INTRODUCTION:

With increasing average population age, the occurrence of fracture has the potential to adversely affect a patient’s quality of life. Determining the mechanical properties that control bone toughness is consequently an important area for study. Bone is a composite of protein matrix (primarily collagen) and hydroxyapatite mineral. The post-yield mechanical behavior of bone matrix during damage is critical because it determines toughness of the whole bone. This investigation focuses on the total energy required to degrade the apparent material (cm) properties of cancellous bone as a function of intrinsic (hard tissue) post-yield material (μm) properties. The greater the mechanical energy input at the apparent level, the lower the likelihood of pathologic fracture.

METHODS:

To investigate the importance of material level post-yield properties to the macro-level apparent behavior of trabecular bone, finite element analysis was used. Two trabecular bone core geometries were obtained from Micro-Computed Tomography (μCT, 50μm voxel) scans of cadaveric T12 trabecular bone core specimens. Scans were cropped to cubic specimens (2.5mmX2.5mmX2.5mm) to reduce computation time. Voxels were directly converted from μCT images (50μm voxel isotropic) to hexahedra. Isotropic and initially homogenous material properties were used for all elements (E<sub>M1</sub>=10GPa, Poisson Ratio=0.3). Axial compression to 0.025 strain was applied to the models. The effects of changes in post-yield material level behavior were investigated by using a strain-based damage rule (Fig. 1). The post-yield material properties (Fig. 1) were varied in the range, E<sub>M1</sub>(200MPa-4400MPa), ε<sub>M1</sub>(0.0025-0.01), and ε<sub>M2</sub>(0.0025-0.1) creating N=207 combinations of post-yield material level behavior that were applied to the 2 geometries. The model’s apparent resistance to fracture was assessed by calculating the input mechanical energy (J/L) as a function of E<sub>M1</sub> and ε<sub>M1</sub>. The volume of damaged bone was negatively correlated with toughness (Primary: R<sup>2</sup>=0.33, p<0.001, Secondary: R<sup>2</sup>=0.05, p=0.0001).

DISCUSSION:

Changes in the collagen matrix may affect material level post-yield mechanical behavior leading to large changes in apparent strength. Models with a larger range of material properties (undamaged, primary and secondary failures) were found to be tougher than those with a more narrow range (only undamaged bone and primary failures). Large deformations of damaged bone matrix play a key role in decreasing bone fragility. Similar large deformations within bone matrix have been observed by serial μCT of bone under load. The model for intrinsic hard tissue material property damage provides a means to determine how changes in post-yield tissue mechanical properties determine the apparent behavior of bone. The model reproduced apparent level behaviors (e.g., softening after peak load, micro-damage accumulation before apparent yield, unload softening, etc.) not previously modeled. This study demonstrates the importance of the post-yield material behavior to apparent bone fragility and also that increases in intrinsic mechanical properties (e.g., failure strain) can reduce apparent strength. The behavior was in agreement with previous findings that alterations to the collagen network, including increased crosslinking (ribosylation [2], formaldehyde [3]) and collagen degradation [4] did not alter the stiffness, however do result in changes to the yield strength, the post-yield behavior and the final fracture of the bone specimens.


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