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MORPHOLOGIE

ORIGINAL ARTICLE

Micro-finite-element method to assess elastic properties of trabecular bone at micro- and macroscopic level

Détermination des propriétés élastiques de l'os trabéculaire à l'échelle micro- et macroscopique par la méthode des microéléments finis

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KEYWORDS
Mechanical properties;
Micro-computed tomography;
Micro-finite-element;
Trabecular bone;
Inverse method

Summary
Objective of the study. — The objective of the present study is to assess the mechanical behavior of trabecular bone based on microCT imaging and micro-finite-element analysis. In this way two methods are detailed: (i) direct determination of macroscopic elastic property of trabecular bone; (ii) inverse approach to assess mechanical properties of trabecular bone tissue.
Patients. — Thirty-five females and seven males (forty-two subjects) mean aged (± SD) 80 ± 11.7 years from hospitals of Assistance publique—Hôpitaux de Paris (AP—HP) diagnosed with osteoporosis following a femoral neck fracture due to a fall from standing were included in this study.
Materials and methods. — Fractured heads were collected during hip replacement surgery. Standardized bone cores were removed from the femoral head's equator by a trephine in a water bath. MicroCT images acquisition and analysis were performed with CTan® software and bone volume fraction was then determined. Micro-finite-element simulations were per-formed using Abaqus 6.9-2® software in order to determine the macroscopic mechanical behaviour of the trabecular bone. After microCT acquisition, a longitudinal compression test was performed and the experimental macroscopic Young's Modulus was extracted. An inverse approach based on the whole trabecular bone's mechanical response and micro-finite-element analysis was performed to determine microscopic mechanical properties of trabecular bone.
Results. — In the present study, elasticity of the tissue was shown to be similar to that of healthy tissue but with a lower yield stress.

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Conclusion. — Classical histomorphometric analysis form microCT imaging associated with an inverse micro-finite-element method allowed to assess microscopic mechanical trabecular bone parameters.

Résumé

Objectif de l'étude. — Déterminer le comportement mécanique de l'os trabéculaire à l'aide d'une acquisition microtomographique par rayons X et d'une analyse par la méthode des microéléments finis : (i) détermination directe du module d'élasticité apparent de l'os trabéculaire ; (ii) approche inverse pour déterminer les propriétés mécaniques du tissu trabéculaire.
Patients. — Trente-cinq femmes et 7 hommes d'âge moyen 80 ± 11,7 ans de l'Assistance publique—Hôpitaux de Paris diagnostiqués ostéoporotiques suite à une fracture de l'extrémité supérieure du fémur due à une chute.
Matériels et méthodes. — Suite à une arthroplastie, des carottes osseuses ont été extraites au sommet de la tête fémorale à l'aide d'un trépan. Une acquisition microtomographique aux rayons X et une analyse des paramètres histomorphométriques ont ensuite été effectuées. Par la suite, le comportement macroscopique de l'os trabéculaire a été déterminé par la méthode des microéléments finis sur le logiciel Abaqus 6.9-2®. Un essai de compression longitudinale a ensuite été réalisé afin de mesurer le module d'élasticité apparent. Enfin, une analyse inverse basée sur le comportement mécanique expérimental apparent combinée à la méthode des microéléments finis a permis de déterminer le comportement microscopique de l'os trabéculaire.
Résultats. — Les résultats ont montré que les propriétés élastiques de l'os trabéculaire présentaient les mêmes caractéristiques que chez des patients sains.
Conclusion. — La méthode classique d'histomorphométrie combinée à une méthode inverse des microéléments finis permet de remonter aux propriétés élastiques microscopiques de l'os trabéculaire.

Introduction

Bone mechanical properties are affected by bone loss and modification of bone quality. The term ''bone quality'' refers to a complex definition that involves intrinsic microstructural properties [1,2]. A definition of bone quality was proposed by Bouxsein [3] as ''the totality of features and characteristics that influence a bone's ability to resist fracture''. In fact, human bone is a composite material whose mechanical properties depend on its hierarchical organization [4—6]. Despite extensive research, a mechanistic framework to describe how the microstructure affects the mechanical behaviour of bone has not been established. The major difficulty lies in intrinsic properties of bone, a tissue which can adapt both structurally and architecturally to its mechanical environment through bone remodelling [7]. For instance, on the microscopic scale local properties of the cortical bone emphasizes the importance of cement lines as an efficient structural component to ensure internal movement at the material level and to prevent the progression of localization damage zones and cracks [8,9].

Bone remodelling is a multi-cellular phenomenon that is not fully understood. Bone cells such as osteocytes transduce mechanical and biochemical information into bone adaptation signals [10,11] triggering microstructural and material modifications through osteoblast and osteoclast activity. Thanks to the development of micro-computed tomography (micro-CT), the trabecular bone microarchitecture has been extensively studied. New histomorphometric indicators are now available to characterize bone pathology and remodeling process [12,13]. However, developing knowledge of the mechanical behaviour of the trabecular bone tissue, i.e., the effective material constituting the trabecular bone is still a challenging issue.

Trabecular bone mechanical properties can be studied on two different scales. On a macroscopic scale, the compression of a trabecular bone sample is characterized by a three-stage stress-strain curve composed of the following parts:

- a linear elastic regime that corresponds to cell edge deformation;
- an ultimate yield stress followed by a plateau corresponding to cell collapse due to fracture of trabeculae and;
- the densification stage [14].

Clearly, macroscopic mechanical parameters such as Young's modulus and ultimate yield stress, which take into account both the microarchitecture and trabecular bone tissue properties, depend on anatomic location and function [15]. However, in all cases macroscopic mechanical properties of the trabecular bone are weaker than mechanical features of the trabecular bone tissue [16].

An alternative approach to direct measurements at the tissue level is to use micro- finite-element models derived from micro-computed tomography (micro-CT) imaging. This approach combines experimental results obtained at the sample level with large finite-element computations to