Introduction: The efficient construction of finite element (FE) models that accurately represent the morphology of biological structures is a major challenge. Typically, the model constructed represents a single patient and, in order to investigate a different individual, the mesh construction process must be repeated. In the present study, statistical shape modeling was used to efficiently construct detailed FE models from QCT data for a set of femurs and to investigate the effect of geometry and material property variations on bone strength.

Materials and Methods: Seven human female femurs (69.9 ± 8.8 years old) were scanned with a density calibration standard (Mindways, Austin, TX) using a clinical CT scanner (Lightspeed Ultra, GE, Chalfont St. Giles, UK). CT data was reconstructed with 0.488 x 0.488 x 1.25 mm voxels and surfaces were defined to describe the outer cortical boundary for each femur (Amira v.4.0, Mercury Computing, Chelmsford, MA). A femur surface was chosen as the template surface, and iterative closest point analyses were performed to align the remaining surfaces to the template. An FE mesh was defined (TrueGrid, XYZ Inc., Livermore, CA) and projected to the template surface. A set of landmarks was defined by 100 attachment points of the FE mesh on the template surface and the landmarks were mapped onto the remaining 6 femur surfaces using a modified closest point transform [1]. Point-to-point correspondence was obtained between landmarks on all femurs using a hierarchical optimization approach [2]. Parametric descriptions of the femur surfaces were developed by mapping the surfaces to a unit sphere [3]. The landmark positions in parametric space were optimized to minimize the variance between corresponding sets of landmarks [2]. The FE mesh was tied to each set of landmarks and projected onto each femur surface to generate a total of 7 individual volumetric FE meshes, each consisting of 11,184 8-node hexahedral elements with mesh-to-mesh correspondence. Image intensity values corresponding to the location of each node in the meshes were determined from the CT data converted to apparent bone ash density. A random field description of the geometry and bone density distribution was defined by forming a joint point and density distribution model for the proximal femurs [2]. A Principal Components Analysis (PCA) of this statistical shape model resulted in 6 non-zero uncorrelated eigenvalues and corresponding eigenvectors, with each eigenvalue, \( \lambda \), giving the variance of the femur geometry and bone density from the mean along the corresponding eigenvector. Variation in the geometry and bone density of the femur set was described as

\[ p = p_m + m \sqrt{\lambda q} \]

where \( p \) is a vector containing the spatial location and apparent density value for all nodes in the finite element model, \( p_m \) is the vector describing the average femur, and deviation from the average femur was determined as the product of a scalar, \( m \), and model standard deviation, \( \lambda \), along the \( q \) direction [2]. Three finite element models were developed: one that represented the mean geometry and density distribution for the set of 7 femurs, as well as one each for the mean ± 1 standard deviation (SD). Elastic-perfectly plastic material behavior was assumed, and isotropic elastic moduli and ultimate stress values were determined as functions of ash density for all bone elements [4]. Fall loading was simulated and the finite element models were solved using LS-DYNA (LSTC, Livermore, CA).

Results: PCA showed that 78% of the variation in the femur finite element models was captured by the first 3 eigenmodes. The finite element model representing the mean ± 1 SD variation in the second eigenmode resulted in an increase in neck angle length, decrease in neck-shaft angle, increase in neck diameter, and an increase in cortex width (Figure 1), all of which have been shown to decrease fracture risk. This independent mode of variation (eigenmode) resulted in the greatest predicted maximum load in a simulated fall configuration (Figure 2).

Discussion: High-fidelity finite element models were developed using shape modeling methodology to describe the complex geometry and material property distribution of a set of human femurs. The variability in shape and density distribution of the bone is represented by a small set of uncorrelated variables, allowing efficient description of model variability and the resulting effect on bone strength. This modeling approach directly relates independent variations in bone geometry and bone density to bone strength through a high fidelity predictive engineering model.


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