INTRODUCTION:
Vertebral strength is a key element in the etiology of osteoporotic spine fracture. Recent work using isolated cores of vertebral trabecular bone suggests that the apparent density of trabecular bone that is vertically aligned predicts trabecular strength better than does the apparent density of the overall specimen [1,2]. Extending this result to the strength of the whole vertebral body may lead to improved clinical assessment of vertebral fracture risk. However, the strength of the vertebral body includes contributions from the endplates and the cortical shell. The presence of the cortical shell, in particular, may mitigate the effect of vertically-oriented trabeculae on vertebral strength because of the shell’s substantial load-bearing role [3]. Addressing this issue, we hypothesized that the apparent density of vertically-aligned trabecular bone in the vertebra predicts vertebral strength better than does the apparent density of all trabecular bone. This study is unique in relating trabecular bone in different orientations to whole-vertebral strength.

METHODS:
Twelve human T9 vertebral bodies (76.9±10.8 years) were scanned using micro-CT (Scanco µCT 80). After coarsening the scans to 60 µm resolution, the trabecular compartment was digitally isolated with a custom code and segmented into individual trabeculae using the individual trabeculae segmentation (ITS) technique [1]. Trabeculae were then classified by their anatomical orientation with respect to the superior-inferior axis: vertical (0-30˚), oblique (31-60˚), and horizontal (61-90˚). The bone volume fraction (BV/TV) in each orientation was then determined using ITS and performed in PMMA and experimentally tested in compression in the superior-inferior axis: vertical (0-30˚), oblique (31-60˚), and horizontal (61-90˚). The bone volume fraction (BV/TV) in each orientation was found by dividing the bone volume in each orientation by the total volume of the trabecular compartment. The vertebrae were then performed in PMMA and experimentally tested in compression in the superior-inferior direction [4]. Vertebral strength was defined as the peak force achieved during loading. To understand the effect of the cortical shell, two high-resolution finite element models per vertebra—one intact model and one with the cortical shell removed—were created from the coarsened scans and virtually compressed to mimic the experiments [5]. All bone tissues in the models were assigned homogeneous material properties (E=10 GPa, ν=0.3). Measured vertebral strength and finite element-predicted vertebral stiffness were correlated with the various BV/TV measures using linear regression. The influence of the cortical shell on the relationship between vertical BV/TV and vertebral stiffness was assessed using a t-test on the regression slopes.

RESULTS:
As hypothesized, vertical BV/TV accounted for substantially more of the observed variation in vertebral strength than did total BV/TV ($r^2=0.83$ vs. 0.56; Fig. 1). A paired analysis of the residuals revealed that vertical BV/TV exhibited significantly less scatter than total BV/TV ($p<0.01$). Neither horizontal BV/TV ($p=0.65$) nor oblique BV/TV ($p=0.13$) was associated with vertebral strength.

Finite element results indicated that the major compressive load paths comprised vertically-oriented tissue (Fig. 2) and that the relationship between vertical BV/TV and compressive stiffness was not influenced by the presence of the cortical shell ($p=0.10$). For the models with the cortical shell, vertical BV/TV was more indicative of vertebral stiffness than was total BV/TV ($r^2=0.95$ vs. 0.86). Similarly, for the models without the cortical shell, vertical BV/TV was more indicative of stiffness than was total BV/TV ($r^2=0.89$ vs. 0.74). Vertical BV/TV better explained vertebral stiffness with the cortical shell than vertebral stiffness without the cortical shell because removing the shell unloads the peripheral vertical trabeculae, thus mitigating their role. Vertebral stiffness predicted from these finite element models was highly correlated with measured vertebral strength ($r^2=0.79$).

DISCUSSION:
Taken together, these findings suggest that observed differences in vertebral compressive strength across individuals primarily reflect variations in the amount of vertically-aligned trabecular bone. This has clinical implications for vertebral strength prediction and clinical fracture risk assessment. Trabecular bone mineral density, which is highly correlated with total trabecular BV/TV, is widely used to predict vertebral strength and is also used to assess fracture risk clinically. If patient-specific measures of trabecular bone mineral density could somehow account for the amount of vertically-aligned trabecular bone, these results suggest that clinical predictions of vertebral strength and fracture risk may be improved. Ongoing research will extend these analyses to different loading conditions with and without the presence of the intervertebral disc.

REFERENCES:

ACKNOWLEDGEMENTS:
NIH AR49828, NIH AR051376, NPACI UCB266, TG-MCA00N019. Micro-CT performed by Dr. Michael Liebschner. Dr. Keaveny has a financial interest in O.N. Diagnostics and both he and the company may benefit from the results of this research. Drs. Liu and Guo are inventors of the ITS software used in this study and they may benefit from the results of this research.

Paper No. 331 • 56th Annual Meeting of the Orthopaedic Research Society

Fig. 1: Vertical bone volume fraction (BV/TV) was a better predictor of vertebral strength than total BV/TV ($p<0.01, n=12$ vertebrae).

Fig. 2: Mid-sagittal cutaway from a human vertebral body (82-year-old male) showing the typical distribution of compressive stress predicted by finite element analysis. In this vertebra, 40% of the vertebra bone was stressed in the highest quartile (red), whereas only 13% and 18% of the horizontal and oblique trabecular bone, respectively, were in this group.