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Characterization of Bone Nonlinear Material Properties Based on Microstructure Characterized by Micro-CT Imaging

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Abstract

Predicting the nonlinear material properties of bone, specifically its stress-strain relationship, is crucial for accurately assessing fracture risk and improving finite element modeling (FEM) for various orthopedic treatments. Bone's nonlinear properties are influenced by its microstructure, which is characterized by the quantity and quality of cortical and cancellous bone, their spatial distribution, porosity, and the presence of fluid within the pores. Although extensive experimental studies have been conducted to understand the behavior of cortical and cancellous components and significant advances have been made in micro-CT-based finite element modeling of bone microstructure, the effect of microstructural characteristics on overall bone strength remains poorly understood due to the complexity of bone microstructure. To address this challenge, this study applies the Microstructure-Free Finite Element Modeling (MF-FEM) approach, which provides greater flexibility in modeling bone microstructure obtained from micro-CT imaging. Unlike conventional microstructure-based FEM, MF-FEM does not explicitly represent microstructure geometry but instead assigns heterogeneous material properties to voxels, eliminating the need for microstructure segmentation. First, voxels within a representative volume of bone are classified into cortical, cancellous, and fluid phases based on intensity thresholds, with each phase described by a nonlinear material model. Then, the material behavior of each voxel is defined by combining the group-level model with variations in voxel intensity. The nonlinear stress-strain relationships of cortical and cancellous bone are characterized through mechanical testing of standard bovine bone specimens. The variation in the stress-strain relationship with voxel intensity is analyzed using relevant statistical methods. MF-FEM predictions are validated by experimental results.