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Incorporating uncertainty in mechanical properties for finite element-based evaluation of bone mechanics

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Abstract

Finite element (FE) models of bone, developed from computed tomography (CT) scan data, are used to evaluate stresses and strains, load transfer and fixation of implants, and potential for fracture. The experimentally derived relationships used to transform CT scan data in Hounsfield unit to modulus and strength contain substantial scatter. The scatter in these relationships has potential to impact the results and conclusions of bone studies. The objectives of this study were to develop a computationally efficient probabilistic FE-based platform capable of incorporating uncertainty in bone property relationships, and to apply the model to a representative analysis; variability in stresses and fracture risk was predicted in five proximal femurs under stance loading conditions. Based on published variability in strength and modulus relationships derived in the proximal femur, the probabilistic analysis predicted the distributions of stress and risk. For the five femurs analyzed, the 1 and 99 percentile bounds varied by an average of 17.3 MPa for stress and by 0.28 for risk. In each femur, the predicted variability in risk was greater than 50% of the mean risk calculated, with obvious implications for clinical assessment. Results using the advanced mean value (AMV) method required only seven analysis trials (1 h) and differed by less than 2% when compared to a 1000-trial Monte-Carlo simulation (400 h). The probabilistic modeling platform developed has broad applicability to bone studies and can be similarly implemented to investigate other loading conditions, structures, sources of uncertainty, or output measures of interest.

Keywords: Bone mechanics; CT scan; Probabilistic; Mechanical properties; Fracture

1. Introduction

Finite element (FE) models developed from computed tomography (CT) scans have become an important tool to evaluate mechanical stresses and strains in bone (Taddei et al., 2004; Hernandez and Keaveny, 2006; Bevill et al., 2006), load transfer related to implant fixation and repair (Taylor, 2006; Haider et al., 2006), bone–cement interface mechanics (Mann et al., 2001; Mann and Damron, 2002), and fracture risk (Perillo-Marcone et al., 2003; Keyak and Falkinstein, 2003; Keyak et al., 2001). Bone fracture continues to be an important issue affecting aging populations and patients with bone diseases, and an understanding of the local bone quality and properties is important in making assessments of fracture potential or implant performance.

These FE models utilize CT intensity in Hounsfield unit (HU) to determine the material properties in a specific finite element or voxel. Numerous studies have sought to define relationships between HU and density, density and Young's modulus, and density and bone strength (e.g. Carter and Hayes, 1977; Bentzen et al., 1987; Hvid et al., 1989; Snyder and Schneider, 1991; Keller, 1994; Rho et al., 1995; Hernandez et al., 2001; Morgan et al., 2003) for various bones, with average relationships fit to the experimental data. In all of these references, large amounts of scatter are present in the experimental data. For example, Keller (1994) reported differences from the mean commonly around 100% (and up to 400%) for modulus

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and strength. The scatter in these relationships has potential to impact the results and conclusions of bone studies. Mupparapu et al. (2006) examined the effects of using different HU–modulus relationships on predicted stress in a proximal tibia with a unicondylar implant and found large differences in modulus assignment and resulting displacements and strains predicted. Using Monte-Carlo simulation, Taddei et al. (2006a) found that bone stresses and strains in the proximal femur were more sensitive to uncertainties in the geometric representation than material properties.

The objectives of the current study were to develop a probabilistic FE-based platform to incorporate uncertainty in bone property estimation for prediction of bone mechanics and fracture risk, and to apply the model to evaluate resulting stresses and risk in the proximal femur under stance loading conditions. In addition, this study evaluated the use of efficient probabilistic methods, as an alternative to the computationally intensive Monte-Carlo method, in making accurate predictions of bone mechanics. The probabilistic model predicts the level of performance (stress or fracture risk) and its likelihood, which provides a more comprehensive evaluation of the physical system and may impact bone study findings as well as clinical assessment.

2. Methods

An automated probabilistic platform was developed that linked probabilistic modeling software (Nessus, SWRI, San Antonio, TX), bone material property assignment (Bonemat, Instituti Ortopedici Rizzoli, Bologna, Italy), and FE analysis (Abaqus, Inc., Providence, RI) to predict the distributions of stresses and risk (Fig. 1). Probabilistic analyses were performed on FE models of five human proximal femurs extracted from CT scans. The CT scans were from three cadavers with an average age of 50. Slice thickness was 3 mm and the field of view was 512 × 512 pixels for all scans. Scan resolutions were 0.586 mm for two patients and 0.547 mm for one patient.

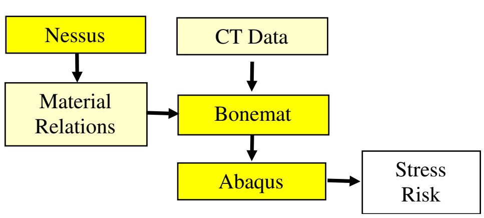

Fig. 1. Automated probabilistic framework was developed by linking probabilistic modeling software (Nessus, SWRI, San Antonio, TX), bone material property assignment (Bonemat, Instituti Ortopedici Rizzoli, Italy), and finite element analysis (Abaqus, Inc., Providence, RI).

Surface geometry was extracted with segmentation of the CT scans using a grayscale-based edge detection algorithm in Scan IP (Simpleware Ltd., Exeter, UK) and then meshed with tetrahedral elements using Hypermesh (Altair Engineering, Inc., Troy, MI). Once meshed, the Bonemat software was used to assign material properties to each individual element. Perillo-Marcone et al. (2003) recommended element edge lengths similar to the CT slice thickness and demonstrated converged stiffness, stress and risk results with an element size of 1.4 mm for CT data with a slice thickness of 1 mm. A mesh convergence study was performed on one femur with element edge lengths of 6, 4.5, and 3 mm (slice thickness), corresponding to 4613, 8776, and 33,150 elements, respectively. The results for the 4.5 and 3 mm element meshes exhibited convergence with details provided in Section 3.

The relationships for Young's modulus and strength, as a function of the apparent ash density, were developed from experimental data for the femur (Keller, 1994). Power law relations between modulus and density and strength and density were utilized (Keller, 1994). The four probabilistic variables were the coefficients and exponents for the modulus and strength relationships (Table 1, Fig. 2). Each probabilistic variable was modeled as a Gaussian distribution with mean values based on the femoral data from 297 specimens with varying mineral contents from Keller (1994). Standard deviation levels (Table 1) for the exponents were assigned the values reported by Keller (1994); standard deviations for the coefficients were set at a level so that a Monte-Carlo analysis of 1000 trials performed with variability in all of the parameters closely bounded the observed scatter in both the experimental modulus and strength data. In each trial of the probabilistic analysis, values for each parameter (a, b, c, d) were generated according to their distributions. Based on Peng et al. (2006), a relationship between HU and apparent bone density of ρ_a (g/cm^3) $= 1 + 7.185 \times 10^{-4}$ HU was used to assign the density to individual elements from the CT data. The material was modeled as isotropic and a Poisson ratio of 0.3 was assumed.

The loading conditions were based on stance phase gait loading and have been shown experimentally to produce clinically relevant fractures (Keyak, 2000; Keyak et al., 2001; Keyak and Falkinstein, 2003). The distal end of each femur was fixed, while a load of 10 kN was applied to the femoral head at an angle of 20° to the shaft axis in the frontal plane (Fig. 3). The applied load of 10 kN was an experimentally measured fracture load under stance conditions (Keyak, 2000). The load was distributed evenly among nodes on the femoral head that were located within 1.5 cm from the center of load application (Keyak et al., 2001).

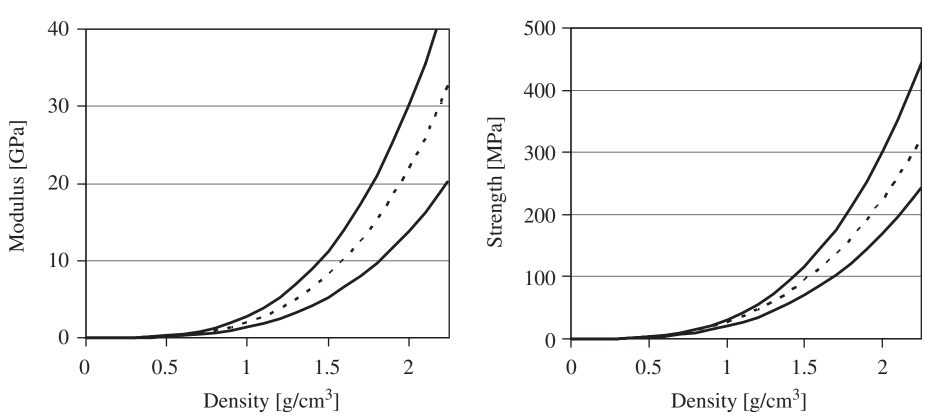

Fig. 2. Variability (1–99% bounds) in the modulus and strength versus density relationships (see Table 1 for corresponding data).