A Novel Approach to Estimate Trabecular Bone Anisotropy from Stress Tensors

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Introduction

Nowadays, continuum finite element models are widely used in bone mechanics studies. In most of these studies, both the geometry and the element material properties are derived from clinical CT scans. In virtual all of the studies done so far, material properties assigned to the bone elements were chosen density-based isotropic. Experimental and theoretical studies, however, demonstrated that cancellous bone can be highly anisotropic and that its anisotropic stiffness tensor can be well predicted from a second rank fabric tensor which describes the average orientation of trabeculae in the sample. The measurement of such a fabric tensor to account for bone anisotropy in FE-models, however, is not possible from clinical CT images since the resolution of such images is not good enough to resolve the trabecular micro-architecture.

It is believed that load-adaptive bone remodeling will result in a bone micro-architecture that has most trabeculae in the direction where, on average, the magnitude of the principal stress is maximal, and less trabeculae in the direction where, on average, the magnitude of the principal stress is minimal. As a result of this adaptive process, the orthotropic axes thus will coincide with the principal directions of the average stress tensor. This suggests that, at least in theory, it would be possible to derive the fabric tensor from the stress tensor, which can be obtained from FE-analyses. This, however, would be possible only if the correct anisotropic material properties are specified in the FE-model, which are not known on beforehand. A possible solution to this problem, that is explored in this study, is to start with isotropic material properties that are updated iteratively to anisotropic material properties based on the fabric tensor estimated from the average stress until no more changes are found. In order to investigate the accuracy of such an approach, it was applied here to CT images of a femur for which also micro-CT images were available. It thus was possible to compare the estimated fabric tensors with the ones measured from the bone micro-architecture.

Materials and Methods

A human proximal femur cadaver bone was scanned in a micro-CT scanner (Scanco Medical AG, Switzerland) at a resolution of 80 microns. The resolution of the micro-CT scans then was reduced in order to simulate clinical CT results. Using an in-house algorithm bone was meshed and exported to ANSYS 12.1 finite element software.

Material properties were based on the element density and fabric values using the Zysset-Curnier fabric-elasticity relationship [1]. Seven different load cases that a proximal femur might be subjected to were applied to the model: walking, going upstairs, going downstairs, standing up, sitting down, stance, knee bending [2]. The generated finite element model was solved for each individual load case. Stress tensors for each load case were calculated and averaged for seven load cases at each element location. Eigenvectors of the averaged stress tensor were calculated and used as an estimate of the fabric tensor. The eigenvalues of the average stress tensor were normalized first, and then taken as the eigenvalues of the fabric tensor. For the first iteration, no fabric estimate was available and the fabric tensor was set to the identity tensor, thus specifying isotropic material properties. In the following increments, anisotropic material properties were assigned based on the fabric tensor calculated in the previous increment and a new estimate of the fabric tensor was calculated. Iterations were repeated until no further reduction was found for the average change in orientation.

In order to validate the results, the fabric tensor was also evaluated directly from the micro-CT images for each element in the FE model. The agreement in orientation of the estimated and measured fabric tensor was quantified as the largest angular deviation between the principal directions. In addition, the degree of anisotropy (DA) was determined as the ratio of the largest over the smallest component. For further validation, two additional FE-models of the femur were generated: one with material properties based on the measured fabric tensors and one with material properties based on estimated fabric tensors. A fall to the side condition was simulated for both models and maximum principal stress values were calculated and a linear correlation coefficient was calculated.

Results

The iterative procedure was continued until the average angle between the estimated major fabric directions of two sequential iterations reaches a minimum value of around 0.07 radians and no further reduction was found (Fig. 1◆). Quantitative comparison of the estimated and measured fabric principal axes resulted in an average angular deviation of 0.19 radians after 15 iterations (Fig. 1▲).

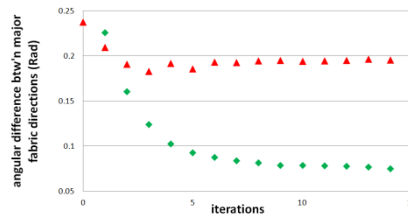

Fig. 1 Average angular difference between 1) estimated and measured (▲) main fabric directions and 2) two sequential estimated fabric directions (◆).

Although, on average, the orientation of the estimated and measured fabric thus compare well, a low correlation was found for DA (*r=0.41*). The stress and strain values calculated from the continuum model based on estimated and measured fabric tensors, however, compared well with a high correlation coefficient (*r=0.89*).

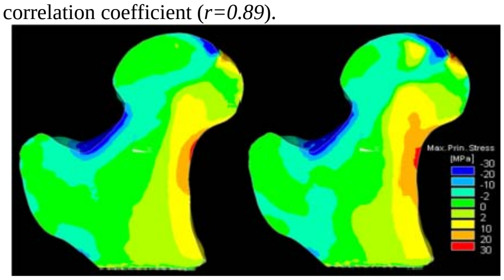

Fig. 2 Maximum principal stress distribution calculated from the model with the measured (left) and estimated (right) fabric tensor.

Discussion and Conclusion

The goal of this study was to investigate the feasibility and accuracy of a novel iterative approach to calculate the fabric tensor from the principal stress distribution. We found that, indeed, this approach can lead to a very reasonable estimate of the fabric tensor orientation. On average, the angular deviation relative to a fabric tensor measured from the bone micro-architecture was less than 0.19 radians, which seems acceptable for most applications. Although, the degree of anisotropy of estimated and measured fabric tensors did not compare well, the stress calculation based on the model with estimated and measured fabric tensor compared very well. This suggests that in those regions where the correspondence was not very good, the stresses are either low or the material anisotropy not very pronounced.

In conclusion, we have demonstrated that this novel approach can be used to estimate the fabric tensor of the proximal femur with some fair accuracy. We expect that this approach can lead to more realistic results in particular for models used to study implants, which are usually anchored in highly anisotropic cancellous bone regions.

References

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Acknowledgement

Funding from the European Union for osteoporotic virtual physiological human project (VPHOP FP7-ICT2008-223865) is gratefully acknowledged.