THE RELATIONSHIP BETWEEN THE FRACTURE TOLERANCE OF 
FEMORAL CORTEX AND BONE DENSITY BY QCT

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INTRODUCTION

Femoral fracture risk is of great clinical significance because of the frequency and high morbidity of hip fractures. Identification of patients with increased fracture risk requires an understanding of the relationship between fracture tolerance and bone density. This relationship, however, is confounded by variation in bone geometry among patients, which affects the material and structural properties of whole bones.

The effects of bone density on the mechanical properties of femoral cortical bone have been isolated by performing strength testing on specimens machined to regular dimensions (Dickenson, et al. 1981; Lotz, et al. 1991; Wall, et al. 1979). These prior studies have used invasive methods to measure bone density. In the current study of femoral cortex breaking properties, non-invasive quantitative computed tomography (QCT) was used to measure bone density, allowing results to be compared to density measures taken in vivo.

METHODS

Rectangular specimens with nominal dimensions of 2 mm x 2 mm x 40 mm were harvested from each quadrant of the distal shaft of 10 fresh-frozen cadaveric femora. Where the cortex was thinner than 2 mm, smaller specimens were obtained.

Bone density was measured for each specimen using a Stratec XCT 3000 Research QCT scanner (Stratec, Pforzheim, Germany). Analysis was performed at the mid-point, with the cortical threshold set at 690 mg/cm³.

Three-point bending tests on the femoral specimens were performed on an MTS materials testing machine (858 Mini Bionix, MTS Systems Corporation, Eden Prairie, MN), using a gauge length of 30 mm. Specimens were loaded to failure at a strain rate of 0.1 second⁻¹ in order to simulate the typical strain rate in an osteoporotic fracture.

Force was measured with a 25-pound load cell (Futek, Irvine, CA). Deflection was measured from high-speed video at 2000 frames per second and by an extensometer mounted to the bending jig with a measuring prong suspended below the specimen. Force-deflection data was used to calculate elastic modulus (E), strength (S_{ULT}), and strain energy per unit volume (SEᵥ). Correlation analysis was performed using SAS statistical software (SAS, Cary, NC).

RESULTS AND DISCUSSION

Mean bone density of the specimens was 1163 mg/cm³ (σ²=78), with a range of 913 to 1274 mg/cm³. Table 1 contains a summary of the mechanical properties determined in
three-point bending, along with the correlation of these properties to bone density. Scatterplots showing the relationship between bone density by QCT \( (D_{QCT}) \) and the mechanical properties are shown in Figure 1.

![Figure 1: Scatterplots of mechanical properties versus bone density by QCT.](image)

Correlation between femoral cortical strength and bone density by QCT was stronger in the current study than in a prior study of tibiae that employed computed tomography (CT) to measure density. (Snyder and Schneider 1991). Although density measures are not directly comparable, the relatively strong correlation of strength and density identified in this study, along with the wide range of mechanical properties, suggests that the specimens may have been more widely distributed in density than in prior studies.

The moderate correlation between specimen strength and density-related parameters in this study and in prior studies indicates that half or more of the variation in the material strength of cortical bone is explained by variation in density. Additional bone quality factors, not reflected in density measurements, may have substantial effects on the material strength of cortical bone. For the whole bone, these effects are added to the variation in structural strength related to bone geometry.

A specimen’s toughness, reflected in its \( SE_V \), describes its ductility and its strength. Bone density’s moderately strong correlation with strength and its very weak correlation with \( SE_V \), suggest that reduced bone ductility is not associated with reduced bone density but is more likely related to other age-related changes.

### REFERENCES


### Table 1: Summary of mechanical properties and correlation to bone density.

<table>
<thead>
<tr>
<th></th>
<th>Mean ( (\sigma^2) )</th>
<th>Range</th>
<th>Spearman Correlation Coefficient with Bone Density by QCT</th>
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</thead>
<tbody>
<tr>
<td>( E ) (MPa)</td>
<td>14,399 (4001)</td>
<td>8739-31,708</td>
<td>0.643 ( (p&lt;0.0001) )</td>
</tr>
<tr>
<td>( S_{ULT} ) (MPa)</td>
<td>217 (41.1)</td>
<td>114-305</td>
<td>0.506 ( (p=0.0027) )</td>
</tr>
<tr>
<td>( SE_V ) (J/cm(^3))</td>
<td>4.76 (1.92)</td>
<td>1.29-8.93</td>
<td>0.186 ( (p=0.292) )</td>
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