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Generation of a Statistical Model of the Whole Femur Incorporating Shape and Material Property Distribution

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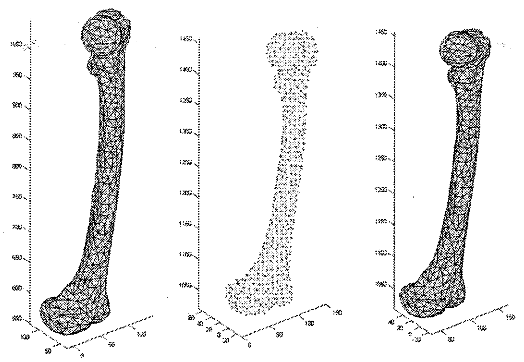
Introduction: Orthopaedic implant designs undergo extensive preclinical testing to ensure their reliability but in use there performance can vary significantly between patients. A possible reason for this is that very few computational studies have incorporated interpatient variability. The vast majority use only a single bone model as constructing multiple models from sources such as CT scans is a time consuming and laborious task. This is despite evidence from recent studies indicating that bone geometry and bone quality have a significant effect on implant performance [1, 2]. The objective of this study is to build a statistical model of the whole femur which incorporates both the natural shape and material property variations which occur between patients. The model will be able to generate new femur instances and suggest the principal modes by which the femur varies in the population.

Methods: This preliminary study used 13 Computer Tomography (CT) data sets which were available from a medical study investigating arterial blood flow. The patients were aged between 43 and 84, 6 female and 7 male. Manual segmentation of bone from surrounding tissue allowed a solid model, defined by a finite element tetrahedral mesh, of one femur from each CT file to be created using Amira® (Mercury Computer Systems, Berlin). Correspondence between each femur example had to be established in order to build the statistical model. To achieve this-a registration scheme was adopted which aimed to morph a baseline tetrahedral mesh onto each femur so that in every instance the corresponding elements describe the same relative area of the bone. This technique was developed in-house based on the extended Iterative Closest Point (ICP) method [3]. One of the femur models was taken as the reference and used as the baseline mesh. By describing each other femur instance as a cloud of surface points the extended ICP algorithm morphed the baseline mesh onto the new geometries (Fig. 1).



Baseline Mesh

New Instance - Described bv Surface Points

New Instance with Morphed Mesh

Fig. 1: Illustrating mesh morphing of a baseline femur mesh onto a new femur model with a coarse mesh example.

Due to the proportional relationship between bone relative density and grey level it is possible to assign material properties to the models from their CT files. For each example the nodes of every element were assigned a grey level value using a material property extraction program BioMesh, which interpolated the grey level at that point in the CT. Using Principal Component Analysis (PCA) the femur instances were analysed, producing a statistical model containing the variation in geometry and material property distribution seen within the training set. The PCA results also indicated the principal modes of variation and their relative significance in describing the differences seen between the femurs in the data set used to 'train' the model.

Results: The first eigenmode of the model was found to describe over 40% of the variation in the model with the second mode explaining a further 10%. It was possible to describe 95% of the variation in the training set with the first 10 modes. The effects of the first two modes in isolation are shown below by varying their respective shape parameters, b, between +/-3√b (Fig. 2). The shape parameter defines the value of the contribution of each eigenmode of the model.

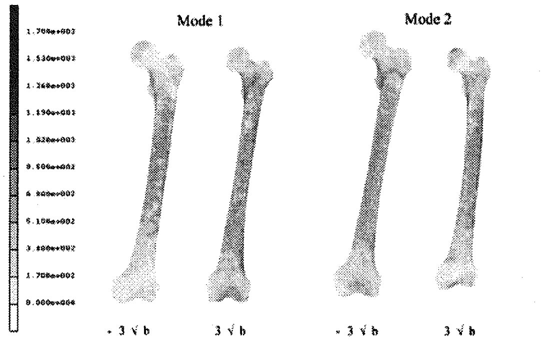


Fig. 2: Plots of the first two principle modes of variation of femoral shape and density distribution, each shown at +3√b and -3√b.

Upon examination it was found that the first mode showed the femur thinning and becoming increasingly dense, this mode was dominated by changes in the material property. The increase in bone density was most notable through the shaft, around the intercondylar notch and the principal medial load bearing trabeculae system within the femoral head. The geometric features shown were a relative twisting of the distal femur and a narrowing of the femoral neck. The second mode contained more geometric information, the most dramatic of which is scale. The decrease in length of the femur is accompanied by straightening of the femur towards the vertical and a tendency for an increase in density on the medial side with a decrease on the lateral.

Discussion: The results of this work have shown that it is possible to create a statistical model of the femur which incorporates the variation in geometry and material property present within the set of data used to create it. The clear limitation of this study is the relatively small number of femurs used. The incorporation of more CT scans into the model will make it more representative of the whole population, this issue will be addressed in the future. However the trends shown offer a previously unseen view of how the morphology of the femur is likely to change between people, a potentially useful insight in prostheses design and testing. Further to this the model is capable of producing unique femurs which are constructed from combinations of the variations contained in the statistical model. This will allow large scale, multi-femur computational analyses to be carried out, which fully incorporate naturally occurring interpatient variability for the first time.

References: 1. Kobayashi et al., 2000, Lancet, 335(9214), 1499-1504. 2. Wong et al., 2005, Proc. IMechE Part H J. Eng. Med, 219(H4), 265-75. 3. Chui et al., 2003, CVIU, 89(2-3), 114-141.

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