INTRODUCTION:

There have been numerous studies of the ability of quantitative computed tomography (QCT) metrics to predict vertebral compressive strength \textit{ex vivo} [1-4]. However, due to differences in sample size and demographics, testing protocols, and outcome measures, there is no clear consensus as to the relative performance of these metrics. The purpose of this study was to compare the predictive capabilities of three standard QCT-based assessment techniques for uniaxial compression of isolated vertebral bodies. The techniques investigated were, in order of increasing structural complexity: 1) bone mineral density (BMD), 2) mechanics of solids models (MOS), e.g., axial rigidity, and 3) finite element (FE) analyses. Our predictive measures were a subset of those most frequently used in the literature [5-7], and we tested a large number of samples (N = 77) from a predominantly elderly, female population.

METHODS:

Eighty-one human thoracic vertebrae (T6 – T10, F = 55, M = 26; 86 ± 7 y.o.) were dissected from 44 fresh-frozen cadavers. The vertebrae were cleaned of the surrounding soft tissue, and the posterior elements were transected at the pedicles. The vertebral bodies were potted in bone cement, and clinical resolution QCT scans were taken on a Phillips MX800 CT Scanner (140 kV, 400 mA/slice, 1 x 1 x 1 mm/pixel resolution) using a solid calibration phantom (Mindways 2100, Mindways, San Francisco, CA).

Using the QCT scans, trabecular bone mineral density (tBMD) was measured for a maximally-sized region of interest within the centrum, and integral bone mineral density (iBMD) was calculated over the entire bone volume including the endplates and cortex. Axial rigidity was computed in three different ways: 1) the product of the tBMD-based modulus and the minimum cross sectional area (E_{tBMD}A_{min}), 2) the product of the iBMD-based modulus and the minimum cross sectional area (E_{iBMD}A_{min}), and 3) the minimum of the axial rigidities for each slice (E_{min}). Finite element models of 1 mm (isotropic) element size were generated directly from the QCT scans using a custom-built algorithm developed from the literature [7, 8] (Figure 1). The bone cement was automatically identified and explicitly modeled (E = 2.5 GPa, n = 0.3)[9]. The vertebral bone was assumed to be a transversely isotropic, linearly elastic-perfectly plastic material. Material properties were assigned on an element-specific basis using previously established density-modulus and density-strength relationships [10]. Large deformation finite element analyses were conducted for uniform axial displacement using commercial software (Abaqus v6.2, Abaqus, Inc., Pawtucket, RI). Vertebral strength was determined from the whole bone force-deformation curve as the axial force at 3% apparent strain [11].

RESULTS:

tBMD was much less strongly correlated with vertebral strength than iBMD (adj. R² = 0.16 vs 0.62, p < 0.01, Table 1). (E)_{min} was the strongest predictor (Figure 2a) with adj. R² = 0.81. FE strength metrics were also strongly correlated with experimental vertebral strength (Figure 2b, adj. R² = 0.80), but their performance was statistically equivalent to that of (E)_{min} (p > 0.05 for difference in adj. R²). Furthermore, (E)_{min} and FE strength were strongly related (adj. R² = 0.94, p < 0.001).

![Figure 1: A QCT-based FE model of a human thoracic vertebral body.](image)

Figure 1: A QCT-based FE model of a human thoracic vertebral body.

Uniaxial compression tests were performed on each specimen at room temperature using a servohydraulic load frame (858 mini-bionix, MTS, Eden Prairie, MN). Specimens were preconditioned by applying 10 cycles of 100 N to 250 N compressive force at 0.1 Hz, followed by displacement-controlled loading at 1 mm/minute until the specimen reached its ultimate force. Four specimens were excluded from the analysis due to errors in the mechanical testing.

![Figure 2: (a) QCT-based slice-by-slice axial rigidity and (b) finite element strength metrics are comparable predictors of vertebral strength in axial compression (N = 77).](image)

Figure 2: (a) QCT-based slice-by-slice axial rigidity and (b) finite element strength metrics are comparable predictors of vertebral strength in axial compression (N = 77).

Table 1: Correlation between QCT-derived strength measures and experimental vertebral strength. p < 0.01 for all regressions.

<table>
<thead>
<tr>
<th>Measure</th>
<th>R²</th>
<th>Adj. R²</th>
<th>RMSE [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>tBMD</td>
<td>0.17</td>
<td>0.16</td>
<td>1368</td>
</tr>
<tr>
<td>iBMD</td>
<td>0.63</td>
<td>0.62</td>
<td>915</td>
</tr>
<tr>
<td>E_{min}</td>
<td>0.81</td>
<td>0.81</td>
<td>1144</td>
</tr>
<tr>
<td>FE</td>
<td>0.80</td>
<td>0.80</td>
<td>649</td>
</tr>
</tbody>
</table>

* R² adjusted for sample size (N = 77).

DISCUSSION:

The results of this study strongly suggest that non-invasive measures of vertebral strength should incorporate both geometry and material property distribution information but that a high degree of structural sophistication, e.g., finite element models, may be unnecessary to accurately predict compressive strength. Our R² values for tBMD[12], iBMD[5] [12], axial rigidity[7], and FE[7] versus strength regressions are in agreement with the literature. However, unlike a previous study by Crawford et al.[7], our results do not indicate that the FE technique is superior to the MOS approach. We believe that our results are a more accurate representation of FE performance for two reasons: 1) Crawford et al.[7] had a much smaller sample size (N = 13) which would lead to artificially inflated R² values, and 2) they compared the FE technique with most simplistic axial stiffness measure tBMD x A_{min}. The results of this study are important clinically because they address the issue of whether research efforts in developing a more accurate method for predicting osteoporotic vertebral fractures should be directed towards creating more sophisticated structural models of the vertebrae.

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REFERENCES: