Influence of Osteoporosis on the Strain Distribution in the Human Tibia

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Introduction
Aging and osteoporosis lead to a decrease in bone density and to a reduced thickness of the cortical shell (Ritzel et al., 1997). Treatment of fractures in osteoporotic bone therefore require an adequate understanding of the internal loading conditions of the bone due to these morphological variations. Since bone formation is driven by mechanical stimulation, changes due to osteoporosis might also be influenced by the loading of the bone. As a consequence it is indispensable to take into account the physiological load scenario when analyzing the effects of morphological changes. To our knowledge, there is no study where both, structural changes and validated physiological loads have been considered to analyze the loading of a whole bone. The goal of this study was to determine the influence of changes in bone density and cortical geometry on the resulting strains in the tibia under physiological loads.

Materials and Methods
QCT-Scans (resolution: 0.234 mm², slice thickness: 1 mm) of twenty human tibiae were analyzed according to geometry, density distribution (BMC) and cortical thickness. From that pool the bone with the lowest BMC and cortical thickness (assumed to be osteoporotic) as well as the bone with the highest values (healthy) were selected for further finite element (FE) analysis. A novel technique based on the geometry of the cortex and the internal density distribution of the bone rather than on the CT voxels was used to build an individual finite element mesh for each bone. Each model consisted of approx. 40,000 elements. Based on a suggested density-modulus relationship (Carter & Hayes, 1977) up to 25 different elastic moduli were assigned to the elements (Fig. 1).

The muscle and joint contact forces before toe off during normal gait (instance of max. of ground reaction force) were derived from a validated analysis of the lower extremity (and scaled to bone length. To account for the muscles attaching at the fibula, the interosseus membrane and fibula were included in the model. Muscles and ligament attachments were taken from anatomy books. The attachment sites of the interosseus membrane as well as the patella ligament were individually derived from the analysis of the bone geometry. While the tibia and fibula consisted of 8-node brick elements the membrane were modeled by truss elements. Two regions of interest in the metaphysis and diaphysis of the bones were chosen to correlate morphological changes with the resulting strains. The mean density of the cancellous bone at 5% distance from the proximal end and the average of the cortical thickness at 50% bone length were compared with the strains at these locations. In addition the strain distribution from 15 to 85% bone length in the cortical shell on the medial, lateral, anterior and posterior side of the osteoporotic and healthy bone were compared.
**Results**

The healthy bone had about 4 times higher values for BMC and a 3 times thicker cortex than the osteoporotic one (Tab. 1). Strains in the metaphyseal region of interest were 1.5 times higher in the osteoporotic tibia while in the diaphysis 2.8 times higher strain values occurred.

<table>
<thead>
<tr>
<th>Location</th>
<th>healthy mean BMC [mg/cm³]</th>
<th>osteoporotic mean BMC [mg/cm³]</th>
<th>healthy compr. prin. strain [µε]</th>
<th>osteoporotic compr. prin. strain [µε]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5% bone length (prox. metaphysis)</td>
<td>204</td>
<td>53</td>
<td>-4184</td>
<td>-6304</td>
</tr>
<tr>
<td>50% bone length (diaphysis)</td>
<td>mean cort. thickn. [mm]</td>
<td>6.9</td>
<td>-525</td>
<td>-1490</td>
</tr>
</tbody>
</table>

Table 1: Comparison of min. principle strains and morphologic parameters

The strain distribution within the cortical shell showed generally higher strains in the osteoporotic tibia (Fig. 2). Towards the metaphyseal regions the strains in the osteoporotic bone increased to an higher extent than in the healthy one. In anterior and lateral direction the absolute strain values, as well as the strain differences were lower. While the healthy bone showed uniform strain curves, a rather scattered strain distribution could be seen for the osteoporotic tibia.

**Discussion**

The results showed that the morphological changes in the osteoporotic tibia caused an increase in the internal strains. Comparison of the morphological changes and the resulting strains illustrates that the reduction of the cortex seems to have an higher influence than the decrease in bone density. It should be mentioned that due to the relationship between density and elastic modulus the accuracy for the determined strains in regions of low density is limited. Also, the model does not account for the anisotropic material properties in cancellous bone, which so far cannot be resolved with the commonly used clinical QCT.

The results demonstrate that the internal loading in an osteoporotic tibia is less uniformly distributed with locally higher strains. This can be taken as indicator for an increased fracture risk. The new technique to detect and model morphological changes from CT-scans including the detailed application of the muscle forces is a basis to optimize implant systems for osteoporotic bone.
Literature

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