INTRODUCTION

Quantitative Computed Tomography Finite Element Analysis (QCT/FEA) of the proximal femur is often used to predict femoral strength, fracture loads, and fracture patterns. Tetrahedral meshes are primarily employed because they are easy to generate. However, the influence of different mesh types on model results remained largely unknown. In the current study we compared QCT/FEA results obtained from two different mesh types, hexahedral (hex) and tetrahedral (tet), for two femurs with very different mineral density.

METHODS

Two female cadaveric femora (one with normal bone mineral density, and one osteoporotic; ages 69, and 93 respectively) were scanned using a Siemens Somatom Definition QCT scanner (Siemens Healthcare, Forchheim, Germany). Scanned images were imported into Mimics (Materialise, Ann Arbor, MI, USA) to build three dimensional models, which were meshed using hex and tet elements. Elastic properties and bone material yield limits were assigned to elements using the grey scale values [1]. The femora were subsequently tested to fracture in a fall on the hip configuration (15° internal rotation, 10° adduction) at a testing speed of 100 mm/s. Fractures were recorded using a high speed video camera (Photron, San Diego, CA, USA) at 6000 frames per second.

To generate the hex mesh, faceted geometry of femora obtained from Mimics was imported into ANSYS ICEM (ANSYS, Canonsburg, PA, USA). The trabecular compartment was first modeled with blocks and then meshed with hex elements. To increase the mesh density in the cortical compartment, an O-grid of smaller hexahedral elements was created between the blocks and the cortical surface (Fig. 1a).

The quadratic tet mesh was generated in ANSYS ICEM starting from the surface triangular mesh created in Mimics Remesher. An expansion factor of ~ 1.2 was used such that the elements in the cortical compartment were much smaller than the elements in the trabecular compartment (Fig. 1b) [1].

Figure 1: a) Hex, and b) Tet meshes for a femur.

A monotonically increasing force was applied in 100 N increments to nodes on the femoral head surface while selected nodes on the trochanter were assigned zero vertical displacement. The distal end was allowed to rotate about a fixed point, mimicking knee rotation. After each load step, elements which exceeded a strain value above yield were considered failed, and were assigned a very low elastic modulus value. Model generated load-displacement curves were analyzed and compared to the experimental curves. Stiffness was calculated as the slope of the linear portion of the load-displacement curve, for both QCT/FEA and experimental curves. Ultimate load was defined as the peak force in the experimental curve; QCT/FEA predicted values were calculated at the same points.

RESULTS

The calculated von Mises strain contours were very similar for both mesh types (Table 1). The predicted fracture patterns based on these contours were neck fractures, same as the experimental fractures.

Table 1: Comparison of FEA model predicted, and experimentally observed fracture patterns.

<table>
<thead>
<tr>
<th>Bone</th>
<th>Hex Mesh</th>
<th>Tet Mesh</th>
<th>High Speed Video</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td><img src="image" alt="Normal" /></td>
<td><img src="image" alt="Tet Mesh" /></td>
<td><img src="image" alt="High Speed Video" /></td>
</tr>
<tr>
<td>Osteoporotic</td>
<td><img src="image" alt="Normal" /></td>
<td><img src="image" alt="Tet Mesh" /></td>
<td><img src="image" alt="High Speed Video" /></td>
</tr>
</tbody>
</table>

Simulated load-displacement curves were very similar (Fig. 2). The calculated stiffness for the normal femur was 2329 N/mm with the hexahedral mesh, and 2236 N/mm with the tetrahedral mesh. For the osteoporotic femur the values were 722 N/mm and 614 N/mm, respectively. The calculated ultimate load for the normal femur was 4345 N with the hexahedral mesh, and 4154 N with the tetrahedral mesh. Similarly, for the osteoporotic femur, the ultimate load values were 1984 N and 1779 N, respectively.

DISCUSSION

The load-displacement curves calculated for the two meshes were in good agreement. Both of our meshes were capable to resolve the cortical compartment with smaller elements to better approximate the change in bone mineral density from the cortex to the cancellous compartment, and consequently the change in elastic and yield properties. Tetrahedral meshes had larger run times but, were somewhat easier to generate. However, for tet mesh, lengthy initial sensitivity studies were needed to obtain mesh independent results that solved in a reasonable amount of time. Although, hex meshes required more efforts to generate, they produced faster computations results. Additionally, because of the small element size in the cortex, they better represented the geometry of the femoral surface and discriminated better between cortical and cancellous compartments. The results from the two mesh types will be investigated further, and compared to experimental results in larger samples to improve their prediction ability.

SIGNIFICANCE

The use of FEA for clinical hip fracture risk assessment requires mesh independent results. In this study, we compared the two commonly used mesh types to estimate proximal femur strength as a determinant of hip fracture and observed similar results.

REFERENCES

ACKNOWLEDGEMENTS
NIH: AR027065Z
Grainger Foundation: Grainger Innovation Fund