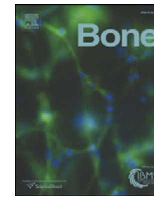
Bone 72 (2015) 71–80

Contents lists available at ScienceDirect

Bone

journal homepage: www.elsevier.com/locate/bone



Original Full Length Article

Trabecular plates and rods determine elastic modulus and yield strength of human trabecular bone

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ARTICLE INFO

Article history:
Received 19 September 2014
Revised 10 November 2014
Accepted 12 November 2014
Available online 15 November 2014

Edited by: David Burr

Keywords:
Individual trabecula segmentation
Microarchitecture
Plate and rod
Finite element
Elastic modulus
Yield strength

ABSTRACT

The microstructure of trabecular bone is usually perceived as a collection of plate-like and rod-like trabeculae, which can be determined from the emerging high-resolution skeletal imaging modalities such as micro-computed tomography (μCT) or clinical high-resolution peripheral quantitative CT (HR-pQCT) using the individual trabecula segmentation (ITS) technique. It has been shown that the ITS-based plate and rod parameters are highly correlated with elastic modulus and yield strength of human trabecular bone. In the current study, plate–rod (PR) finite element (FE) models were constructed completely based on ITS-identified individual trabecular plates and rods. We hypothesized that PR FE can accurately and efficiently predict elastic modulus and yield strength of human trabecular bone. Human trabecular bone cores from proximal tibia (PT), femoral neck (FN) and greater trochanter (GT) were scanned by μCT. Specimen-specific ITS-based PR FE models were generated for each μCT image and corresponding voxel-based FE models were also generated in comparison. Both types of specimen-specific models were subjected to nonlinear FE analysis to predict the apparent elastic modulus and yield strength using the same trabecular bone tissue properties. Then, mechanical tests were performed to experimentally measure the apparent modulus and yield strength. Strong linear correlations for both elastic modulus ($r^2 = 0.97$) and yield strength ($r^2 = 0.96$) were found between the PR FE model predictions and experimental measures, suggesting that trabecular plate and rod morphology adequately captures three-dimensional (3D) microarchitecture of human trabecular bone. In addition, the PR FE model predictions in both elastic modulus and yield strength were highly correlated with the voxel-based FE models ($r^2 = 0.99$, $r^2 = 0.98$, respectively), resulted from the original 3D images without the PR segmentation. In conclusion, the ITS-based PR models predicted accurately both elastic modulus and yield strength determined experimentally across three distinct anatomic sites. Trabecular plates and rods accurately determine elastic modulus and yield strength of human trabecular bone.

Introduction

Osteoporosis is a common disease that occurs with age, in which reduced bone mass and strength leads to increased risk of fracture. Millions of fragility fractures occur directly because of osteoporosis, often at trabecular-dominant bone sites. Indeed, the trabecular bone plays an important role in load transmission and energy absorption in major joints such as the knee, hip, and spine [1–3]. For example, the trabecular bone carries more than 75% of the load in a vertebral body [4]. It is believed that, in addition to the bone volume fraction (the ratio of the volume of bone tissue to the overall bulk volume), the detailed microarchitecture, including trabecular orientation and connectivity, is important in governing the mechanical properties of trabecular bone [5–8]. Moreover, two major types of trabeculae – namely the trabecular plate and rod – play critical and distinct roles in determining the apparent strength and failure behavior of the trabecular bone. Recently, an individual trabecula segmentation (ITS) analysis technique has been developed to decompose the entire trabecular bone network into a collection of individual plates and rods. The ITS technique was further used to assess trabecular plate and rod morphology of both micro-computed tomography (μCT) and high-resolution

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http://dx.doi.org/10.1016/j.bone.2014.11.006
8756-3282/

peripheral quantitative computed tomography (HR-pQCT) images of human trabecular bone [9]. Studies using this ITS technology demonstrated that trabecular microarchitecture changed from plate-like to rod-like in osteoporosis and other metabolic bone diseases, and suggested that a conversion from plate-like to rod-like trabecular bone was an important etiologic factor in age- and osteoporosis-related bone fragility [10–13]. The ITS technique has also demonstrated the importance of trabecular plates and axial trabeculae in supporting mechanical loads imposed on human vertebrae [6]. Furthermore, ITS-based morphological analysis identified microstructural abnormalities in postmenopausal women as indicators for increased risk of fractures independent of areal bone mineral density (aBMD) [14] and revealed dramatic differences in trabecular microarchitecture between different ethnicities [15,16].

We have demonstrated that the ITS-based morphological parameters such as plate bone volume fraction (pBV/TV) and axial bone volume fraction (aBV/TV) are highly correlated with experimentally and computationally determined elastic modulus and yield strength of human trabecular bone [9,17]. To further examine the biomechanical roles of trabecular plates and rods, we developed an ITS-based, specimen specific, plate–rod (PR) microfinite element (μFE) modeling strategy. These PR μFE models are constructed exclusively by ITS plate and rod segmentations, maintaining essentially all the plate and rod microarchitecture: number, shape, volume of trabecular plates and rods, orientation and connectivity between trabecular plates–plates, plates–rods, and rods–rods. Alternatively, specimen specific, voxel-based μFE models do not make any assumption regarding trabecular types but fully represent the original three-dimensional (3D) trabecular microarchitecture. Recently, we examined the accuracy and efficiency of the PR modeling strategy in an idealized, synthetic trabecular bone structure model, and demonstrated that the elastic modulus that was predicted by the ITS-based PR model correlated strongly with those by the voxel-based model at various voxel sizes [18]. Additionally, conversion from the voxel model to the PR model resulted in a 47-fold reduction in the number of elements [19]. Independently, Vanderoost et al. developed specimen-specific skeleton based beam–shell μFE models for simulating trabecular bone elastic modulus [35].

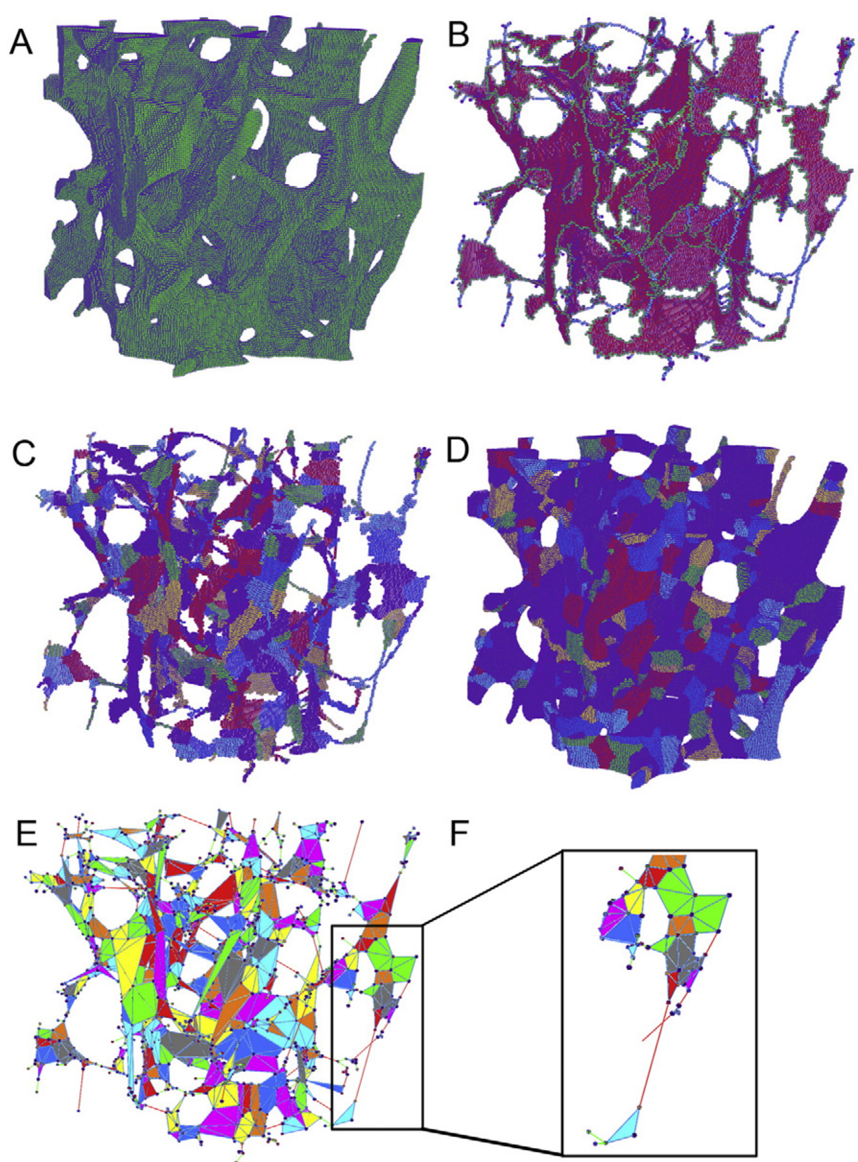

Fig. 1. Illustration of ITS-based PR modeling on a cubical trabecular bone specimen. (A) Original 3D volume of the trabecular bone. (B) Microstructural skeleton with the trabecular type labeled for each voxel. Plate skeleton voxels are shown in red, surface edge voxels in green, rod skeleton voxels in blue. (C) Segmented microstructural skeleton with individual trabeculae labeled by color for each skeleton voxel. (D) Recovered trabecular bone with individual trabeculae labeled by color for each voxel. (E) PR model with shell and beam elements and color indicating different trabeculae. (F) Details of the beam–shell connection, note that the thickness of shell and beam elements was not depicted.