

# PROBABILISTIC SHAPE-BASED FINITE ELEMENT ANALYSES OF BABOON FEMURS

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## INTRODUCTION

The construction of finite element models that accurately represent the complex morphology of biological structures is a major challenge. Uncertainty and variability exist in the input variables (i.e. bone geometry and density, loading, etc.) to the models and, accordingly, the predicted model response will also be uncertain.

A finite element model describing a set of baboon femurs was developed using statistical shape modeling methodology. Probabilistic finite element analyses were used to investigate the effects of variability in bone geometry and apparent density distribution along with the error in determining elastic modulus from the apparent density on FE model predictions.

## METHODS

Three fresh-frozen right femurs were obtained from baboons that had died due to natural causes (Southwest National Primate Research Center/Southwest Foundation for Biomedical Research, San Antonio, TX). The proximal third of each femur was scanned along with a density calibration phantom in a micro-CT system (Explore RS, GE Healthcare) and 96  $\mu\text{m}$  dimensionally isotropic voxels were reconstructed.

An iterative thresholding scheme was used to extract the bones from the imaging data (ImageJ, NIH) and triangulated surfaces

were defined to describe the outer cortical boundary for each femur (MicroView, GE Healthcare). Surfaces were aligned using Procrustes analyses (ImageJ, NIH).

A computational finite element mesh was defined (TrueGrid, XYZ Scientific Applications, Inc.) and projected to each femur surface to produce a set of volumetric mesh geometries, each consisting of 11,824 8-node hexahedral continuum elements. Using a linear relationship between densities in the calibration phantom and corresponding image intensities, nodal intensity values were converted to apparent density (Taddei, et al., 2004).

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 (Pepin, et al., 2002). A Principal Components Analysis (PCA) of this shape model resulted in a set of eigenvalues and eigenvectors, with each eigenvalue,  $\lambda$ , giving the variance of the femur geometry and bone density from the mean along the corresponding eigenvector,  $q$ . PCA demonstrated that 99.94% of the model variation was explained by a single eigenvalue (Bredbenner, et al., 2006)

Variation in the geometry and density distribution of the femur set was described in terms of the average description and the dominant eigenvalue as:

$$\mathbf{p}_v = \bar{\mathbf{p}} + m\sqrt{\lambda} \mathbf{q},$$

where  $\mathbf{p}_v$  is a vector containing the spatial location and apparent density value for all nodes,  $\bar{\mathbf{p}}$  is a similar vector describing the average femur, and deviation from the average femur was determined as the product of a scalar,  $m$ , and model standard deviation,  $\sqrt{\lambda}$ , along the  $\mathbf{q}$  direction. The parameter  $m$  was modeled as a random variable with a mean of 0.0, a standard deviation of 0.4, and a normal distribution.

Apparent densities were determined for each element as the mean of the included nodal densities and were binned into a total of 7 apparent density levels to reduce computational requirements. Isotropic elastic moduli were determined as a function of apparent density for all bone elements using an empirical relationship given as:

$$E [GPa] = 1.99 \left( \rho_{\text{apparent}} [g/cm^3] \right)^B,$$

where  $B$  was modeled as a random variable with a mean of 3.46 and a standard deviation of 0.12 (Keller, 1994).

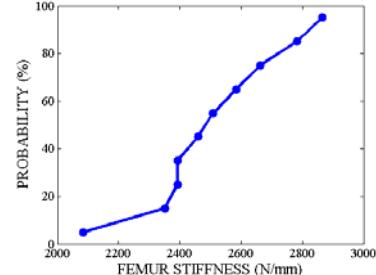
Distal nodes in each model were fixed and a 1.0 mm displacement was prescribed to a set of 8 nodes on the proximal side of the femoral head. Finite element models were solved using LS-DYNA (LSTC) on a Linux-based cluster. Femur stiffness was determined by dividing the distal reaction force by the applied displacement.

Using commercially-available probabilistic code (NESSUS, Southwest Research Institute), the effects of shape ( $m$ ) and bone property ( $B$ ) variation and uncertainty were determined using the Latin Hypercube analysis method.

## RESULTS AND DISCUSSION

The assumed variability in geometry and bone density distribution and the error

associated with determining modulus resulted in predicted femur stiffness values ranging from 2085 to 2866 N/mm (Fig. 1). There is a 90% probability that femur stiffness is within this range.



**Figure 1:** The cumulative distribution function demonstrates the effects of input variability on predicted femur stiffness.

## SUMMARY/CONCLUSIONS

High-fidelity finite element models were developed using shape modeling methodology to describe the variability in geometry and material property distribution determined from imaging data for a set of baboon femurs. Probabilistic methods were used to demonstrate the variability in femur model stiffness associated with variation in geometry and bone density distribution and the error associated with determining elastic modulus from the apparent density.

## REFERENCES

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