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Computed-tomography-based finite-element models of long bones can accurately capture strain response to bending and torsion

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ABSTRACT

Finite element (FE) models of long bones constructed from computed-tomography (CT) data are emerging as an invaluable tool in the field of bone biomechanics. However, the performance of such FE models is highly dependent on the accurate capture of geometry and appropriate assignment of material properties.

In this study, a combined numerical–experimental study is performed comparing FE-predicted surface strains with strain-gauge measurements. Thirty-six major, cadaveric, long bones (humerus, radius, femur and tibia), which cover a wide range of bone sizes, were tested under three-point bending and torsion. The FE models were constructed from trans-axial volumetric CT scans, and the segmented bone images were corrected for partial-volume effects. The material properties (Young's modulus for cortex, density–modulus relationship for trabecular bone and Poisson's ratio) were calibrated by minimizing the error between experiments and simulations among all bones.

The R^2 values of the measured strains versus load under three-point bending and torsion were 0.96–0.99 and 0.61–0.99, respectively, for all bones in our dataset. The errors of the calculated FE strains in comparison to those measured using strain gauges in the mechanical tests ranged from -6% to 7% under bending and from -37% to 19% under torsion.

The observation of comparatively low errors and high correlations between the FE-predicted strains and the experimental strains, across the various types of bones and loading conditions (bending and torsion), validates our approach to bone segmentation and our choice of material properties.

1. Introduction

Quantitative computed-tomography (QCT) based finite element (FE) models have shown to accurately predict fracture load and fracture sites under specific loading conditions (Bessho et al., 2007; Schileo et al., 2008). However, poor capture of bone-material properties results in high errors in the FE analysis (Schileo et al., 2007b; Taddei et al., 2006). FE models that capture bone inhomogeneity using an appropriate density–modulus relationship improve accuracy in predicting surface strains (Austman et al., 2008; Barker et al., 2005; Schileo et al., 2007b; Taddei et al., 2006).

The literature reveals a wide spread of experimentally derived density–modulus relationships (Helgason et al., 2008; Taddei et al., 2006), making it possible to choose material parameters that compensate for poor geometry of a FE model and help achieve good accuracy for certain bones and loading conditions. Further, studies that attempted to optimize material properties under various loading conditions are limited (Austman et al., 2008; Barker et al., 2005; Schileo et al., 2007b). One specific study of the distal ulna (Austman et al., 2008) revealed that bones with lower densities produced low errors when using the Morgan equation (Morgan et al., 2003) and bones with higher densities produced low errors when using the Carter-and-Hayes equation (Carter and Hayes, 1977). Consequently, cortical and trabecular bones need to be considered separately when establishing density–modulus relationships (Barker et al., 2005; Bessho et al., 2007).

The partial-volume effect is a serious problem when using CT to extract bone geometry and material properties due to the blurring of structure boundaries (Augat et al., 1996; Dougherty, 1996). Some investigators adopted 0.4 mm shell elements to represent the outer surface of the cortex and assigned these shell elements Young's modulus of the tetrahedral element underneath, with a minimum value of 10 GPa (Bessho et al., 2007). However, their accuracy of simulated surface strains compared to measured surface strains was comparatively poor. Therefore, it may be advantageous to model the cortex using a constant Young's modulus derived from mechanical tests of pure cortical-bone specimens.

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