Data-Driven Multiscale Modeling for Vertebral Trabecular Elasticity

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INTRODUCTION: Vertebral fracture is the most common type of osteoporotic fracture, with nearly one million cases occurring annually in the US [1]. Current clinical assessment of vertebral fracture risk relies primarily on average bone mineral density and has limited accuracy [2]. Computed tomography-based finite element (FE) modeling has long been viewed as promising but remains constrained by the trade-off between reliability and resolution, limiting its clinical translation [3,4]. In this study, we present a data-driven multiscale modeling framework for predicting the elastic behavior of the vertebral trabecular centrum, as a prelude to extending the framework to the inelastic behavior of the entire vertebra. Critically, this framework breaks through the resolution-reliability tradeoff, preserving accuracy while increasing efficiency, and increasing the predictive performance of FE models at clinical imaging resolutions.

METHODS: A total number of 2297 trabecular microvolumes (5×5×5mm^3, Fig. 1a top) were extracted from microcomputed tomography (µCT80 of Scanco) images of 24 L1 vertebral trabecular centra (12 male and 12 female, age 80.42 ± 11.04 years old). The microstructure was characterized by one- and two-point correlation functions (representing bone mineral density and bone tissue distribution, respectively), followed by feature compression via an autoencoder algorithm, thus enabling interpolated microstructural representations through a range of imaging resolutions (37 µm – 1 mm). The corresponding elastic properties were measured via computational homogenization using an energy criterion and simplified as orthotropic constitutive matrices, reducing data complexity while preserving essential mechanical anisotropy. The resulting, high-fidelity dataset links 3D microstructures to apparent-level mechanical properties and was subsequently used to train a random forest model to predict the homogenized constitutive matrices directly from the image data. These predictions were then used to construct the "upscaled continuum finite element" (ucFE) model (mesoscale with 5mm element, Fig. 1d bottom), for which the micromodel of trabecular centrum (microFE models with 37µm elements, Fig. 1d top) served as ground truth. Finally, the compressive stiffness in the superior-inferior direction and the bending stiffness for anterior flexion were computed for each L1 trabecular centrum through numerical simulations of ucFE models.

RESULTS: At the apparent scale (5×5×5mm^3, Fig. 1a), the random forest model explained over 88% of the variation in stiffness computed by homogenization of the microvolumes (Fig. 1c), whereas volume fraction explained only 67% (Fig. 1b). At the organ scale (vertebral centrum, Fig. 1d), the performance was similarly high: the ucFE models explained over 90% of the variation in each of the compressive and bending stiffnesses computed by microFE simulations of the micromodels (Fig. 1e), while reducing the computational time from hours to seconds. Importantly, the coefficient of variation for ucFE-predicted stiffness exceeded 85% even at 1mm imaging resolution – higher than traditional quantitative computed tomography-based FE modeling under comparable conditions [5] (Fig. 1f). The values of compressive and bending stiffnesses evaluated via ucFE models were also in good agreement with the prior findings [6].

DISCUSSION: The development of the data-driven multiscale modeling framework provides an efficient and accurate approach for estimating vertebral trabecular elasticity. The incorporation of bone tissue distribution (i.e. 2-point vs 1-point correlation) substantially enhances the reliability of estimations, and the resulting random forest model enables ucFE models that markedly reduce computational time. Importantly, the n-point correlation function characterizes the trabecular microstructure in a continuous manner, thereby ensuring consistent prediction across different imaging resolutions. Compared with the traditional Cowin model of fabric-based elasticity [7], the two-point correlation captures finer details of the trabecular microstructure and will accommodate more effectively regions of irregular microstructure and the vertebral cortex, as well as vertebral inelastic behavior.

REFERENCES: [1] Riggs BL & Melton III LJ, *NEJM*, 1986;314; [2] Schuit SCE et al., *Bone*, 2004;34; [3] Luan S & Morgan EF, *JMBBM*, 2025;163; [4] Pahr DH et al., *JMBBM*, 2014;33; [5] Liebschner MA et al., *Spine*, 2003;28; [6] Roux JP et al., *JBMR*. 2010;25; [7] Cowin SC, *MoM*, 1985;4.

SIGNIFICANCE/CLINICAL RELEVANCE: The presented data-driven multiscale modeling framework provides an efficient and accurate approach for estimating vertebral trabecular elasticity, holding promise for extending to the entire vertebral body and inelastic behavior, even at clinical imaging resolutions.

ACKNOWLEDGEMENTS: This work was supported by NIH grant AR054620.

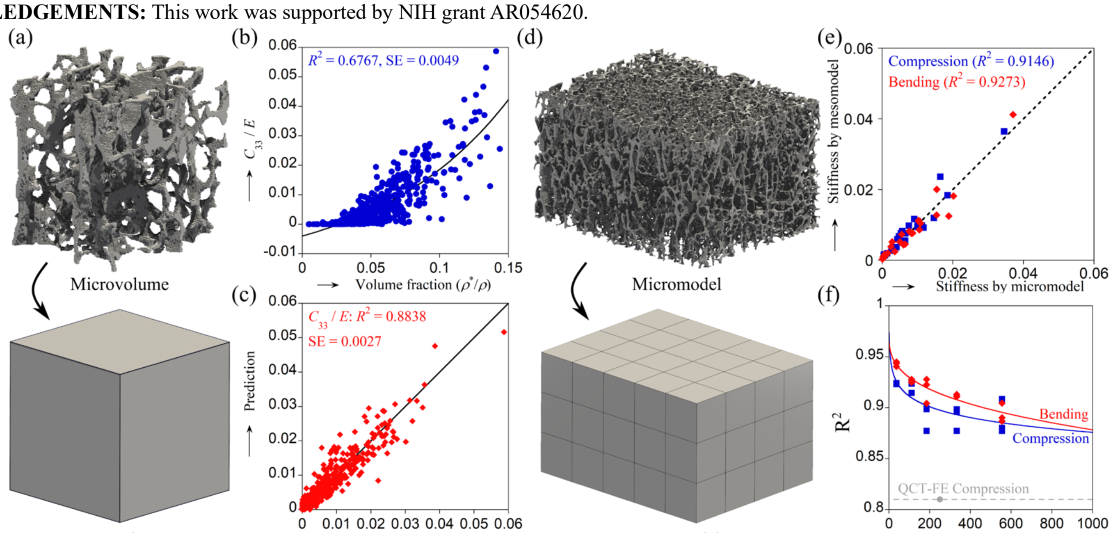

Figure 1. Performance of data-driven multiscale modeling of vertebral trabecular elasticity: a) a typical 5mm cubic volume represented as microvolume and mesovolume; apparent-level predictions of C33 (superior-inferior direction) estimated via b) one-point correlation and c) one- and two-point correlation functions; d) a typical vertebral trabecular centrum represented as micromodel and mesomodel; e) organ-level predictions of compressive and bending stiffness via ucFE modeling, and f) variation in the R^2 values (for stiffness prediction) with imaging resolution.