Heterogenous tissue modulus improved prediction of mechanical behavior in human vertebral cancellous bone

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INTRODUCTION: Architecture-based finite element (FE) models examine mechanical behavior in virtual biopsies of cancellous bone noninvasively and nondestructively [1,2]. Most FE models use homogeneous material properties, but models with element-specific heterogeneous moduli better predict mechanical behavior in rabbit femora [3] and human scapulae [4] than do models with homogeneous moduli across all elements, and increased spatial variation in both bone mineral distribution [5] and tissue modulus [6] affect this behavior. Element-specific moduli (E_{elem}) can be assigned using empirically derived relationships based on tissue mineral density (ρ) measured with micro-computed tomography (microCT). E-ρ relationships vary across studies [7] and differ by bone site [8]. The effect of heterogeneous material properties has not yet been assessed in FE models of human vertebral cancellous bone, and the effects of sex, vertebral site, or metabolic disorders such as osteoporosis on model accuracy have not yet been studied. We hypothesized that heterogeneous models will provide more accurate prediction of apparent modulus than homogeneous models and that model accuracy depends on clinical osteoporosis status.

METHODS: Human cancellous bone cores (8.25-mm diameter) were obtained from excised T12 and L2 vertebrae of 19 cadaver spines (11 female, 10 male). Cores were classified as osteoporotic (n=15) or non-osteoporotic (n=22) based on DXA T-score. All cores were scanned with microCT. Scans were reconstructed (17-μm voxels) and calibrated using a cortical bone mineral standard (ρ=1.15 g/cc). After removing the vertebral end plates, bone cores were fitted with brass endcaps [9] and tested to failure in compression at 0.50% strain/sec. Experimental apparent elastic modulus (E_{exp}) was calculated from the resulting stress-strain data. A 17-mm tall region from the center of each microCT scan was converted into a FE mesh with 8-noded linear brick elements and assigned isotropic material properties with a constant Poisson's ratio of 0.3 and variable tissue modulus based on the voxel mineral densities. Three different modulus-density relationships were used, similar to those previously studied in rabbits [3]: 1) uniform homogeneous with a single modulus for all elements and all specimens (U_{Hom}, $E_{elem} = 1.5*E_c$, n=10); 2) specimen-specific homogeneous scaled based on mean voxel density and assigned to all elements within a specimen (SS_{Hom}, $E_{elem} = 1.5*E_c*(\rho_{mean}/\rho_c)^1$, n=10); and, 3) specimen-specific heterogeneous based on specific voxel density and assigned at each element of each specimen (SS_{Het}, $E_{elem} = 1.5*E_c*(\rho_{vox}/\rho_c)^1$, n=37), in which ρ_{mean} is the mean tissue density of all voxels for each specimen, and ρ_c and E_c are the density and compressive tissue modulus (assumed to be 20 GPa) of the cortical bone mineral standard, respectively. For the homogeneous models, 10 specimens (5 osteoporotic, 5 non-osteoporotic) were selected to span the range of E_{exp} obtained from mechanical testing (112-930MPa). To simulate experimental testing, a compressive strain of 0.25% was applied to each model. FE-predicted apparent modulus (E_{pred}) was computed using nodal reaction forces (Abaqus) and compared to E_{exp} with linear regression. The effects of osteoporosis status, vertebral site, sex, and model parameters on regression slope were determined using analysis of covariance (ANCOVA) with Bonferroni correction (SAS).

RESULTS: Comparing E_{exp} to E_{pred} for the SS_{Het} models, the regression slope (0.96) was not significantly different from unity (p=0.67, Fig. 1a), indicating a good fit of the models with heterogeneous material properties to experimental data. Regression slope for the SS_{Hom} models (0.61) was less than both unity (p=0.0005) and SS_{Het} (p=0.0033) slopes but not significantly different from U_{Hom} slope (p=0.017), indicating a poorer prediction with homogeneous properties scaled from ρ_{mean}. For the SS_{Het} models, regression slopes did not differ between groups or from unity by osteoporosis status (p=0.33), vertebral site (p=0.11), or sex (p=0.80) (Fig. 1b-d), suggesting predictions with these models were robust.

DISCUSSION: Specimen-specific heterogeneous material properties improved prediction of apparent modulus in architecture-based FE models of human vertebral cancellous bone. Contrary to previous findings in rabbit femoral bone [3], SS_{Hom} models predicted apparent modulus less accurately than did SS_{Het} models, possibly due to differences in species [10] or bone site [8]. Previous FE studies examining the role of tissue heterogeneity in cancellous bone properties examined a small sample size of 3 to 5 [5,3,6], a less clinically relevant site [4], or used an assumed mineral distribution from localized tissue measurements [5,6]. Our study examined tissue heterogeneity in micro-FE models for a site at high risk for osteoporotic fracture using a larger sample size and with accurate mapping of CT-derived tissue modulus reflecting true *in vivo* mineral distributions.

SIGNIFICANCE: This study examines the role of material heterogeneity in the performance of finite element models of human vertebral cancellous bone, a site with crucial load-bearing function that commonly experiences osteoporotic fracture. Incorporating true tissue heterogeneity in virtual biopsy models may improve fracture risk predictions in the aging population.

REFERENCES: **1.** van Rietbergen 1995 *J Biomech* 28:69. **2.** Keyak 1990 *J Biomed Eng* 12:389. **3.** Bourne 2004 *J Biomech* 37:613. **4.** Knowles 2019 *Ann Biomed Eng* 47:615. **5.** van der Linden 2001 *J Biomech* 34:1573. **6.** Jaasma 2002 *J Biomech* 35:237. **7.** Helgason 2008 *Clin Biomech* 23:135. **8.** Morgan 2003 *J Biomech* 36:897. **9.** Keaveny 1994 *J Biomech* 27:1127. **10.** Currey 1984 *Philos Trans R Soc Lond B Biol Sci* 304:509.

ACKNOWLEDGMENTS: Funding through NIH (T32 AR007281, S10 RR014801, P30 AR046121). We thank Dr. Ken Mann, SUNY Upstate Medical University, for cadaver spines and usage of lab facilities.

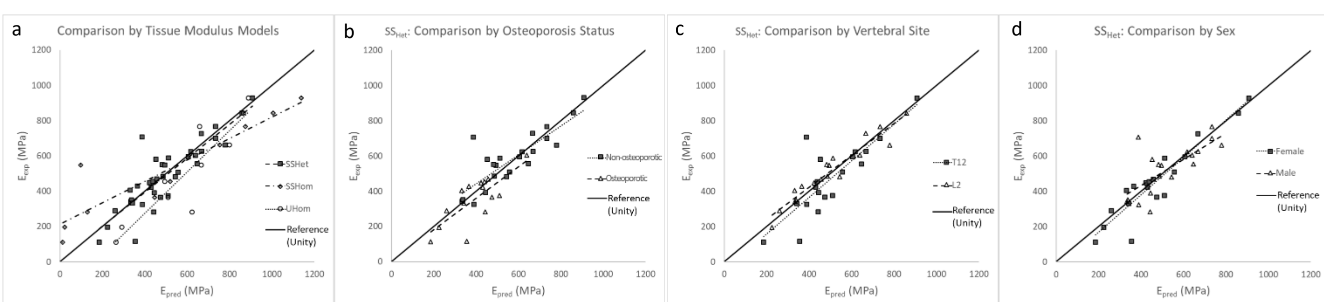

Figure 1. Experimental vs. predicted modulus compared for a) tissue modulus models and for SS_{Het} by b) osteoporosis status, c) vertebral site, and d) sex.