A Novel Approach to Estimate Trabecular Bone Anisotropy using a Database Approach

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Introduction
Continuum finite element (FE) models of bones and bone-implant configurations have become a standard pre-clinical tool to estimate bone strength. These models are usually based on clinical CT scans. In virtually all of these models, material properties assigned to the bone elements are chosen as isotropic with a stiffness based only on the density distribution. It has been shown, however, that trabecular bone can be highly anisotropic and that its elastic behavior is best described as orthotropic, with principal directions aligned to those of a fabric tensor that describes the microstructural orientation of the bone. The use of orthotropic models in FE analysis derived from CT scans, however, is hampered by the fact that the measurement of such a fabric tensor is not possible from clinical CT images due to the low resolution of such images. In this study we explore the concept of using a database of high-resolution bone models to derive the fabric information that is missing in clinical images. By combining the density information measured from the CT scan with fabric information from the database, patient-specific anisotropic properties can be defined. The first goal of this study was to investigate if such models with database-derived fabric produce similar stress and stiffness results as models based on the actually measured bone fabric. The second goal was to investigate if such models can provide more accurate results than isotropic models.

Materials and Methods
A database (DB) of 30 human proximal femurs (mean age; 76.65±10.04 yr) was generated from micro-CT scans (XtremeCT, Scanco, Switzerland) with a nominal isotropic resolution of 82 μm. Continuum FE models were generated from the images using a pre-defined mesh template that was morphed to the bone contour by identifying a number of anatomical landmarks. Each element within the mesh template is at a specific anatomical location which enables to identify a specific anatomical location on all samples (Grassi et al., 2011). For each element within the cancellous bone, a spherical region around the element centroid with a radius of 2 mm was defined. Bone volume fraction (BV/TV) and the mean-intercept fabric tensor were analyzed for that region.

Four additional femurs, for which micro-CT images were available as well, were used as test cases. For these bones BV/TV and fabric values were calculated for each element using the same approach as for the DB models. For each test case, three models were generated. In the first model, orthotropic material properties were specified based on the actual fabric and density measurements. In the second model orthotropic material properties were specified based on the actual density measurement and fabric derived from the DB. To do so, the DB model with a density distribution most similar to that of the test bone was selected and its fabric was mapped to the test model. In the third model, isotropic material properties were specified based on the actual density measurements (Figure 1).

For all models elastic properties were derived from density and fabric using the Zysset-Curnier relationship (Zysset and Curnier, 1995). All models were loaded by a force representing the stance phase of walking and the stress distribution and whole bone stiffness of the orthotropic models based on DB-derived fabric and of the isotropic models were compared to that of the orthotropic model based on actual fabric measurements, which was taken as the gold standard. Differences were quantified by calculating regression slopes and root-mean-square errors (RMSE). One-way ANOVA was used to test significance (p < 0.05).

Results
Contour plots of the principal stress component with the largest magnitude are shown in Figure 2. The results show that all models produce a similar stress distribution. However, compared to the gold standard, the DB-derived orthotropic model underestimated the stress by 18% [RMSE=6.9 MPa] while the isotropic model overestimated the stress by 36% [RMSE=7.8 MPa], indicating that the former is slightly more accurate. For the DB-derived orthotropic models a non-significant underprediction of whole bone stiffness by 22% was found (RMSE=3.9 kN/mm). The isotropic models significantly and far overpredicted whole bone stiffness by 38% (RMSE=6.6 kN/mm) (Table 1).

![Figure 2. Principal stress with the largest magnitude distribution (sample#4): orthotropic model with measured fabric, gold standard (left), orthotropic model with DB derived fabric (middle) and isotropic model (right).](image)

Table 1. Calculated whole bone stiffness values for test cases.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Gold Standard [kN/mm]</th>
<th>DB-derived Orthotropic Model [kN/mm]</th>
<th>Isotropic Model [kN/mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>9825.3</td>
<td>5475.2</td>
<td>13334.4</td>
</tr>
<tr>
<td>2</td>
<td>8545.2</td>
<td>5879.9</td>
<td>13682.7</td>
</tr>
<tr>
<td>3</td>
<td>12884.4</td>
<td>7034.2</td>
<td>20988.2</td>
</tr>
<tr>
<td>4</td>
<td>11120.8</td>
<td>12755.8</td>
<td>19712.9</td>
</tr>
</tbody>
</table>

Discussion and Conclusion
The results indicate that the concept of using a DB to estimate patient-specific anisotropic material properties can considerably improve the stress calculation. Differences in stiffness were rather large for both models, but it should be noted that the results can be further improved by tuning constants in the density-elasticity relationship. The mesh-morphing approach used here can be used as a versatile tool to map the missing fabric information, as well as any other microstructural information to the patient models. We expect that this approach can lead to more accurate results in particular in cases where bone anisotropy plays an important role, such as in osteoporotic patients and around implants.

References

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