Determining the Patient-Specific Anisotropy by cQCT in Vivo

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Abstract

Motivation

Human cancellous bone is a patient-specific, load-bearing tissue. Considerations of the spongious tissue's patient-specific mechanical characteristics promise to enable better fracture risk predictions, the design of patient-specific implants, and other applications.

However, trabeculae require about 0.015mm voxel spacing for their detailed structural representation. Computed tomography (CT) images of such spatial resolutions require radiation exposures that are prohibitive for use in vivo. Consequently, exact patient-specific quantifications of the spongiosa's mechanical behavior are unavailable a priori, e.g., before the patient undergoes surgery.

Following is a new method and its validation for computing patient-specific elasticities based on clinical quantitative computed tomography (cQCT).

Approach and Validation

Spongious tissues consist of marrow and trabeculae, a heterogeneous, non-repetitive structure. Rodney Hill proposed a general and exact description of two phases. Rietbergen et al. developed this idea into the "direct mechanics assessment of elastic symmetries and properties of trabecular bone architecture."

Ralf Schneider implemented this direct mechanics approach for use on high-performance computers. The author developed a modified version of this software during the research. For microfocus computed tomography (μCT) scans, we rely on binary segmentation to extract the trabecular structure. The software decomposes the image into seamless, grid-parallel cuboid volume elements (VEs) of edge lengths 0.6mm, 1.2mm, 2.4mm, or 4.8mm, for which we compute effective stiffness matrices. These matrices represent the 3-dimensional, equidistant 4th-rank tensor field of mechanical elasticities of the bone. We then reorient these grid-parallel, 6x6 effective stiffness matrices to characterize the orthotropic symmetries best. The results of this process chain constitute the ground truth of this abstract.

This research aims to compute patient-specific anisotropies in vivo based on cQCT with a voxel spacing of 0.173x0.173x0.6mm. In collaboration with Peter Helwig and with the confirmation of the ethical review board, we collected and published samples of human femoral

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heads of patients undergoing surgery for THAs. Jan-Peter Schenkengel and his colleagues at the hospital Heidenheim scanned the femoral head with a cQCT scanner and an in vivo protocol. Additionally, we scanned the bone sample with a μCT scanner at a voxel spacing of 0.015mm.

We define the high-resolution μCT scans as the ground truth of this research. The clinical CT scan is reoriented in silico to spatially register exactly with the μCT scan of the identical bone sample.

The μCT based computations of mechanical elasticities rely on a binary segmentation of the voxel image. For cCT images, instead, we apply a direct voxel conversion based on Hounsfield values to the clinical scans. We assume that the CT attenuation depicted in the voxels of the CT scan is the superposition of the attenuation of all structural bone features contained in the respective voxel. Hence, applying a reasonable radiodensity-elasticity relationship from the literature allows us to assign mechanical properties to all voxels in a cCT image. Now, we can compute a direct mechanics assessment of the clinical image. The spatially registered cCT and μCT scans allow for comparing the anisotropies in vivo to the ground truth.

Results and Conclusions

Correlations of the spatially registered μCT to cCT comparison of the orthotropic effective stiffness give a coefficient of determination of r$\hat{}$2 $\geq$ 0.893. Eight of nine parameters have an r$\hat{}$2 greater than 0.9 for this representative VE edge length of 2.4mm with all parameter slopes around m $\approx$ 1, small intercepts b, and a p-value $<$ 0.001. Such correlations hold despite several probable inaccuracies, which implies even higher correlations in future research.

Outlook
Probable inaccuracies are identified and can be accounted for in further research, enabling even more detailed representations of elasticities in vivo. Once these improvements are confirmed, we investigate many different bone samples. In addition, we aim to validate the method based on the opportunistic use of cQCT images that will be collected from tissues in vivo.