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LARGE-SCALE MICRO-FINITE ELEMENT SIMULATION OF COMPRESSIVE BEHAVIOR OF TRABECULAR BONE MICROSTRUCTURE

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Abstract: *Microstructural finite element analysis has become a standard technique for evaluation of mechanical properties of trabecular bone. Due to the high complexity of the trabecular bone microstructure, the FE models have a very large number of elements (about 1 million elements per cubic cm in 50 μm^3 resolution). To perform FE analysis of the microstructural FE models based on micro-CT scanning of whole bone samples (e.g. vertebral bodies) it is needed to solve 10^7 – 10^8 equations. This article deals with comparison of approaches using voxel-based microstructural FE models to calculate the overall mechanical properties of trabecular bone.*

Keywords: ***voxel FE models, elastic properties, trabecular bone, parallel computing, MPI***

1. Introduction

Inverse estimation of material properties (namely stiffness and strength) of trabecular bone using FE models of its microstructure is important not only as a nondestructive tool for early prediction of osteoporotic fracture, but can be successfully applied in other research areas, e.g. in animal models to study effect of various growth factors on bone formation.These microstructural FE models are used to perform a numerical simulation of mechanical experiment. Usually, the micro-FE model is subjected to unit load in three mutually perpendicular directions and elastic constants are determined from the 'virtual experiment'.

In the present study a parallel solution strategy is described for solving such a large problem in parallel utilizing existing open-source programs. Our main aim was to demonstrate the scalability of proconditioned conjugate gradient (PCG) parallel solver for large linear elasticity problems. Two architectures are used, one distributed shared memory (DSM) system (SGI Altix), second shared memory system (Intel Xeon X5560) tested using two problems of different size. The larger problem (rat vertebra) is solved on SGI Altix 4700 series equipped with 56 2-core Intel Itanium-2 processors and SGI's NUMAlink processor interconnect and 288 GB RAM. The smaller problem (sample of human trabecular bone) is solved using a 16-core system based on Intel Xeon X5560 processors with 48 GB RAM. Total number of unknowns in these models was approximately 14.10^6 and $1{,}7.10^6$, respectively.

2. Materials and Methods

To develop high-resolution micro-FE model of trabecular bone at different resolution, two experiments were performed. In the first experiment, only a cylindrical sample has been extracted from human proximal femur. The sample (diameter 5 mm and height 8 mm) was mounted on a rotating table and placed in a shielded X-ray box. The second experiment involved scanning whole vertebra. In this case L4 vertebra of a laboratory rat has been chosen. Direct conversion from micro-CT volumetric data to voxel micro-FE models requires only setting appropriate threshold to distinguish between the bone and empty space. The threshold value was chosen iteratively using one selected reconstructed cross-section of the vertebra.

To compute the overall stiffness of the vertebral body in the infero-superior direction a unit displacement has been prescribed on the top surface of the vertebral body. The lower surface of the body was fixed (all nodes with minimal z-coordinate were prescribed zero displacements in three directions).

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Based on our previous nanoindentation results [Jirousek et al (2011)] the tissue-level material properties were prescribed: Young's modulus of elasticity E_{TISSUE}=15 GPa, Poisson's ratio: μ_{TISSUE}=0.2.

From the volume data, 100×100×100 voxels were selected in the middle part for easy comparison of orthotropic elastic properties. The coordinate axes were aligned such as to keep Z-axis in the direction of loading during the experiment. Total number of nodes was 566,790 for the 100×100×100 voxel model and 4,791,142 for the FE model of rat vertebra. Prior the computations, the FE models were verified for mesh connectivity.

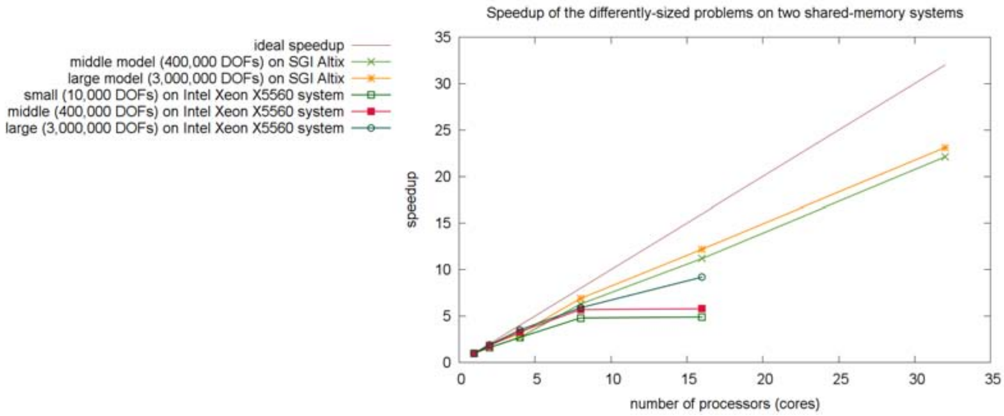

Fig. 1: Speedup of the PCG solver for differently-sized problems on the two architectures

3. Conclusions

In the paper, solution strategy for large-scale FE models originating from micro-CT data of trabecular microstructure of whole bones was presented. These micro-FE models are intended for validation of computationally less-demanding numerical models, but can be successfully used for numerical studies of implant-bone interaction, for studies of different approaches to vertebroplasty or in animal models for verification and comparison of drug treatments.

From the inverse calculation of the orthotropic properties of micro-FE model of the the trabecular bone sample E_X =1.06 GPa, E_Y =1.97 GPa and E_Z =1.86 GPa were determined with agreement to previously published results, see Jirousek and Zlamal (2011).

Since the memory requirements for the PCG solver are slightly over 1 GB per million DOFs, one can easily compute the maximal number of unknowns solvable on a shared memory system. One limitation exists for the SGI Altix systems - the memory available for one processor is limited (in our configuration, each processor is eqquipped with 2 GB RAM) and therefore the user must decide how to partition the problem not to exceed the memory available for the single processor. On the other hand, the extensibility of the Altix 4700 is remarkable – the system can contain up to 2048 dual-core Itanium 2 processors (connected by the NUMAlink 4 interconnect) equipped by up to 128 TB of memory.

As a conclusion, it can be stated, that for very-large problems with more than 10 million unknowns the EBE-PCG solver (despite its low memory requirements) is inconvenient due to its slow convergence. In this case, more powerful and more scalable strategy should be employed, such as the Algebraic Multigrid (AMG) solvers.

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