COMPARISON OF IN SITU AND IN VITRO CT SCAN-BASED FINITE ELEMENT ANALYSES OF PROXIMAL FEMORA

+*Keyak, J H (A-NIH); *Falkinstein, Y (A-UC Irvine College of Medicine)
+Dept. of Orthopaedic Surgery, University of California, Irvine, California. 101 City Drive South, Orange, CA 92868-5382, (714) 456-3660, Fax: (714) 456-7547, jhkeyak@uci.edu

INTRODUCTION: Finite element (FE) models for predicting proximal femoral fracture load are useful for research related to the prevention of hip fracture. CT scan-based non-linear FE models have been shown to predict proximal femoral fracture load precisely in vitro.1 However, if these models are to be used in vivo, we need to know the effect of using CT scan data obtained in situ instead of in vitro. In the present study, we examined the extent to which FE models from CT scans of proximal femora in situ and in vitro yield comparable predictions of fracture load.

METHODS: Two human cadavers were obtained for this study: Subject A, female, age 51; and Subject B, male, age 61. Causes of death were breast cancer (Subject A) and lung cancer (Subject B). Examination of radiographs and CT scans by a radiologist revealed no metastases or other abnormalities in the femora. The left femur from each donor was studied under single-limb stance-type loading with displacement applied to the femoral head at 20° to the shaft in the coronal plane.

Each cadaver was placed on the table of a GE HiSpeed Advantage CT scanner, and the femora were scanned in situ along with a solid, calcium hydroxyapatite calibration phantom (Image Analysis, Inc., Columbia, KY). The femora were then retrieved, stripped of soft tissue, immersed in water to reduce artifacts, and CT scanned in vitro. The scanner settings for both the in situ and in vitro scans were as follows: 80 kVp; 280 mAs; 3-mm slices; 512x512 matrix; pixel size for Subject A in situ, 0.938 mm; all other pixel sizes, 0.674 mm.

A three-dimensional nonlinear FE model of each femur was generated from the CT scan data using 3-mm linear cube-shaped elements. Ash density, elastic modulus, and material strength of each element were computed from the calibrated CT scan data as described previously.1 To account for the use of a solid calibration phantom instead of a liquid phantom, a conversion relation was applied to the calibrated CT scan data.3 Elements on the loaded surface of the femoral head were assigned an elastic modulus of 20 GPa and a strength representation by an initial perfectly plastic phase at the yield stress, followed by a strain softening phase and, ultimately, a perfectly plastic phase.

To represent the desired loading, displacement was incrementally applied to the femoral head and the models were restrained distally. The direction of displacement was determined by defining the shaft and cervical axes of each femur on wireframe plots of the CT scan-derived bone geometry using an interactive graphics program. The in situ and in vitro cases for each femur were viewed side-by-side to ensure that these axes were defined identically, to the extent possible. The displacement vector was then directed at 20° to the shaft axis within the plane defined by the shaft and cervical axes.

The FE analysis, which computed the femoral head reaction force at each displacement increment, was performed with ABAQUS version 5.4 using the distortion energy failure theory, geometric nonlinearity, and automatic time stepping options. FE-predicted fracture load (F_FE) was defined as the maximum total reaction force at the femoral head.

RESULTS: F_FE for the in situ and in vitro-derived models differed by 5.2% for Subject A and 13.3% for Subject B (Table 1). The computed force versus displacement curves were similar for the in situ and in vitro-derived models (Fig. 1).

Redefining the shaft and cervical axes resulted in maximum changes in displacement direction of about 1°. These changes in displacement direction caused a 1.5% change in F_FE for Subject A (from 12,598 N to 12,403 N) and a 1.8% change in F_FE for Subject B (from 22,659 N to 22,262 N). Comparison of the derived bone geometry showed that the femora CT scanned in situ appeared smaller than those scanned in vitro by about 1 mm for Subject A and 1.5 mm for Subject B.

DISCUSSION: This study has shown that the effect of using CT scan data obtained in situ instead of in vitro is modest, with a 5.2% difference for the smaller, female subject and a 13.3% difference for the larger, male subject. The effect of uncertainty in displacement direction on fracture load was less than 2%, indicating that these differences in fracture load can be attributed primarily to differences in the CT scan data used to generate the models. Furthermore, despite the fact that the derived geometries of the femora CT scanned in situ were smaller than those CT scanned in vitro, fracture loads for the in situ cases were greater. Therefore, the differences in fracture loads must be due to differences in the quantitative CT scan data used to calculate the bone material properties. These quantitative data are influenced by the presence of soft tissue and bone (pelvis and the contralateral femur) in scans obtained in situ, causing increased noise, streak artifact, and beam hardening.

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Table 1. FE-Predicted Fracture Loads In Situ and In Vitro

<table>
<thead>
<tr>
<th>Subject</th>
<th>F_FE In Situ (N)</th>
<th>F_FE In Vitro (N)</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (female)</td>
<td>12,598</td>
<td>11,978</td>
<td>5.2%</td>
</tr>
<tr>
<td>B (male)</td>
<td>22,659</td>
<td>19,998</td>
<td>13.3%</td>
</tr>
</tbody>
</table>

Fig. 1. Computed force versus displacement for the femora scanned in situ (dashed line) and in vitro (solid line). Subject A (left); Subject B (right).