Introduction

Bone mineral density (BMD) of the spine is moderately correlated with experimental measurements of vertebral compressive strength [1], and epidemiology studies utilize bone mineral density (BMD) as an overall measure of bone strength in calculating vertebral fracture risk [2]. However, most osteoporotic spine fractures involve anterior wedge deformities [3], which are presumably related to an anterior bending load. If compressive (axial) and bending behaviors of vertebrae are not highly correlated, then multiple metrics of vertebral strength that can differentiate between different fracture types may improve fracture risk prediction clinically. While modest correlations have been reported \((r=0.58)\) between theoretical measures of bending and axial rigidity of vertebrae with simulated osteolytic defects [4], we are aware of no reports on the relationship between bending and axial mechanical properties of intact vertebrae. Thus, the overall goal of this study was to investigate the relationship between the bending and axial mechanical behaviors of the vertebral body. Detailed “patient-specific” finite element computer models were used because they made it possible to analyze the structural properties of vertebrae for different types of loading conditions in a controlled fashion that would not be possible using purely experimental means. Our specific objectives were to: 1) determine the correlation between the vertebral body axial and bending stiffness values, and 2) assess the vertebral features that influence the bending/axial stiffness relationship.

Methods

QCT scans were taken of 18 vertebral bodies from 18 cadavers (L1-L4; age: 37-90; M=11, F=7) using a clinical scanner (GE 9800; General Electric, Milwaukee, WI, U.S.A: 140kV, 70mA, 0.25 mm/pixel, 1.5 mm slice thickness, bone algorithm). Midvertebral trabecular BMD (mg/cm²) was calculated for each vertebral body using commercially-available software (QCT PRO, Mindways Software, Inc., San Francisco, CA). A voxel-based finite element model of each vertebral body was generated from the QCT data using 3x3x3 mm³ element sizes in which each element had its own QCT-derived mechanical properties.

A rigid plate was attached to the nodes on the top surface of the vertebra through which either uniform compression or pure bending moment boundary conditions were applied. For the compression load case, axial stiffness was defined as the ratio of the resultant force to the applied displacement; for the bending load case, bending stiffness was defined as the applied moment divided by the angular displacement of the rigid plate. All finite element analyses were linear, and assumed linear elastic but non-uniform material properties of the bone.

Results

Although bending stiffness was moderately correlated with axial stiffness \((r=0.70, p<0.001)\) (Figure 1), bending stiffness could differ considerably among vertebral bodies having similar axial stiffness values. For example, two vertebral bodies with axial stiffness values that differed by less than 1% exhibited bending stiffness values that differed by 84%. While the ratio of bending to axial stiffness was independent of the axial stiffness (Figure 1), bending stiffness was greater in vertebral bodies that possessed larger anterior-posterior diameters and higher concentrations of bone mineral density in the anterior region (Figure 2). As expected, axial stiffness was moderately \((r=0.46, p=0.002)\) correlated with bone mineral density, but we found no correlation for bending stiffness (Figure 3).

Discussion

While these data indicate that bending and axial stiffnesses are highly correlated, substantial scatter in this correlation was demonstrated. This suggests that some individuals can have vertebrae that fall within the normal ranges of axial compressive strength, but that are very weak for bending. Such individuals may be predisposed to fracture from anterior bending loads, and this may explain why DXA or any simple metric of vertebral strength based only on bone density is so poor at predicting vertebral fracture. Indeed, our own data show that bone density from QCT cannot be used to determine bending behavior and that the ratio of bending to axial behaviors cannot be predicted by the compressive behavior. These results were derived from 18 cadavers that are typical of the elderly population that are at risk for fracture. Taken together, these results provide strong support for the concept of using more than one metric of bone strength for vertebral fracture risk prediction. The concept of using more than one metric of vertebral strength may also provide additional insight into the effects of drug treatments and other interventions in the prevention and treatment of vertebral osteoporotic fracture. The finite element “voxel-based” models used here, which have been used in many other research studies [5, 6], provide a highly feasible means of providing such measures in a clinical context.

References: