Trabecular bone elastic properties depend on μMRI-derived measures of bone volume fraction and fabric

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Introduction: As the mechanical properties of trabecular bone (TB) vary according to test direction, a structure-based prediction of bone's mechanical properties requires the knowledge of TB orientation. Assuming TB approximates an orthotropic material (i.e. has at least two planes of symmetry), its orientation can be captured by a second-rank fabric tensor in the form of a 3x3 matrix [1,2]. The invariants (e.g. eigenvalues) of the fabric tensor have been related to the elastic constants of TB by assuming a homogeneous tissue modulus and alignment of the principal fabric and mechanical axes [3]. On the basis of ex vivo images (e.g. optical reconstructions of specimen sections and μCT images), the addition of fabric measures have significantly improved the prediction of experimentally-determined [4] and micro finite element (μFE) derived TB elastic constants [5]. In this work, the contribution of fabric measures is investigated in micro-magnetic resonance (μMR) images of distal tibia specimens and tibia of live subjects. Fabric measures are derived from two techniques; the mean intercept length (MIL) [6] and spatial autocorrelation function (ACF) [7]; and elastic constants are determined from μFE simulations.

Methods: Previously acquired [8] μMR images of human distal tibia specimens were analyzed in concert with in vivo images of the distal tibiae of sixteen subjects (5 male, 11 female, 24-84 years old). The in vivo images were acquired using a four-channel phased array ankle coil on a 3T Siemens Tim Trio scanner (Erlangen, Germany) with an accelerated isotropic FLASE sequence (TE/TR=11/80ms, R=1.8/scan time=17 mins, 160 μm isotropic voxel size). Specimen and in vivo images were processed to yield bone volume fraction (BVF) images (Fig. 1a and b) with pure bone and pure marrow corresponding to intensities of 100 and 0, respectively. Three $(8\text{mm})^3$ subvolumes of TB were extracted from posterior (P), lateral (L), and anterior-medial (AM) portions of the tibia specimens where the TB orientation is known to be different (Fig. 1a). A single subvolume (Fig. 1b) was selected from the anterior portion of each in vivo image where signal-to-noise ratio was highest. All subvolumes were subjected to orientation analysis via MIL and ACF in which angularly-sampled measurements of MIL and the full-width-at-half-maximums of the spatial autocorrelation function were fit to ellipsoids, denoted in matrix form as $\mathbf{H}_{MIL}$ and $\mathbf{H}_{ACF}$ (Fig. 1d and e). Six stress/strain simulations were performed via μFE analysis (Fig. 1f) where each element was assigned a modulus proportional to its BVF with pure bone assigned a value of 15GPa. From the resulting compliance tensor (Fig. 1g), nine orthotropic elastic constants (three Young's moduli – E_{ii} (i=1, 2, 3), three shear moduli – G_{ij} (j=1, 2, 3), and three Poisson's ratios – v_{ij}) were determined and subsequently fit to a model of the normalized fabric eigenvalues λ_1, λ_2, λ_3 and power-law functions of bone volume divided by total volume (BV/TV) where the exponent α was varied from 1 to 3.

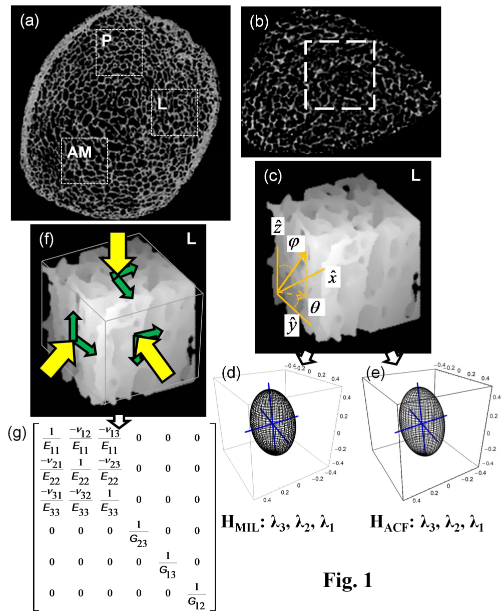

Fig. 1

Results and Conclusions: Fig. 2a-c show power-law dependences between E_{ii} and BV/TV to vary by test direction and anatomical location within the trabecular bone. When pooling the three anatomical locations, BV/TV with α=1.6 predicted 74% of the variation in E_{ii} (Fig. 2d). BV/TV was not a significant predictor of pooled E_{ii} in the in vivo subvolumes (Fig. 2g). When including eigenvalues of $\mathbf{H}_{MIL}$ and $\mathbf{H}_{ACF}$ following the orthotropic model, the best fit was obtained for α=1.5. The models combining fabric and BV/TV were highly predictive of pooled E_{ii} in which the data from all three test-directions were combined (R^2_{adj}≈0.97 for specimen - Fig. 2e and f, R^2_{adj}≈0.93 for in vivo - Fig. 2h and i). Pooled G_{ij} and v_{ij} were also better predicted when including fabric measures (not shown). MIL- and ACF-based fabric measures significantly improved (indicated by * in Fig. 2e, f, h, and i) the BV/TV-based prediction of elastic constants independent of sub-region and test direction. Results emphasize (1) the importance of fabric as a predictor of bone mechanical properties, and (2) that these relationships can be assessed in the limited resolution and SNR regime of μMRI.

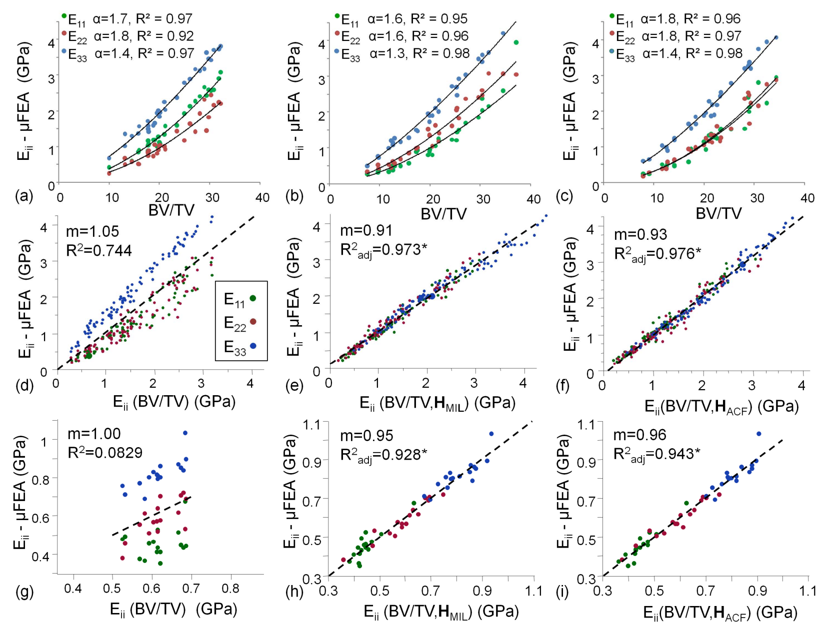

Fig. 2 Dependence of E_{ii} on BV/TV for posterior (a), lateral (b), and anterior-medial (c) subvolumes. Pooled fits of μFE-derived E_{ii} by models of BV/TV (d), BV/TV and H_{MIL} (e), BV/TV and H_{ACF} (f) in specimen and in vivo subvolumes (g-i), respectively.

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