A NOVEL APPROACH TO MODEL TRABECULAR BONE USING TOPOLOGICAL IMAGE ANALYSIS

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INTRODUCTION: Computational models of trabecular bone microstructure are valuable in understanding the etiology of age-related fractures and predictions of fracture risks. Current high-resolution microcomputed tomography (µCT) or micro magnetic resonance imaging (µMRI) modalities provide a powerful three-dimensional tool for characterization of trabecular bone microstructure. Finite element (FE) models based on the voxel-to-element conversion of images of trabecular bone have become routine in trabecular bone mechanics and added tremendous insights in the structure-function relations of trabecular bone. One of the significant disadvantages of these voxel based FE models is their extremely large size, which limits their applications in nonlinear failure analysis of trabecular bone, especially at the whole bone level [1]. In this study, a novel approach based on a rigorous topological image analysis technique [2] is proposed to model trabecular bone. In this approach, microstructures of trabecular bone can be pattern-recognized and segmented into two basic types: rods and plates, while maintaining the essential microstructural parameters such as bone volume fraction and connectivity. In the current study, the accuracy of the developed algorithms was validated in idealized trabecular rod and rod-plate models.

METHODS: A 3D digital image thinning algorithm with topology and shape preserving properties was used in this study [2,3]. The algorithm consisted of four parts: 1) skeletonization; 2) topology analysis; 3) pattern recognition; and 4) FE interface. The algorithm first processed the 3D bone voxels into a thinned skeleton representation. Each skeleton voxel was then classified based on its morphological features to: a curve (rod), a surface (plate), or a junction. The topological information was then used to recognize patterns of rods or plates as well as their connectivity. Finally, the algorithms interface with a commercial finite element software (ABAQUS, RI) to create a reduced model (Fig. 1). To test the accuracy of the algorithm as well as the difference between the resulting reduced FE models and the voxel based FE models, the algorithm was applied to idealized microstructures of trabecular bone, where the structures are known. A 5x5x5 rod model and a 5x5x5 rod-plate model were used (with one unit cell shown in Fig 1). Each unit of rod model consisted of eight interconnected rods with length 1000 µm with varying diameter: 100 µm, 200 µm, 300 µm and 400 µm, respectively. Each unit of rod-plate model consisted of two plates 1000x1000 µm2 connected by 4 rods each 1000 µm long. The thickness of plates and the diameter of the rods varied between 100 µm, 200 µm, 300 µm, and 400 µm. The physical models of rods or rods-plates were converted into simulated µCT images, which were processed using the developed algorithm. Both rod model and rod-plate model are digitized using two resolutions: 50 µm and 100 µm. In ABAQUS, each rod was modeled as a two-node beam element with a circular cross section while each plate was modeled as 4 three-node shell element. For the voxel based FE models, each bone voxel of the image was converted to an 8-node brick element. The FE analysis of voxel based model was performed using an element-by-element pre-condition conjugate gradient program. The resulting FE models (both ABAQUS and voxel based) were subjected to uniaxial compression to calculate the axial apparent Young’s modulus Ea. The bone tissue was modeled as an isotropic, linear elastic material with a Young’s modulus E of 15 GPa and a Poisson’s ratio of 0.3.

RESULTS: The reduced models of both rod and rod-plate structure consisted of constant 1,500 beam/shell elements regardless of the resolution and the diameter of the rod or the thickness of the plate. The number of elements of voxel based models varied between 5,076 to 424,332 for the rod model, and 17,226 to 738,594 for the rod-plate model. Therefore, the reduction in the size of trabecular bone models ranged between 3 to 490 fold. The prediction in the Young’s modulus of the reduced model demonstrated an excellent linear relationship with the corresponding voxel based model when the simulated trabecular images were at the 50 µm resolution (Fig. 2). The apparent modulus of the voxel based model was slightly higher than the reduced model, indicating that the voxel based model was stiffer. For the lower resolution (100 µm), sometimes, the reduced model deviated from the voxel based model due to the aliasing error (e.g. a 150 µm radius rod can not be distinguished from a 100 µm radius rod if sampled at the 100 µm resolution). For the rod-plate model, the reduced models predicted almost the exact same modulus and density relationship as the voxel based models (Fig. 2). The prediction in the modulus and density relationship diverged in the rod models in the relatively high density range (Fig. 2).

DISCUSSION: In the current study, the accuracy of a novel imaging analysis approach for modeling trabecular bone was tested in idealized microstructures of trabecular bone. The results demonstrated an excellent predictive power of the reduced models in the idealized cases. The discrepancy of the model predictions at the low resolution is limited by the digital nature of the images rather than the technique. This also confirms the previous voxel based FE modeling studies that a minimum of five voxels are needed to accurately represent a single trabecula [1,4]. The current novel approach is still under development and being applied to real microimages of trabecular bone, which may provide an additional tool in accurately modeling trabecular bone microstructure.

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