A NEW FINITE-ELEMENT SOFTWARE PIPELINE FOR THE MICRO-STRUCTURAL ANALYSIS OF THE PROXIMAL FEMUR

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INTRODUCTION

Understanding how the trabecular and cortical compartments contribute to the load-bearing capacity of the human proximal femur has important implications to both clinical practice and basic-science [1]. Advances in computing power and computed-tomography (CT) scanners over the last two decades now makes it possible to run large-scale micro-structural finite-element (FE) analysis of the femur, providing in-depth information on the trabecular and cortical bone mechanics. However, current microstructural femur models require large supercomputing power, ad-hoc software and the common point-load simplification of the hip contact force that lead to numerical artefacts in the femoral head region. We present a novel software pipeline for generating micro-structural FE models of the human femur, determine the hip pressure distribution on the femoral head, solve the elastic problem and post-process the large result file.

METHODS

An ex-vivo femur from a healthy woman (41 year old, 179 cm tall, 104 kg weight) was obtained from the Melbourne Femur Collection [2]. A stack of 1706 consecutive transaxial images, 1536 x 1536 pixels (82 µm isotropic pixel size) was obtained using a high-resolution pQCT (Xtreme CT; Scanco Medical, Bruettisellen, Switzerland). The new software pipeline included image processing (CT Analyser v1.14, Skyscan), in-house pre- and post-processing and the preconditioned conjugate gradient (PCG) solver implemented in ANSYS (ANSYS Inc., USA). Pre-processing involved segmentation of bone voxels using uniform thresholding (min=96, max=255) and a 3D-sweep algorithm applied to remove isolated voxels (speckles). The linear hexahedrons mesh was generated using an in-house lossless variation of the Vertex Pooling algorithm [3]. The hip contact pressure distribution was calculated using an in-house routine by (a) defining a superficial element layer using Delaunay triangulation, (b) assuming Hertzian pressure distribution and (c) using the average hip contact force during single leg stance [4]. The model was fully constrained at the most distal element layer and solved by setting a convergence tolerance of 1e-6. The mesh generation speed was assessed by generating a 1.45 billion Degree-Of-Freedom (DOF) model using a stack of 500 images, 984×984 pixels, binarized as a full homogenous solid. The resultant of the hip contact pressure distribution was compared to the input point force. Simulations were run on a single PC with 512 GB memory (RAM) and 8 CPUs shared-memory parallel computation procedure. Time to solution was recorded. The von Mises stress was visualized over a transversal cross-section using the ANSYS built-in tool and an in-house Matlab routine. Performance was compared with the state-of-the-art micro-structural FE models of the femur [5].

RESULTS AND DISCUSSION

The femur model was a 333 M DOFs model generated in 22'. The 1.45 billion DOFs model was generated in 2.7 hours, requiring 4.7 GB memory. The resultant of the pressure distribution differed by less than 26.5 N from the point force in input. The PCG solution required 94 CPU hours, 6 processors and 441 GB of memory. These results compare favourably with the largest published microstructural FE femur model [5], which required 722 CPU hours, 2176 processors and 10 TB of memory for solving an 840 M DOFs model using an algebraic multi-grid system [5].

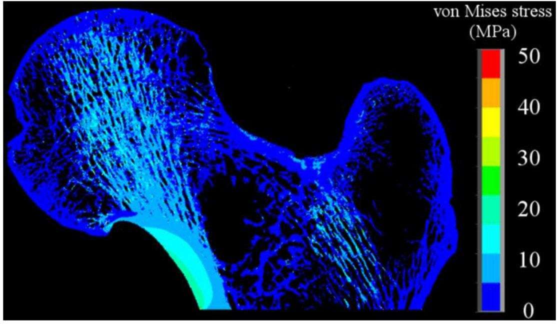

Figure 1: The von Mises stress during single leg stance.

Visualization over a femur cross-section (Fig. 1) of element results required ~4 hours using the ANSYS built-in tool as compared to ~3 seconds using the in-house Matlab routine.

CONCLUSIONS

The new software pipeline is a valid solution for generating, solving and post-processing micro-structural models of the human femur.

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