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Reliable simulations of the human proximal femur by high-order finite element analysis validated by experimental observations

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Abstract

Background: The mechanical response of patient-specific bone to various load conditions is of major clinical importance in orthopedics. Herein we enhance the methods presented in Yosibash et al. [2007. A CT-based high-order finite element analysis of the human proximal femur compared to in-vitro experiments. ASME Journal of Biomechanical Engineering 129(3), 297–309.] for the reliable simulations of the human proximal femur by high-order finite elements (FEs) and validate the simulations by experimental observations.

Method of approach: A fresh-frozen human femur was scanned by quantitative computed tomography (QCT) and thereafter loaded (in vitro experiments) by a quasi-static force of up to 1250 N. QCT scans were manipulated to generate a high-order FE bone model with distinct cortical and trabecular regions having inhomogeneous isotropic elastic properties with Young's modulus represented by continuous spatial functions. Sensitivity analyses were performed to quantify parameters that mostly influence the mechanical response. FE results were compared to displacements and strains measured in the experiments.

Results: Young moduli correlated to QCT Hounsfield Units by relations in Keyak and Falkinstein [2003. Comparison of in situ and in vitro CT scan-based finite element model predictions of proximal femoral fracture load. Medical Engineering and Physics 25, 781–787.] were found to provide predictions that match the experimental results closely. Excellent agreement was found for both the displacements and strains. The presented study demonstrates that *reliable and validated* high-order patient-specific FE simulations of human femurs based on QCT data are achievable for clinical computer-aided decision making.

Keywords: Proximal femur; Finite element analysis; p-FEM; Computed tomography; Bone biomechanics

1. Introduction

The mechanical response of an individual patient's bone, and the proximal femur in particular, is of major clinical importance for orthopaedists. Simulation of an individual's bone response to loads is nowadays limited because of difficulties in acquisition of bone's exact complex geometry and its anisotropic and inhomogeneous material properties which vary among individuals.

In the past three decades, three-dimensional finite element (FE) analyses were performed for predicting bone's mechanical response (see Keyak et al., 1990; Viceconti et al., 1998; Taddei et al., 2006, and references therein). FE methods are attractive because at the macro level the bone exhibits elastic linear behavior for loads in the normal range of regular daily activities Keaveny et al. (1994). Bone's geometrical representation may be easily obtained from Quantitative computed tomography (QCT) scans (Keyak et al., 1990; Lotz et al., 1991a; Couteau et al., 2000; Viceconti et al., 2004; Bessho et al., 2007) and structure-based models were shown to be appropriate when surface strains are of interest (Viceconti et al., 1998; Couteau et al., 2000; Taddei et al., 2007). The determination of bone's inhomogeneous mechanical properties and their assignment to the FE mesh is yet a major unsolved problem. The proximal femur consists of cortical (compact) and trabecular (cellular) regions. Homogenized

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mechanical properties of both regions as well as isotropic Young's modulus E were experimentally associated with bone apparent density (ρ_{app}) or bone ash density (ρ_{ash}) (Lotz et al., 1990, 1991b; Keaveny et al., 1994; Keller, 1994; Wirtz et al., 2000). Bone's density in turn can be correlated to QCT Hausfeld Units (HUs) resulting in E(HU) relationship (see e.g. Keller, 1994; Keyak and Falkinstein, 2003). The complexity in determining material properties is enhanced by the anisotropic response which is distributed inhomogeneously throughout the bone. The various material properties cannot be obtained from a scalar value (the HU) in QCT scans, so simplifications have to be applied. For example, an FE study (Peng et al., 2006) compared the response of the femur when isotropic or orthotropic material properties were assigned under two loading conditions (double-leg standing and single-leg standing) showing that differences between the two material property assignments are small.

In previous FE studies conventional h-version FE methods (h-FEMs) were applied in most of which the inhomogeneous distribution of material properties was attained by assigning constant distinct values to distinct elements (see, e.g. Taddei et al., 2007 and references therein), thus the material properties became mesh dependent. Furthermore, the bone's surfaces were approximated by piecewise flat tesselation or piecewise parabolic tesselation, which introduced slight un-smoothness of the surface, therefore limited the possibility to obtain accurate strain measures on bone's surface. For example, the recent study of Bessho et al. (2007) uses a semi-automatic tetrahedral mesh generation combined with shell elements on the peripheral surface for the FE analysis of many proximal femurs, mainly to assess their strength to fracture but not for the mechanical response (although good load to deflection response is mentioned). Some studies do show good experimental correlation between h-FEM's results and fracture load, but to the best of our knowledge, only three studies investigated quantitatively the differences between computed strains and displacements, and these measured experimentally on a femur bone (Lotz et al., 1991a; Keyak et al., 1993; Taddei et al., 2007; Yosibash et al., 2007). Only partial agreement is found, suggesting the need for better simulations.

In a recent work by the authors Yosibash et al. (2007) the p-version FE (p-FE) method was suggested for the simulation of the proximal femur mechanical response. p-FEMs have many advantages over conventional h-FEMs: accurate surface representation, faster numerical convergence rates achieved by increasing the polynomial degree p of the shape functions over the same mesh thus controlling numerical errors easily. Also, the inhomogeneous Young's modulus can be described as a spatial inhomogeneous function within the model, and elements may have large aspect ratios (required in cortical regions being thin and long) and may be strongly distorted (Szabó and Babuška, 1991). In Yosibash et al. (2007) p-FEM results for a human fresh-frozen proximal femur model were compared to a corresponding experiment showing good correlation for displacements and partial correlation for the strains. The p-FE structure-based model was created from QCT data having an internal surface separating trabecular and cortical regions. An isotropic inhomogeneous material model was adopted for which Young's modulus was determined as follows: First, in the cortical and trabecular regions HUs were recalculated in each voxel using a moving average (Kenney and Keeping, 1962) (see simplified concept in Taddei et al., 2004). Next the spatial representation of the apparent density (ρ_{app}) was determined by least-mean square methods (LMS). Finally Young modulus was represented as a smooth function by an $E(\rho_{app})$ connection according to Cody et al. (2000), independent of the mesh.

Because of the unsatisfactory simulation results for the strains, and following the experience gained in our previous work, herein a new and improved model creation and experimental procedure are followed on another human fresh-frozen bone. A new loading machine with better measuring devices was used, a larger number of strain gauges were bonded on the bone's surface, horizontal displacement of femur's head was recorded, and finally two different configurations of load application (a flat plate in addition to a cone) were considered. A new method for the generation of bone's surfaces from QCT data was employed (smoothing algorithms were used with fewer patches) and hexahedral meshes were also created. We also reinvestigated the influence of E(HU) relations on the results and performed many sensitivity studies of the FE models. The new methods resulted in an excellent correlation (for both displacements and strains) for the p-FE results and in vitro experimental observations. The results in Yosibash et al. (2007) were reanalyzed according to the newly presented methods showing a considerably better agreement with experiments.

2. Methods

A fresh-frozen femur of a 21 year-old female donor was deep-frozen shortly after death (caused by a stroke). The bone was determined to be free of skeletal diseases by inspecting the general medical history of the donor, taking X-ray images to ensure that no bony lesions were present and taking bacterial and viral cultures. After defrosting, soft tissue was removed from the bone by a combination of sharp and blunt dissection. The bone was degreased with ethanol, and at sites with minimal curvature on which strain gauges (SGs) were to be applied the bone was roughened with 400 grit sandpaper and again cleaned with ethanol. Strain gauges were serially bonded to the bone using M-Bond 200 Cyanoacrylate Adhesive (Measurements Group, Inc., Raleigh, NC, USA).

The proximal femur was cut and affixed with six bolts to a cylindrical sleeve and fixed by PMMA. Thereafter QCT scans were performed on a Phillips Brilliance 16 CT (Eindhoven, Netherlands) with following parameters: 140 kVp, 250 mAs, 1.5 mm slice thickness, axial scan without overlap, with pixel size of 0.73 mm (512 pixels covering 373 mm field size). Mechanical experiments started following the QCT scans, 8 h after bone mounting and lasted for 36 h. During the bone preparation and between tests it was hydrated and stored in a cold humid container and in refrigeration overnight. Following the in vitro experiments a p-FE model was generated based on QCT scans and simulations performed to mimic