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Biomechanics of Bone Structure and Strength: From In-Vivo To In-Silico Analysis

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ABSTRACT

Bone tissue, which forms the skeleton, is a remarkable material. It displays a fascinating wide variation in architecture, varying from dense and compact (cortical bone) to highly porous structures build of a complex network of struts and plates (trabecular bone) (Fig. 1). Even more intriguing are its dynamic capabilities; it is lightweight and strong, can grow, and can adapt and repair itself in such a way that it can last a lifetime. With these architectural and dynamic characteristics, it is also a very complex material. As yet, the processes that take place during formation, adaptation and repair are not fully understood. And, although it has often been suggested that the bone structure is somehow mechanically optimized, it is unclear what exactly it is optimized for and how it can achieve this supposed optimized state.

Over the last decade, new answers to these questions have been found thanks to the development of two new techniques for analysis of complex trabecular bone architectures. The first is micro-CT scanning. With this technique, high-resolution cross-sectional images of bone samples can be created at a resolution good enough to resolve the trabecular architecture. By stacking a large number of sequential cross-sectional images, it now is possible to create a 3-D reconstruction of the bone that accurately represents its internal and external architecture (Fig. 1). Originally limited to small bone samples, new equipment now enables micro-CT scanning of whole human bones and even bone in-vivo. The second technique is a computational one: micro- finite element (micro-FE) analysis[1]. With this technique, voxels in the 3-D reconstruction are converted to 3-D brick elements in a finite element model for mechanical analysis. This

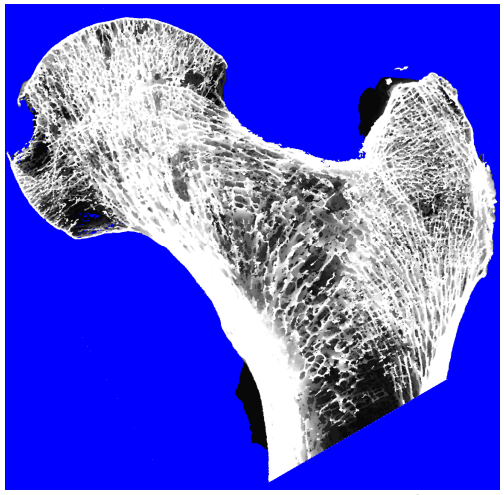

Fig. 1 micro-CT reconstruction of a proximal human femur cut in half to reveal the trabecular bone

generally results in a micro-FE model with a very large number of elements (on the order 10^5 to 10^8). Using dedicated iterative solvers based on a conjugate gradient (CG) algorithm and parallel computer systems, it is now possible to solve such large problems[2,3]. By combining these techniques it thus becomes possible to analyze a computational 'replica' of the bone in the computer, hence, redirecting the analysis from in-vivo to 'in-silico'

In this presentation, it is shown first which computational tricks this micro-FE technique exploits to solve such very large FE-problems. In the second part, it is shown how this technique can be used to quantify bone 'optimality' and bone strength. Clinical applications will be discussed as well[4,5]. In the last part of the presentation, it is demonstrated how this technique can be used to simulate hypothetical mechanisms that were proposed to explain bone formation and adaptation in order to test their veracity[6].

REFERENCES

[1] van Rietbergen B, Weinans H, Huiskes R, Odgaard A. A new method to determine trabecular bone elastic properties and loading using micromechanical finite-element models. J Biomech. 1995 Jan;28(1):69-81.

[2] Van Rietbergen B, Huiskes R, Eckstein F, Rüegsegger P. Trabecular bone tissue strains in the healthy and osteoporotic human femur. J Bone Miner Res. 2003 Oct;18(10):1781-8.

[3] Verhulp E, van Rietbergen B, Huiskes R. Load distribution in the healthy and osteoporotic human proximal femur during a fall to the side. Bone. 2008 Jan;42(1):30-5. Epub 2007 Sep 6.

[4] Pistoia W, van Rietbergen B, Lochmüller EM, Lill CA, Eckstein F, Rüegsegger P. Image-based micro-finite-element modeling for improved distal radius strength diagnosis: moving from bench to bedside. J Clin Densitom. 2004 Summer;7(2):153-60.

[5] Boutroy S, van Rietbergen B, Sornay-Rendu E, Munoz F, Bouxsein ML, Delmas PD. Finite Element Analyses Based on In Vivo HR-pQCT Images of the Distal Radius is Associated with Wrist Fracture in Postmenopausal Women. J Bone Miner Res. 2007 Nov 12;

[6] Ruimerman R, Hilbers P, van Rietbergen B, Huiskes R. A theoretical framework for strain-related trabecular bone maintenance and adaptation. J Biomech. 2005 Apr;38(4):931-41.