≤0.2 µm for displacements and ≤30 µε for strains) support the validity of the loading scheme. Due to venous plexus, DIC data on posterior aspects were incomplete.

Simulated lesions, even of 25 mm diameter, did not cause vertebral body collapse nor endplate failure.

FE models accurately predicted: (i) longitudinal and circumferential displacements (R^2 = 0.96, slope = 1.15); (ii) longitudinal strains (median error 0.6%, 95% error within 27%). Circumferential strains were systematically overestimated (median error 39%).

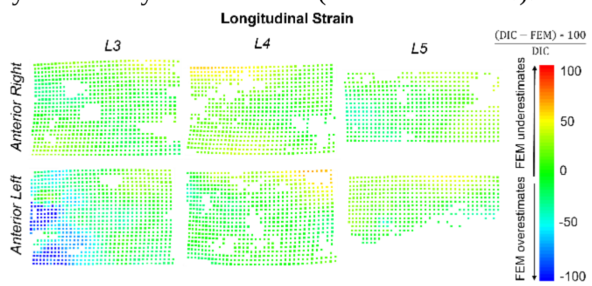

Figure 2: Maps of strain % accuracy of FE vs. DIC

Discussion

We developed and validated a new set-up to apply a uniform contact pressure upon the vertebral endplate.

A CT-based FE model of vertebral bodies could accurately predict longitudinal and circumferential displacements, and longitudinal strains.

There is initial evidence that simulated lytic lesions even of large diameter but not involving the cortex cannot induce collapse under physiological compressive loads.

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