

STABILITY OF BONE-IMPLANT CONSTRUCTS: A COMPUTATIONAL MECHANICS APPROACH BASED ON HIGH RESOLUTION COMPUTED TOMOGRAPHY

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INTRODUCTION:

Bone grafts and biomaterials are often used to aid the repair of complicated fractures. Their healing process can be analyzed using recently developed high-resolution *in vivo* peripheral quantitative computed tomography (pQCT). However, although providing detailed information about bone structure, pQCT does not give information on mechanical stability. Such information could potentially be derived from micro finite element analyses (μ FE) which have successfully been used to determine bone stiffness of bone samples measured with μ CT. Therefore, this study was conducted to test the feasibility of pQCT-based μ FE to assess the mechanical stability of bone-implant constructs. Specifically, our aims were to implement an efficient solution of the large scale μ FE, and to provide experimental validation.

METHODS:

A simplified *ex vivo* model was established that based on ovine radii, post mortem implanted T-plates, cortical screws and bio-material. Four radii were biomechanically tested and measured with a pQCT device having a resolution of 93 μ m (Radios, Scanco Medical, Bassersdorf, Switzerland). Each bone was analyzed three times: 1. intact, 2. after removing a 1cm cortical slab, and subsequent placement of a T-plate; 3. similar as in the previous case, but with addition of a biomaterial (Fig. 1).

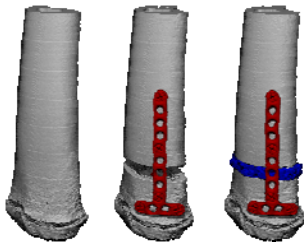


Figure 1: Models as derived from high-resolution computed tomography of the ovine radii. Original bone (left); Bone with induced gap, fixation by T-plate (middle); Additionally with implanted biomaterial (right).

The pQCT data were automatically segmented into the different components of the models. Metal-induced scanning artifacts could be largely eliminated by means of semi automatic image processing. μ FE models were created by direct voxel-to-element conversion. In order to reduce the time to solve the FE models they were downscaled by a factor of two, which still allowed resolving trabecular structures. Boundary conditions were applied that simulated the experimental tests. These models then were solved using an iterative element-by-element (EBE) solver [1]. However, EBE solvers show heavily decreased performance for very large FE models, especially when

largely varying material properties are present. To improve throughput, we developed a parallel FE solver that implements the conjugate gradient algorithm complemented by smooth aggregation multigrid preconditioning [2, 3]. The models were processed on 256 nodes on a Cray XT3 system (CSCS, Manno, Switzerland).

RESULTS:

The downscaled μ FE models consisted of about 12 million dofs. When using the sequential FE solver, they were solved in 4 hours for the bone only models to 72 hours for the models with the different materials. For the parallel code, this was reduced to 70-140 seconds, respectively. For the bone-implant constructs a good correlation was found between the μ FE calculated stiffness and the biomechanical tests ($R^2=0.91$).

DISCUSSION:

In this study we showed that it is possible to accurately quantify mechanical stability of systems of bone implants using high-resolution *in vivo* pQCT systems in combination with μ FE. The complex implant and screw geometries, as well as the individual trabeculae could be included easily in the μ FE models. In comparison to the conventional sequential FE solver the new parallel FE solver showed more robust convergence and was up to 1850 times faster when using 256 CPUs.

Another advantage of the new parallel FE solver is its ability to handle much larger models; hence, downscaling of the μ FE models is no longer needed. A typical full-scale model, consisting of 90 million dofs, was solved in 81 seconds on 512 CPUs; this was 3200 times faster than solving the downscaled model with the sequential code, even if the latter had 8 times fewer dofs.

In conclusion, our highly automated processing techniques in combination with the new FE solver show high potential to quantify bone healing and implant stability in patients. Application of these methods to pQCT datasets of a clinical study is currently underway in order to assess fracture repair.

REFERENCES:

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- [3] Arbenz et al., Proceedings of PARA'06: Workshop on the State-of-the-Art in Scientific Computing.

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