Shear Strength Behavior of Human Trabecular Bone

INTRODUCTION
Trabecular bone is adapted to sustain compressive loads along its principal material orientation. However, loads during falls are not oriented along the principal material orientation and can generate substantial shear stress relative to the principal material orientation1. Likewise, large shear stresses can develop at bone-implant interfaces2. In analyzing risk of bone failure in such situations, the shear strength of bone may be more important than the compressive strength. While the compressive properties of human trabecular bone has been extensively studied, very few studies have explored the shear strength of human trabecular bone or the associated failure mechanisms, particularly across different densities and anatomic sites. Addressing this limitation, we sought to compare the shear and compressive strengths of human trabecular bone across a range of densities and anatomic sites and to explore the underlying failure mechanisms. This study is unique since it provides a comprehensive characterization of the shear strength behavior of human trabecular bone.

METHODS
Fifty-four trabecular bone specimens (5mm cube) were taken from forty-seven human cadavers (age = 68±9.5, 48-82; n=36 male, n=18 female), across four anatomic sites: vertebral body, femoral neck, greater trochanter, and proximal tibia (volume fraction BV/TV range of 38%). Micro-CT images of these specimens at 22-66 μm were used to build finite element models. To estimate both the apparent compressive and shear strengths for each specimen, two non-linear finite analyses, including both material and large-deformation geometric non-linearities, were performed on each specimen, one for compression loading and the other for pure shear loading. The bone tissue was modeled using the same tissue elastic modulus for every specimen (E=19 GPa), and an experimentally validated non-linear material model having tension-compression strength asymmetry1. The amount of failed tissue and the mode of failure at tissue-level (compressive vs. tensile) were calculated at the apparent yield point. Statistical analysis was performed to observe the dependence of strength and tissue failure outcomes on bone volume fraction and trabecular bone micro-architecture parameters. To validate the model estimates of strength, the model prediction of the relation between compressive strength and bone volume fraction was compared against the relation as obtained from direct mechanical testing.

RESULTS
For both compression and shear loading, strength was strongly correlated (R²=0.95) with bone volume fraction in a non-linear fashion, each relation having an exponent close to 1.7 (Figure 1, left). Consistent with other similar exponents, the ratio of shear-to-compressive strength did not depend on the bone volume fraction (p > 0.71) (Figure 1, right). After accounting for bone volume fraction, there was no effect of anatomic site on these trends. There was excellent agreement between model and experiment for compressive loading (Figure 1, left), thus validating the model predictions for compressive strength. Although the ratio of shear to compressive strength did not depend on bone volume fraction, this variable did vary appreciably (mean±SD = 0.44±0.16, range = 0.25-1.00), particularly when the bone volume fraction was less than about 0.20. This variation was partially explained by the standard deviation of the trabecular separation, Tb.Sp.SD (r=0.48). Under shear loading, there was mostly tensile tissue failure at the tissue level (Figure 2), due to tensile stretching of the trabeculae oriented obliquely to the principal material orientation of the specimen. Under compression loading, there was a mixture of tissue-level tensile and compressive failure, the tensile failure being more common in highly porous specimens due to large-deformation effects.

DISCUSSION
These results demonstrate that human trabecular bone is much weaker in shear than compression and that both the compressive and shear strengths vary in a similar fashion as bone density increases. Even so, the ratio of shear to compressive strength for any given specimen does depend on the trabecular microarchitecture. The primary reason for this dependence is a change in failure mechanism for compressive strength in highly porous specimens, when large-deformation effects become important as individual trabeculae bend and buckle. There was not any such density-related change in failure mechanism for shear loading.

SIGNIFICANCE
These results provide unique insight into the shear strength behavior of human trabecular bone, and have direct relevance to whole-bone and bone-implant strength assessment in a variety of clinical applications.

REFERENCES
(2) Cheal et al., J of Orthop Research, 1991, 10(3): 405-422
(3) Bevill et al., Bone, 2006, 39(6), 1218-1225

Figure 1: Left: Compressive and shear apparent yield stresses versus bone volume fraction. The finite element compressive strength estimate had excellent agreement with experimental data obtained from mechanical testing. Right: The strength ratio (mean = 0.44) displayed much large scatter below a bone volume fraction of about 0.20. The von Mises criterion (0.58) over predicted this ratio for most specimens.

Figure 2: Tissue failure distribution for a slice of a low-density (BV/TV = 0.07) and high-density (BV/TV = 0.26) specimen. Red regions denote tissue failure in tension and blue regions denote tissue failure in compression. The Z-axis denotes the principal material orientation.