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Accuracy of continuum-level voxel models for strength predictions of the proximal femur

E. Verhulp, B. van Rietbergen, R. Huiskes

Eindhoven University of Technology, Department of Biomedical Engineering

Introduction

Hip fracture is a serious problem that mostly affects the elderly. The combination of osteoporosis and an increased fall risk results in an exponential rise in hip fracture incidence with age. In a recent study micro-finite element (μ FE) models of the proximal femur were analyzed during a fall to the side [1]. The huge models incorporated the detailed trabecular structure, but demanded a lot of CPU time and memory. This inhibits the use of μ FE models as clinical tools for the prediction of bone strength. Replacing the detailed architecture with a continuum representation, however, drastically decreases the computational demands, but the accuracy of such models is not completely known. The goal of this study was to determine the effect of this replacement on the accuracy.

Material and methods

Based on close matched age, body weight and length, a healthy and osteoporotic human proximal femur were selected for the creation of two large-scale μ FE models [2]. Boundary conditions were applied to simulate a fall to the side onto the greater trochanter (Fig. 1).

The original μ FE meshes were scaled down to create continuum-level voxel meshes. A scale factor of 38 was chosen to create continuum meshes consisting of 3 mm voxels; a resolution obtainable *in vivo*. The density in each voxel was determined from the original distribution of cortical and trabecular tissue and subsequently converted to an isotropic modulus with empirically determined density-modulus relationships (Table 1). These relationships were adjusted from Keyak et al. [3] in order to match the properties of both the trabecular and cortical bone in the μ FE model.

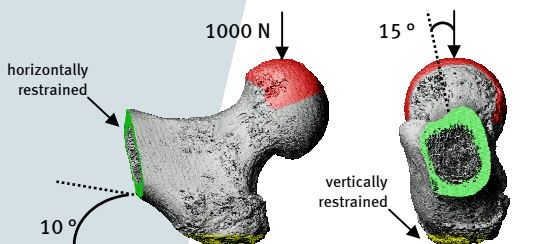


Fig. 1: Orientation of the proximal femur during the fall simulation with applied boundary conditions.

Stresses and strains were computed in each continuum FE model and compared with the original μ FE models. The highest value of the maximum principal strain in the basicervical cortex was determined. This ratio of this value and the yield strain of human cortical bone in tension was used to estimate the apparent yield load.

Table 1: Relationships between density and modulus

Relationship	Density range
$E = 33900\rho^{2.20}$	$\rho \leq 0.27$
$E = 11164\rho - 1112$	$0.27 < \rho < 0.60$
$E = 15597\rho^{2.01}$	$\rho \geq 0.60$

Results

The use of continuum-level FE models instead of the μ FE models reduced the CPU time and memory from approximately 330 hours and 18 gigabytes to 10 seconds and 8 megabytes, respectively. Contour plots for the maximum principal strain and stress are shown in Fig. 2. The predicted yield loads for the continuum models differed not more than 5 % from the values obtained with the μ FE models.

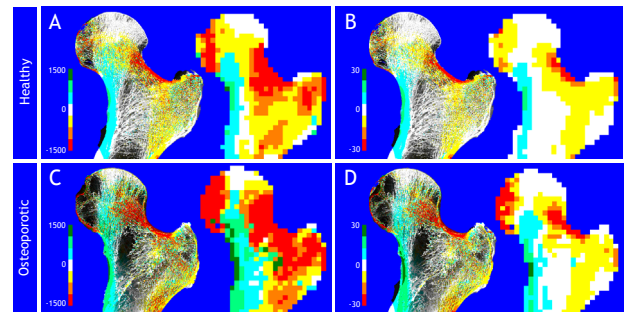


Fig. 2: Contour plots of the absolute maximum principal strain (A and C in μ strain) and stress (B and D in MPa) in the healthy and osteoporotic proximal femur. For a better comparison the mean tissue stress in the continuum-model voxels was determined based on volume fraction.

Discussion

Patient-specific continuum-level FE models of the proximal femur can be easily constructed and solved. The results presented in this study indicated that the detailed trabecular architecture can be safely replaced by its continuum representation when it comes to stress and strain prediction in the thick cortical shell. The values of the trabecular core are less reliable, since the density-modulus relationships neglect the anisotropic nature of trabecular bone. Moreover, a straightforward yield or failure criterion, required for accurate strength predictions of the proximal femur, does not seem to exist for trabecular bone [4].

References:

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