QCT-Based Finite Element Models Do Not Accurately Predict Vertebral Failure Under Anterior Flexion

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Introduction: Wedge fractures are the most commonly observed type of clinical vertebral fracture [1] and are associated with a combination of compression and bending loads [2]. Patient-specific finite element (FE) models built from quantitative computed tomography (QCT) scans allow for predictions of bone strength and fracture patterns [3]. However, the advantage of QCT-based FE models over bone mineral density (BMD) for estimating fracture risk is not yet clearly established [4], and the accuracy of these models for predicting vertebral strength under loading associated with wedge fractures has been questioned [5]. Even for simple axial compression of a spine segment, loading across the endplates is highly non-uniform [6], suggesting that QCT-based FE simulations of the vertebra should carefully consider the choice of boundary conditions. Time-lapsed micro-computed tomography (μCT) in conjunction with digital volume correlation (DVC) provides experimentally measured deformation fields throughout an entire vertebra and can be used to assess the impact of various idealizations of boundary conditions on the performance of the FE simulations. The overall goal of this study was to make this assessment for thoracic vertebrae loaded in axial compression combined with anterior flexion. The objectives were: 1) to quantify experimentally the displacement fields throughout the vertebral body using time-lapsed μCT and DVC; and 2) to examine the effect of idealized boundary conditions on the accuracy of the FE results.

Methods: Specimen Preparation. Fourteen T7-T9 human spine segments were dissected from fresh-frozen spines (age: 35-91 years; mean ± standard deviation: 69.4 ± 15.9 years; 9 male, 5 female). Mechanical Testing and Imaging. The specimens were first imaged with QCT (GE; 0.31x0.31x0.625 mm/voxel). After preconditioning, the specimens were loaded in compression with anterior flexion in a stepwise manner (0.25mm/step and 0.5°/step) to failure, with a μCT scan (Scanco Medical; 37 μm/voxel) performed prior to each loading step. Loading was applied directly to the T7 and T9 vertebral bodies but not the T7 and T9 posterior elements. Images from all load increments were aligned using image registration. DVC. An irregular mesh that conforms to the geometry of the T8 vertebral body was generated using hexahedral elements with ~1.9mm side length. The displacements occurring at each load increment were measured experimentally using a custom DVC technique [7]. Nonlinear FE Analyses. Voxel-based FE models of T8 were generated from QCT images using hexahedral elements with a 0.625mm side length. Isotropic, linear elastic material properties and yield strengths were assigned based on BMD [8,9]. A crushable-foam constitutive model (Abaqus FEA 6.12, Dassault Systèmes) with strain hardening coefficients of 1.181 and 0.540 in compression and tension, respectively [9], was used for the post-yield behavior. Two sets of boundary conditions were used: 1) “Experimentally Matched” boundary conditions were the DVC-measured displacements at the superior and inferior endplates; and 2) “Idealized” boundary conditions were a uniform compressive displacement and a uniform angular displacement applied to the superior endplate. The Idealized
boundary conditions were applied such that no net vertical displacement was applied at the posterior edge, and that the average displacement across the superior endplate equaled the average displacement applied in the Experimentally Matched boundary conditions. Only small displacements (< 0.2mm) were observed at the inferior endplate, thus the inferior endplate was fixed in the Idealized boundary conditions. Statistical Analyses. The experimentally measured displacements throughout the interior of T8 were compared to the corresponding FE-computed displacements using linear regression (JMP 11, SAS Institute). For these comparisons, the FE nodal displacements were averaged over 2mm regions in order to match the spatial resolution of the DVC measurements, and points with measured displacements lower than the DVC detection limit (three times the standard deviation of the DVC displacement error (0.0556 mm)) were excluded [10]. FE-computed failure forces and moments were regressed against the corresponding measured values. The median percent errors between measured and FE-computed values of displacements, axial force, and flexion moment were computed.

Results: Failure initiated at the superior endplate (Figure 1) for all specimens. Immediately following the ultimate force or moment, the maximum axial displacement ranged 0.3-2.8 mm and was observed at the anterior-central endplate for eight specimens (Figure 1A) and at the anterior ring apophysis for six specimens. As loading continued, the deformation progressed both inferiorly and anteriorly, producing a wedge-shaped deformity. Both FE models captured some of the general, qualitative features of the deformation; however, the Idealized models did not predict the localized deformation occurring superiorly. $R^2$ values for the comparisons of measured and FE-computed displacements in 13 specimens improved from 0.02-0.59 ($p = 0.0001-0.088$) for the case of Idealized boundary conditions to 0.19-0.78 (all $p < 0.0011$) for the case of Experimentally Matched boundary conditions. For the remaining specimen, displacements throughout the vertebral body remained small (≤ 0.3 mm) and poor agreement was observed for both cases ($R^2 < 0.02$, $p > 0.33$). The median percent error in displacement was lower ($p = 0.0005$) for the case of Experimentally Matched vs. Idealized boundary conditions. Better agreement with measured values of ultimate force was also found with the Experimentally Matched boundary conditions ($R^2 = 0.58$ vs. 0.49 (Figure 2B); paired t-test p-value = 0.078 vs. 0.0004). However, no correlation was observed between the measured and FE-computed ultimate moments for either set of boundary conditions ($R^2 < 0.03$; $p > 0.57$).

Discussion: Although the loading applied to the T7-T9 spine segments was relatively simple, the T8 vertebral bodies within these segments experienced more complex loading conditions, which often featured large, localized displacements located at or just anterior to the center of the superior endplate. Consequently, FE analyses incorporating experimentally measured displacements at the T8 endplates produced more accurate predictions of the deformations throughout the vertebral body, and of ultimate force, than FE analyses using idealized boundary conditions. However, neither set of boundary conditions produced accurate predictions of ultimate moment, and the absolute errors in predicted displacements throughout the vertebral body were high. These results suggest the role of the mechanical properties of the adjacent intervertebral discs and vertebrae in producing irregular loading of the level of interest. These results also indicate that the errors in the FE predictions may be due to inaccuracies in the material properties assigned in the models. Further improvements in material modeling and estimating boundary conditions—perhaps via assessments of intervertebral disc health—are needed to produce accurate predictions of vertebral failure by QCT-based FE models.
**Significance:** QCT-based FE analyses incorporating realistic loading at the vertebral endplates produced more accurate predictions of vertebral failure than the analyses using idealized loading. However, inaccuracies in the FE predictions remain, suggesting that further improvements to the FE models are required before widespread application in predictions of vertebral fracture.

**Figure 1.** (A) Three-quarter section view of vertebral body before loading (gray) and at load increment following peak of loading (blue); (B-D) Experimental and FE displacement fields in axial direction at the load increment following peak of loading; (E-G) Three-quarter section views of B-D; Positive values indicate downward displacement.
Figure 2. (A) Median percent error for FE-computed axial displacements compared to experimental data using the Experimentally Matched and Idealized boundary conditions; (B) FE-computed axial force for each specimen plotted against experimental force.