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Short communication

Anatomic variation in the elastic inhomogeneity and anisotropy of human femoral cortical bone tissue is consistent across multiple donors

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ABSTRACT

Numerical models commonly account for elastic inhomogeneity in cortical bone using power-law scaling relationships with various measures of tissue density, but limited experimental data exists for anatomic variation in elastic anisotropy. A recent study revealed anatomic variation in the magnitude and anisotropy of elastic constants along the entire femoral diaphysis of a single human femur (Espinoza Orías et al., 2009). The objective of this study was to confirm these trends across multiple donors while also considering possible confounding effects of the anatomic quadrant, apparent tissue density, donor age, and gender. Cortical bone specimens were sampled from the whole femora of 9 human donors at 20%, 50%, and 80% of the total femur length. Elastic constants from the main diagonal of the reduced fourth-order tensor were measured on hydrated specimens using ultrasonic wave propagation. The tissue exhibited orthotropy overall and at each location along the length of the diaphysis ($p<0.0001$). Elastic anisotropy increased from the mid-diaphysis toward the epiphyses ($p<0.05$). The increased elastic anisotropy was primarily caused by a decreased radial elastic constant (C_{11}) from the mid-diaphysis toward the epiphyses ($p<0.05$), since differences in the circumferential (C_{22}) and longitudinal (C_{33}) elastic constants were not statistically significant ($p>0.29$). Anatomic variation in intracortical porosity may account for these trends, but requires further investigation. The apparent tissue density was positively correlated with the magnitude of each elastic constant ($p<0.0001$, $R^2>0.46$), as expected, but was only weakly correlated with C_{33}/C_{11} ($p<0.05$, $R^2=0.04$) and not significantly correlated with C_{33}/C_{22} and C_{11}/C_{22}.

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1. Introduction

Elastic inhomogeneity in human cortical bone tissue is commonly accounted for by power-law scaling relationships with apparent tissue density, mineral density, or porosity (Hernandez et al., 2001; Keller et al., 1990; Schaffler and Burr, 1988; Zioupos et al., 2008), but limited experimental data exists for anatomic variation in elastic anisotropy (Espinoza Orías et al., 2009). Experimental investigations of elastic anisotropy and inhomogeneity in cortical bone tissue have typically, for expediency, used specimens excised from the femoral mid-diaphysis. However, the proximal and distal ends of the diaphysis are more clinically relevant to common orthopaedic procedures and adaptive responses to mechanical loading.

Ultrasonic wave propagation has been used to enable non-destructive measurement of elastic constants on small specimens that can be sampled from various anatomic locations (Ashman et al., 1984; Van Buskirk et al., 1981). A recent study showed that elastic constant magnitudes decreased and elastic anisotropy increased from the mid-diaphysis toward the epiphyses of a human femur (Espinoza Orías et al., 2009). The elastic symmetry of tissue in the distal and extreme proximal portions of the diaphysis was orthotropic, but was reasonably approximated as transversely isotropic near the mid-diaphysis. These trends were significantly correlated with the apparent tissue density and were suggested to be useful for numerical models of the human femur accounting for anisotropic and inhomogeneous tissue properties. However, a limitation was that tissue was sampled from a single elderly male donor. Therefore, the objective of this study was to confirm the above anatomic trends across multiple donors while also considering possible confounding effects of the anatomic quadrant, tissue density, donor age, and gender.

2. Materials and methods

Whole femora were harvested from the lower extremity of 9 human donors, including 6 females (ages 41, 59, 73, 89, 93, and 99) and 3 males (ages 18, 53, and

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