ACCURATE PREDICTION OF VERTEBRAL STRENGTH USING VOXEL-BASED NON-LINEAR FINITE ELEMENT MODELS

INTRODUCTION:
Finite element models have shown great promise as a means to advance the technology of bone quality assessments in the hip [1] and spine [2]. Unlike densitometry-based techniques, which are based on statistical correlations, finite element models are based on mechanistic principles. Efforts to better understand the sensitivity and robustness of these modeling techniques will help make them more accurate and precise for use in clinical and research applications.

The success of patient-specific finite element models relies on the strong relationships between quantitative computed tomography (QCT)-derived bone mineral density and elastic modulus and strength of trabecular bone cored from vertebrae.[3] However, previous studies that have used such relationships have reported that the whole bone finite element models underpredict the measured strength.[2, 4] Motivated by research that identified end artifacts in trabecular bone specimens [5], we believe that the peripheral connectivity of trabecular bone cores is disrupted by the coring process and leads to an effective loss of load-carrying capacity. The presence of such an artifact may help explain some of the model limitations. The overall goal of this study was to establish that, once such “side-artifacts” have been corrected, bone-specific voxel-based, non-linear finite element models can predict vertebral strength in both a precise and accurate manner.

METHODS:
QCT scans were taken of 13 vertebral bodies (L1-L4; age: 37-87; M=6, F=7) using a clinical scanner (GE 9800). The vertebral bodies were then compressed to failure between two rigid platens.

A finite element mesh was created for each vertebra by converting each QCT voxel into a finite element. The axial modulus of each finite element (E, MPa) was assigned as a function of the local QCT-derived bone mineral density [3] (Model Type I; Fig. 1). Vertebral trabecular bone cores (n=53; 8 mm diameter) were microCT scanned (22 microns) to determine the mean trabecular spacing (TbSp).[6] A corrected axial modulus (Ecorr) was developed that assumed that the cross-sectional radii of the tested specimens was effectively reduced by one half of TbSp (Fig. 2). These corrections were applied to each finite element using: 1) the mean value of the TbSp (Model Type II), and 2) a derived relationship between specimen BMD and TbSp (Model Type III). Elastic-plastic transition for each element was modeled at a bone mineral density-determined yield stress value.[7] The nonlinear finite element model was uniformly compressed to 3% apparent strain and the resultant reaction force calculated.

RESULTS:
The modulus-corrected models resulted in uniform strength increases that closely matched the measured values. Whereas the Type I models underpredicted vertebral strength by a mean of 16%, the Type II and III models overpredicted on average by less than 8%. All model types were strongly correlated with measured strength (r²>0.85) and displayed excellent precision. In addition, the type II and III model regressions resulted in slope and intercept values that were not significantly different from one and zero, respectively (Table 1; Fig. 3), establishing their accuracy. Type II performed the best in terms of having slope closest to unity and the lowest standard error.

DISCUSSION:
These results show that voxel-based finite element models exhibit a notable sensitivity to an assumed side artifact in trabecular bone material properties. In theory, these artifacts are present because trabeculae on the periphery of specimens prepared for in vitro testing are necessarily broken during specimen preparation and therefore lose their ability to carry and transmit load. As a result, the QCT-derived mechanical property relationships underestimate the true in situ behavior.

After correcting for such errors, the models resulted in both precise and accurate measures of strength. More importantly, since the models required no calibration or curve fitting, they provided a purely mechanistic prediction of vertebral strength.

In conclusion, this study establishes that after corrections for material property experimental side artifacts, non-linear voxel-based finite element models can prospectively predict strength of vertebrae in both a precise and accurate fashion.

Table 1: Linear regression values between vertebral strength and finite element model strength. The p-values reflect t-tests for the slope=1 and intercept=0.

<table>
<thead>
<tr>
<th>Type</th>
<th>Slope±SE</th>
<th>Intercept±SE</th>
<th>r²</th>
<th>SE (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.35±0.17*</td>
<td>470±670*</td>
<td>0.86</td>
<td>710</td>
</tr>
<tr>
<td>II</td>
<td>1.05±0.13*</td>
<td>470±670*</td>
<td>0.86</td>
<td>710</td>
</tr>
<tr>
<td>III</td>
<td>1.10±0.14*</td>
<td>600±700*</td>
<td>0.85</td>
<td>730</td>
</tr>
</tbody>
</table>

SE=standard error, * denotes p<0.05, ** denotes p<0.02

REFERENCES:

AFFILIATED INSTITUTIONS FOR CO-AUTHORS:
** Department of Neurological Surgery, UCSF
*** Technische Universiteit Eindhoven, The Netherlands

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