INTRODUCTION: High-resolution peripheral quantitative computed tomography (HR-pQCT) is a promising clinical tool that permits separate measurements of trabecular and cortical bone compartments at the distal radius and tibia. It has an isotropic voxel size of 82 µm, which is high enough to assess the fine microstructural details of trabecular architecture. Moreover, patient-specific finite element analysis (FEA) can also be performed using HR-pQCT images to estimate the mechanical competence of whole bone segments. It has been reported that alterations of cortical and trabecular architecture detected by HR-pQCT are associated with fractures in postmenopausal women, which are partially independent of areal BMD as assessed by DXA [1], and that FEA of HR-pQCT images of the distal radius is associated with wrist fracture in postmenopausal women [2]. However, microstructure of one skeletal site may be different from that of another site. Furthermore, it is unclear whether and to what extent these peripheral measurements reflect bone strength of vertebral bodies, the site of frequent osteoporotic fractures. Currently, central quantitative computed tomography (cQCT) is the most commonly used clinical imaging modality to quantify the structural and mechanical properties of the lumbar spine. We therefore evaluated relationships between the stiffness of the radius and tibia estimated by HR-pQCT-based FEA with that of the lumbar spine which was estimated from cQCT-based FEA in the same human subjects. Subsequently the estimated stiffness of the distal radius, distal tibia, and lumbar spine was used to determine any differences between normal and osteoporotic subjects.

MATERIALS AND METHODS: We included 36 female subjects (23-49 yrs old) who underwent cQCT (GE LightSpeed 64 VCT, GE Healthcare) scans of the lumbar spine and HR-pQCT (XtremeCT, Scanco Medical AG) scans of the distal radius and tibia during the course of their participation in a cross-sectional case-control study of idiopathic osteoporosis in premenopausal women. Eleven premenopausal women with osteoporosis were included, on the basis of a history of low-trauma fractures or low bone mineral density measurements at the spine, proximal femur or non-dominant forearm. Twenty-five women qualified as normal controls with normal bone density and no history of fractures.

The segmented HR-pQCT images of the distal tibia and radius of each subject were obtained by the standard patient analysis software provided by the manufacturer (Fig. 1). Each data set had 110 slices with an isotropic voxel size of 82 µm. Each bone voxel was converted to an eight-node brick element. Bone tissue was modeled as an isotropic, linear elastic material with a Young’s modulus (Ey) of 15 GPa and a Poisson’s ratio of 0.3. A uniaxial compression was applied along the axial direction (z) of the model and the model was subjected to linear analysis to determine stiffness using an element-by-element pre-condition conjugate gradient solver.

A 3D dataset with 40 slices was obtained from each cQCT scan with an anisotropic voxel size of 0.9370x0.9372x2.5 mm [3]. A semi-automatic thresholding technique was developed to segment vertebral bodies (with posterior elements removed), and the second lumbar vertebra L2 was extracted from each cQCT image. Then, the Hounsfield Unit values were converted to mineral density values (g/cm³) using a linear regression of the calibration phantom images (Image Analysis, Columbia, KY). A finite element model was built for each L2 vertebra by converting each bone voxel to an eight-node brick element [3] (Fig. 1). A thin layer of PMMA (grey layer in Fig. 2, 1~2 voxels tall, Young’s modulus Ey=2.5 GPa, and Poisson’s ratio ν=0.3) was added on top of the endplates to facilitate applications of uniform displacement boundary conditions [3]. The vertebral bone tissue was assumed to be a transversely isotropic, linear elastic material. Material properties were assigned in an element-specific fashion by mapping the cQCT mineral density value of each element to an axial elastic modulus based on a previously established density-modulus relationship for vertebral bone [4] (Fig 2). A uniaxial compression displacement boundary condition was applied to each model. Then, the FE model was input into Abaqus 6.7, a commercial software program, to determine the axial stiffness of the vertebral body.

The stiffness of the distal tibia, radius and vertebral body were correlated with each other using a linear regression. The differences in stiffness among women with or without IOP were assessed by Student’s t-test.

RESULTS: The mean stiffness values of the vertebral body, distal radius and tibia are shown in Table 1. The mean stiffness of the 3 skeletal sites was significantly lower in the IOP group as compared to the control group (p<0.001). Positive and correlations were found between the stiffness of the distal radius and vertebral body (r²=0.31, p<0.001), distal tibia and vertebral body (r²=0.20, p=0.005), and between the distal tibia and radius (r²=0.71, p<0.001).

![Figure 1. HR-pQCT images of the distal tibia (Left) and radius (Right).](image1)

![Figure 2. cQCT-based FE models of human vertebral bodies (L2). The distributions of axial elastic moduli were shown for control (Left) and IOP (Right) group (grey elements indicate PMMA layers). A portion of the vertebral body was removed for illustrative purpose.](image2)

Table 1. Mean stiffness of vertebral body, distal radius and tibia in control and IOP groups.

<table>
<thead>
<tr>
<th></th>
<th>Vertebral Body</th>
<th>Distal Radius</th>
<th>Distal Tibia</th>
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<tbody>
<tr>
<td>Control</td>
<td>8.0±1.2</td>
<td>89.8±14.5</td>
<td>257.5±44.5</td>
</tr>
<tr>
<td>IOP</td>
<td>6.2±0.9</td>
<td>68.7±20.1</td>
<td>191.9±50.6</td>
</tr>
</tbody>
</table>

DISCUSSION: In this study, the stiffness of peripheral and central skeletal sites of the same subjects were assessed by two clinical imaging modalities and FEA techniques. For the first time, the relationships between the mechanical competences of multiple skeletal sites were examined in vivo. The significant and positive correlations suggest that estimated mechanical competence of the distal radius and tibia assessed by HR-pQCT could be helpful in predicting vertebral bone strength. Moreover, this study suggests that both HR-pQCT and cQCT-based FE models are sensitive tools that can detect changes in the mechanical competence of the distal radius, tibia and lumbar spine. These observations suggest that HR-pQCT-based FE analysis is a promising clinical tool with which fracture risk can be predicted.


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