VARIABLE-MODULUS FINITE ELEMENT MODELS MORE ACCURATELY PREDICT THE ELASTIC BEHAVIOR OF CANCELLOUS BONE THAN HOMOGENEOUS-MODULUS MODELS

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Introduction: Large-scale finite element models are gaining acceptance for predicting cancellous bone structural performance. These models are based on accurate trabecular architecture, but generally assume a homogeneous tissue modulus. In this study, we examined the ability of a homogeneous tissue modulus to accurately capture the orthogonal elastic behavior measured for cancellous cubes. Four-millimeter cancellous cubes removed from the medial and lateral distal femoral condyles of rabbits were previously tested in uniaxial compression. Significant medial-lateral differences were found in elastic modulus and bone volume fraction, but not in mean intercept length. Therefore, we hypothesized that the cancellous architecture alone would be insufficient to capture the experimental behavior in FE simulations, and that variation in the local tissue material properties would be required to accurately model the tests.

Methods: Microcomputed tomography scans (22.5 um isotropic resolution) were thresholded, coarsened two-fold and converted to large-scale finite element models for each cube (n=10). In addition to architecture, the scans provided a quantitative measure of the x-ray attenuation at each voxel, which correlates with the mineralized tissue density. The local elastic modulus was calculated from the tissue density using a power law relationship [2]. Simulations were performed using a single homogeneous tissue modulus of 10 GPa, a cube-specific homogeneous modulus calculated from the mean local tissue modulus, and a heterogeneous modulus based on the mean local tissue value. Each simulation was performed with applied displacements and boundary conditions similar to the experimental tests for each orthogonal direction. Structural moduli from the three different cases were compared to the experimentally measured values.

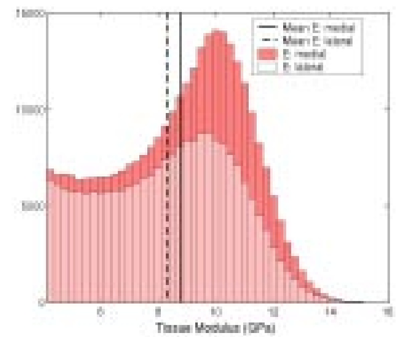

Figure 1. CT-calculated modulus distribution for representative medial and lateral cubes

Results: When results from the three different tissue moduli were compared to the experimental data, on average the variable modulus matched the experimental data better in 2 of 3 loading directions (Figure 2). The variable modulus prediction was better than the cube-specific homogeneous modulus for 6 of 10 cubes in each loading direction. For the individual cubes, both homogenous models overpredicted the structural stiffness. The variable modulus underpredicted the structural behavior in 23 of 30 tests.

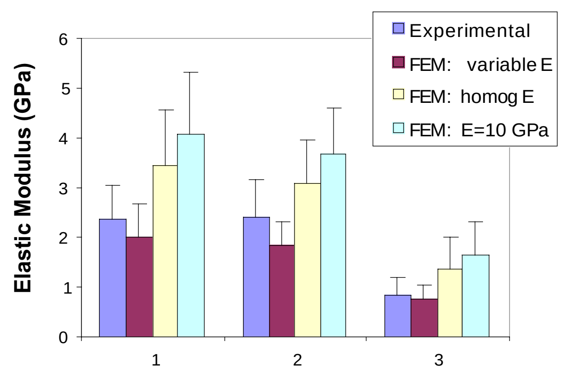

Figure 2. Apparent modulus for: experimental, FEM with variable tissue modulus, FEM with mean tissue modulus, and FEM with imposed modulus E = 10 GPa

Discussion: The difference in tissue modulus distribution between medial and lateral specimens helps to explain the significant apparent modulus differences found in both the experimental and computational components of this study. The orthogonal behavior of the experimental results is predicted by all three models. In all cases, the individual cube-based homogeneous modulus is preferable to the 10GPa homogeneous case for predicting modulus in the region of interest. The variable modulus case may be, but is not always a preferable predictor of modulus. The method of determining homogeneous modulus from the averaged CT values may needs to be investigated for the purpose of improving the model accuracy. The findings of this study suggest that explaining the anisotropic structural behavior of cancellous bone requires both architectural and material measurements.

Acknowledgments: The authors acknowledge support from the Whitaker Foundation and the National Science Foundation (Grant BES 9875838). We thank Dr. Stephen Doty for specimen preparation, and Enhanced Vision Systems for microCT scans.

References: [1] Bourne et al. (2001) BMES Conference 2001; [2] Keaveny *et al*. (1997) J Orthop Res; [3] van Rietbergen *et al*. (1995) J Biomech; [4] van Rietbergen *et al*. (1996) Intl J Num Meth Eng; [5] Ulrich *et al*. (1997) Bone Res Biomech; [6] van der Linden *et al*. (2001) J Biomech