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Statement of Competing Interests: No Competing Interests

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Abstract

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 (±S.D.) 80±11.7 years from hospitals of Assistance Publique-Hôpitaux de Paris (APHP) 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 performed 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.

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 micro-tomographique par rayons X et d'une analyse par la méthode des micro-éléments finis: i) Détermination directe du module d'élasticité macroscopique de l'os trabéculaire ; ii) Approche inverse pour déterminer les propriétés mécaniques du tissu trabéculaire.

Patients: 35 femmes et 7 hommes d'âge moyen (±D.S.) 80±11.7 ans de l'Assistance Publique des Hôpitaux de Paris (APHP) diagnostiqués ostéoporotiques suite à une fracture de l'extrémité supérieur du fémur due à une chute.

Matériels et méthodes: Suite à une arthroplastie, des carottes osseuses ont étés extraites au sommet de la tête fémorale à l'aide d'un trépan. Une acquisition micro-tomographique par rayons X et une analyse des paramètres histomorphométriques ont ensuite été effectués. Par la suite, le comportement macroscopique de l'os trabéculaire a été déterminé par la méthode des micro-éléments-finis sur le logiciel Abaqus 6.9-2 ®. Un essai de compression longitudinal a ensuite été réalisé afin de mesurer le module d'élasticité macroscopique. Enfin une analyse inverse basée sur le comportement mécanique expérimental macroscopique combiné à la méthode des micro-élements-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 mais avec une limite élastique plus faible.

Conclusion: La méthode classique d'histomorphométrie combinée à une méthode inverse des micro-éléments-finis permet de remonter aux propriétés élastiques microscopiques de l'os trabéculaire.

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

1. 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 remodeling [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 (microCT), 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: i) a linear elastic regime that corresponds to cell edge deformation, ii) an ultimate yield stress followed by a plateau corresponding to cell collapse due to fracture of trabeculae and iii) 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 (microCT) imaging. This approach combines experimental results obtained at the sample level with large finite-element computations to calibrate effective properties of the tissue [17]. However, due to edge artefacts and microCT imaging treatments [18,19], most of these studies report low values of calibrated effective tissue moduli compared to experimental results. Two studies [20,21] on bovine tissue and one on a small number of cadavers [22] found values of trabecular bone tissue Young's moduli that are close to cortical values. Moreover, large finite-element analysis performed on trabecular bone samples using specific trabecular tissue elasticities obtained by nanoindentation technique gives a good approximation of the experimental Young's modulus value of bone sample [23,24].

The main objective of the present study is to assess the mechanical behaviour of the trabecular bone based on microCT imaging and micro-finite-element analysis. Therefore, two methods are detailed on a cohort of osteoporotic patients: i) direct determination of macroscopic elastic properties of the trabecular bone, ii) inverse approach to assess mechanical properties of the trabecular bone tissue.

2. Patients

Thirty-five females and seven males (forty-two subjects) mean aged (±S.D.) 80±11.7 years from hospitals of Assistance Publique-Hôpitaux de Paris (APHP) were included in this study. All subjects were diagnosed with osteoporosis following a femoral neck fracture due to a fall from standing. Fractured heads were collected during hip replacement surgery. Subjects with a medical history of neoplastic disease, a radiologic aspect compatible with a pathological fracture or a refusal to participate were excluded.

3. Materials and methods

3.1. Samples

Standardized bone cores of 7 mm diameter were removed from the femoral head's equator by a trephine in a water bath. The two extreme surfaces were polished (grit #1200) to obtain a fresh, standard, cylindrical sample of human trabecular bone with a mean radius of 3.5 mm and a mean length of 8.7 mm as depicted in Figure 1a.

(FIGURE 1)

3.2. MicroCT imaging

Standardized bone cores were placed into a cryotube (10 mm inner diameter and 86 mm length) filled with phosphate-buffered saline (PBS) solution to prevent desiccation. The tubes were set onto a brass spigot made to fit cryotubes and were examined with a Skyscan 1172 microCT (Skyscan, Aartselaar, Belgium) using the cone-beam method. Projection images on the CCD

camera were obtained at 60 kV and 100 μA with a 0.5-mm aluminium filter at 35x magnification for which the voxel size was 8 microns in all three spatial directions. A 0.25° rotation was applied between successive image acquisitions to provide a series of 720 projection images. From this series of projection images, a stack of 2D sections was reconstructed for each bone sample (Figure 1b) and stored as .bmp files with indexed grey levels ranging from 0 (black) to 255 (white). The number of sections needed for the entire core height was close to 1100. 3D reconstruction and analysis was performed using microCT results in CTan software. NRecon (v.1.6.6, Skyscan) and CT-analyser (v.1.12, Skyscan) and bone volume fraction (BV/TV) was then determined.

3.3. Finite-element meshing

For each sample, a finite-element mesh was generated based on the images acquired during initial microCT. A special treatment was performed on the microCT images to carefully build an accurate tetrahedral finite-element mesh that was representative of the sample's microarchitecture. First, the micro-scanned images were converted to an exploitable 8-bit image format in axial slices with 256 grey-levels as the procedure described in Figure 2. The images were then smoothed using a 3D median filter to reduce the noise generated during image acquisition (Figure 2a). Afterwards, the images with 256 grey levels were segmented (Figure 2b) using a threshold defined as the minimum of the %pixel on grey-level histogram of all slices [25,26]. All voxels with a grey level higher than the defined threshold were considered to represent bone. Subsequently, a 3D surface mesh based on the segmented images was generated by the software Avizo fire® (Figure 2c). Because the initial large number of edges was not directly exploitable, a simplified model of the surface contour was built. (Figure 2d). The last step is the creation of a finite-element mesh of the 3D volume using tetrahedral elements (Figure 2e). All islands formed by unconnected regions of the mesh were deleted prior to mesh

generation. This procedure led to a mesh composed of approximately 250 000 nodes and 800 000 elements on average.

(FIGURE 2)

3.4. Mechanical compression test

After acquisition of the histomorphometric parameters, each sample was placed horizontally into a customised micro-compression device [27,28] run by the software LabVIEW 7.1® to load the cylinder along its long axis. A preload of 10 N was applied to immobilize the sample. In the first step, a compression loading-unloading cycle (10N-60N) was applied at constant velocity (1 µm/s). Then, the compression test was performed until the plastic stress plateau was reached; this was followed by an unloading step. The force-displacement curves were recorded at a rate of one point per second to determine the experimental macroscopic Young's Modulus E_s^{exp} during the unloading step as depicted in the right hand side of the Figure 1c. Afterwards, the cylindrical sample was placed back into the tube sample holder to undergo a second microCT acquisition.

3.5. Macromechanical finite element analysis

For the purpose of this study, finite-element simulations were performed using the software Abaqus 6.9-2 ®. The constitutive law used for bone tissue was isotropic, linear-elastic/ideally-plastic and characterised by three parameters: the Young's modulus E_{Tr}, the Von Mises yield Stress σ_{Tr} and Poisson's ratio υ_{Tr}. The subscript Tr corresponds to the trabecular tissue to contrast with the subscript s characterizing the sample macroscopic values. Poisson's ratio was set to the regular value of 0.3 [19]. The Young's modulus E_{Tr} for trabecular bone tissue corresponds to a full filled trabecular bone sample, i.e. BV/TV =100%. Micro- finite-element

205 simulations were performed with a bone tissue Young's modulus $E_{Tr} = 20$ GPa for the linear
206 elastic/ideally plastic behaviour law usually given for cortical bone in the literature. Boundary
207 conditions were defined to reproduce the boundary conditions of the experimental compression
208 test in a realistic manner. A uniform displacement was imposed on nodes located on the
209 sample's top axial surface in the bone core axis. Displacements and rotations of the nodes
210 located on the opposite (bottom) axial surface were blocked in the bone core axis direction.
211 After the finite element analysis of the axial compression test, the macroscopic stress-strain
212 curve enabled the determination of the macroscopic Young's modulus E_s^{num} of the trabecular
213 bone sample (Figure 1d).

214 3.6. Inverse micro-finite-element method
215

216 Based on finite element analysis, the trabecular bone tissue modulus E_{Tr} and yield stress σ_{Tr}
217 were determined using an inverse method already detailed in several studies [17,22]. In this
218 method, trabecular bone tissue properties were obtained by calibrating the mechanical
219 behaviour-law parameters of the micro-finite-element model to match the sample's
220 macroscopic experimental measurements (Figure 1c-d).

221 In a first numerical step using micro-finite-element analyses, compression tests were simulated
222 with an arbitrary tissue modulus of 20 GPa. The macroscopicYoung's moduli of specimens
223 E_s^{num} were extracted from their numerical stress-strain curves. As the macroscopic Young's
224 modulus varies linearly with trabecular bone tissue modulus in the elastic domain, the trabecular
225 bone tissue modulus E_{Tr} can be derived directly as the ratio between the experimental and
226 numerical macroscopic Young's modulus of the sample E_s^{exp} and E_s^{num} as expressed by the
227 equation (1).

$$E_{Tr} = 20 \times \frac{E_s^{exp}}{E_s^{num}} \quad (1)$$

In a second numerical step, the specific-subject trabecular tissue Young's modulus E_{Tr} previously determined from linear analyses was used in each simulation. The value of the trabecular tissue yield stress σ_{Tr} was then calibrated to reproduce the nonlinearity observed on the macroscopic experimental force-displacement curves. Calibration was performed with a manual trial-and-error procedure.

3.7. Statistical analysis

Successive linear regressions were performed to assess possible correlations among the different studied parameters. A value of α=0.05 was used as the threshold of statistical significance. Every result with $p<0.05$ was considered to be statistically significant. All statistical analyses were performed with the freeware R 2.13.2.

4. Results

4.1. Experimental macroscopic mechanical behaviour assessment

For the forty-two bone specimens BV/TV mean value was 22±4.6% with a range from 14.5% to 32.1%.

For each subject, macroscopic Young's modulus E_s^{exp} and yield stress σ_s^{exp} were measured on the load deflection curve of the micro-compression test. The mean (±S.D.) value of macroscopic Young's modulus E_s^{exp} measured for the forty-two bone specimens was 1.55±0.67 GPa with a range from 0.43 MPa to 3.02 GPa. The mean (±S.D.) yield stress σ_s^{exp} was 4.8±2.41 MPa with a range from 1.46 MPa to 12 MPa.

No significant linear correlations between any macroscopic mechanical parameters and age was found (R^2=0.0045 and p=0.7 for E_s^{exp} vs. age, R^2=0.0273 and p=0.3 for σ_s^{exp} vs. age). However, the macroscopic Young's modulus and stress yield σ_s were significantly correlated with bone volume fraction (R^2=0.5779 and p<0.05, R^2=0.4955 and p<0.05, respectively), see Figure 3.

(FIGURE 3)

4.2. Numerical macroscopic mechanical behaviour assessment based on microCT images

From the numerical test, macroscopic Young's modulus E_s^{num} was determined. The results are depicted in Figure 4 and compared to the experimental Young's modulus E_s^{exp} determined previously. The mean (±S.D.) value of the macroscopic Young's modulus E_s^{num} obtained from the simulation for the forty-two bone specimens was 1.71±0.71 GPa with a range from 0.6 GPa to 3.5 GPa. The Young's modulus obtained from the experimental tests and the simulations were comparable (p=0.3).

(FIGURE 4)

Linear correlations between the numerical macroscopic Young's modulus E_s^{num} and either age or bone volume fraction BV/TV was also investigated. No significant linear correlation with age was found (R^2=0.0045 and p=0.7). However, E_s^{num} was significantly correlated with bone volume fraction (R^2=0.6195, p<0.05) as depicted in Figure 5.

(FIGURE 5)

4.3. Trabecular bone tissue Young's modulus and yield stress assessment based on microCT images and experimental compression test

4.3.1. Trabecular bone tissue modulus using an inverse method

The results of the simulations (E_s^{num}) and the experimental tests (E_s) were implemented into equation (1). Mean (±S.D.) value of 18.92±5.43 GPa with a range from 9 GPa to 29 GPa for the trabecular bone tissue modulus E_{Tr} was computed for the forty-two bone specimens (Figure 6).

(FIGURE 6)

4.3.2. Trabecular tissue yield property using nonlinear micro-finite-element analyses

The mean (±S.D.) value of trabecular bone tissue yield stress σ_{Tr} for the forty-two specimens was 86.5±16.51 MPa with a range from 65 MPa to 160 MPa (Figure 6).

5. Discussion

In this study, trabecular bone samples of forty-two subjects diagnosed with osteoporosis following a femoral neck fracture due to a fall from standing were analyzed. Macroscopic and microscopic mechanical properties were investigated using micro-finite-element analysis coupled to an inverse approach. This method assess how macroscopic and microscopic mechanical properties of trabecular bone can be determined based only on its microarchitecture. The determination of the trabecular bone tissue elasticity by this method has been reported in numerous studies, but to our knowledge only one has used this approach to assess the Young's modulus of trabecular bone specimens from women with and without femoral neck fractures

[29]. Computed numerical macroscopic Young's modulus and yield stress are significantly correlated with bone volume fraction and comparable to the experimental measurements. Trabecular bone tissue Young's modulus mean value is consistent with experimental measurements from nanoindentation technique found in the literature. Moreover, this method shows how to identify the trabecular bone tissue yield stress to reproduce the nonlinearity observed on the macroscopic experimental force-displacement curve. Altogether in accordance with the literature, results of this study show that the elasticity of the trabecular bone tissue is similar to that of healthy one but with the yield stress lower than in cortical tissue.

At the macroscopic scale, the mean (±S.D.) value of bone volume fraction for the forty-two specimens was 22±4.6% with a range from 14% to 32%, which is in good agreement with several studies [23,30]. Moreover, macroscopic Young's modulus and yield stress were significantly correlated with bone volume fraction. As described previously in other studies, bone volume fraction was relevant to quantify bone quality [31]. From a mechanical point of view, whole bone properties strongly vary between anatomic sites [15]. Indeed, bone quality is greater for human proximal tibial bone than for the human greater trochanter. For instance, trabecular bone retrieved from the ilium, which is not a common site of fragility fractures, differs completely from trabecular bone extracted from the femoral head. In this context, exact values of the mean macroscopic mechanical parameters are difficult to compare, and we can only claim that our experimental and numerical results are of the same order of magnitude as values found in the literature [23,32,33].

Macroscopic mechanical property of trabecular bone can be determined based only on its microarchitecture. Linear elastic finite-element analysis, with homogeneous mechanical behaviour of trabecular tissue, performed on high-resolution microCT images converted into a micro-finite-element mesh provided the relationship between bone stress and bone strain. This method was also validated by Chevalier *et al.* [20] and recently by Wolfram *et al.* [24], who

directly used microscopic Young's modulus obtained from nanoindentation measurements in finite-element computations. Likewise in our study, numerical and experimental macroscopic elasticities were quite comparable. Nevertheless, several studies have investigated the effect of heterogeneous mineral distributions on the mechanical response [34–39] leading to non-homogeneous mechanical parameters distribution. They showed that "mineral heterogeneity has only a minor influence on the macroscopic elastic properties of human cancellous bone". Therefore, it is reasonable to assume homogeneous mechanical behaviour of trabecular tissue.

In this study, microscopic mechanical properties of trabecular bone are determined by an inverse approach based on the whole trabecular bone's mechanical response and micro-finite-element analysis as first used by Rietbergen *et al.* in 1995 [17]. Since that study, the determination of trabecular bone tissue elasticity by this method has been reported in numerous studies, but to our knowledge only Homminga *et al.* [29] used this approach to assess the Young's modulus of trabecular bone specimens from women with and without femoral neck fractures. In this study, Homminga *et al.* concluded that no significant difference in the elasticity of trabecular tissue between osteoporotic and healthy specimens was observed, and they determined a Young's modulus value of 10 GPa. This result, two times less than cortical bone values, was in concordance with several studies based on this method [35,40,41] but in direct contradiction with experimental measurements performed by ultrasonic and nanoindentation techniques. To explain the very low values obtained using the micro-finite-element method, several authors highlighted the end artefacts, the boundary conditions of the simulation and the thresholding method [42,43]. Especially, the global threshold value chosen can greatly influence the finite-element analysis through the estimation of bone volume fraction [44], which has been shown to be correlated with macroscopic mechanical behavior and relevant to quantify bone quality [31]. Studies that successfully eliminated these artefacts found modulus values similar to the values for cortical bone [21,22]. In the present study to avoid the mentioned

349 artefacts, the whole experimental bone sample was meshed, boundary conditions that simulate
350 experimental conditions were applied and an automatic threshold described by Chappard *et al.*
351 [25] was used. Application of this method to samples from osteoporotic patients gave a mean
352 (±S.D.) trabecular bone tissue Young's modulus of 18.92±5.43 GPa. This value is almost two
353 times greater than results obtained by Homminga *et al.* [29] on a similar population, but very
354 close to experimental measurements from nanoindentation technique. For instance, Turner *et*
355 *al.* [45] retrieved trabecular bone tissue Young's moduli from the distal femoral condyle using
356 ultrasonic and nanoindentation techniques of 17.5 GPa and 18.14 GPa, respectively. Also,
357 femoral cortical bone microscopic Young's moduli in the transverse and longitudinal directions
358 were 15-17 GPa and 21-24 GPa, respectively due to the anisotropy [45,46]. Therefore, the
359 consensus today is that the elastic modulus of trabecular bone tissue is similar to that of cortical
360 bone. Altogether, this results indicate that osteoporotic population trabecular bone tissue
361 elasticity is fully comparable to those of healthy population.

362 Microscopic trabecular bone tissue yield stress identification for the elastic/ideally-plastic
363 behavior law can be performed with a manual trial-and-error procedure on an inverse micro-
364 finite-element analysis. Since, yield stress due to trabecular bone tissue damage is difficult to
365 assess, Bayraktar *et al.* [22] were the first to propose this method on elderly trabecular bone
366 samples and found a mean (±S.D.) value of 84.9±11.2 MPa in compression. The authors
367 concluded that compressive and tensile yield stress was higher by 20-30 % for cortical bone in
368 [22,47]. In the present study, the mean (±S.D.) value of the yield stress on an osteoporotic
369 population was 85.6±16.7 MPa, which also indicates that the yield stress of osteoporotic
370 trabecular bone tissue is lower compared to healthy cortical tissue.

371

372 **6. Conclusion**

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In conclusion, a study of forty-two patients with fractured femoral necks was undertaken to evaluate the mechanical behaviour of trabecular bone in the femoral head at different scales. At the macroscopic scale, the bone volume fraction plays an important role in the determination of bone quality. Macroscopic mechanical property of trabecular bone can be determined based only on its microarchitecture by high-resolution microCT images and micro-finite-element analysis. The method gives macroscopic trabecular bone Young's modulus comparable to experimental results. Microscopic mechanical properties of trabecular bone can be assessed by an inverse approach based on the whole trabecular bone's mechanical response and micro-finite-element analysis. The results obtained by this method support the hypothesis that osteoporotic population trabecular bone tissue elasticity is comparable to those of healthy population. However, it indicates that the yield stress of osteoporotic trabecular bone tissue is lower compared to healthy cortical tissue. Consequently, micro-finite-element analysis can be used as an additional method to classical histomorphometric analysis in order to characterize bone quality by macroscopic and microscopic trabecular bone mechanical properties identification. The framework presented in the current study is suitable to assess bone biomechanical performance from patients with osteoarthritis or those undergoing treatment with anti-resorptive agents.

Acknowledgements

The support of the research project: BIOPRO Grant ANR-08-BLAN-0169 and Equipex IVTV Grant ANR-10-EQPX-06-01 are acknowledged. The authors gratefully acknowledge Didier Hannouche, and Frederic Zadegan for their Helpful discussions.

Conflicts or disclosures

Romain Rieger, Jean Charles Auregan and Thierry Hoc declare that they have no conflict of interest.

Figures legend

Figure 1 : Schematic approach for the estimation of the trabecular bone microscopic and mechanical properties using micro-finite-element methods. (a) Bone retrieval procedure and imaging, (b) finite-element meshing and trabecular bone tissue linear elastic/ideally plastic behaviour law definition, (c) experimental compressive test performed at the sample scale, and (d) Finite element compressive test. E_s^{exp} : Experimental macroscopic Young's modulus ; E_s^{num} : Numerical macroscopic Young's modulus ; σ_s^{exp} : Experimental macroscopic yield stress ; σ_s^{num} : Numerical macroscopic yield stress ; Y_s : Maroscopique ultimate compressive stress ; E_{Tr} : Trabecular bone tissue Young's modulus ; σ_{Tr} : Trabecular bone tissue yield stress.

Figure 2 : Finite element meshing process from microCT images in 8 bits format (256 grey levels) performed on Avizio Fire®. (a) Smothing using 3D median filter; (b) Segmentation by defining a threshold; (c) 3D surface mesh generation (4.10^7 facets); (d) 3D surface mesh simplification (400 000 facets); (e) 3D tetrahedral meshing (250 000 nodes and 800 000 elements).

Figure 3 : Evolution of the macroscopic mechanical parameters versus bone volume fraction BV/TV. E_s^{exp} corresponds to the macroscopic Young's modulus and σ_s^{exp} to the yield stress.

Figure 4 : Macroscopic Young's modulus E_s from experimental test compared to the one obtained from micro-finite-element analysis E_s^{num} with a default trabecular bone tissue Young's modulus of 20 GPa.

Figure 5 : Evolution of macroscopic Young's modulus E_s^{num} versus bone volume fraction BV/TV.

Figure 6 : Trabecular bone tissue Young's modulus E_{Tr} and yield stress σ_s obtained from inverse micro-finite-element analysis.

Légendes des figures

Figure 1 : Schéma décrivant l'aproche de determination des propriétés mécaniques microscopique et macroscopique à l'aide de la méthode des micro-éléments-finis. (a) Extraction des échantillons osseux et imagerie, (b) maillage éléments-finis et loi de comportement linéaire élastique/plastique parfait, (c) Essai de compression expérimentale sur l'échantillon, and (d) Essai de compression par éléments-finis. E_s^{exp} : Module de young macroscopique experimental ; E_s^{num} : Module de young macroscopique numérique ; σ_s^{exp} : Limite d'élasticité macroscopique experimental ; σ_s^{num} : Limite d'élasticité macroscopique numérique; ; Y_s : Contrainte limite

macroscopique en compression ; E_{Tr} : Module d'élasticité du tissu osseux trabéculaire ; σ_{Tr} : Limite d'élasticité du tissu osseux trabéculaire.

Figure 2 : Maillage éléments finis obtenus par micro-tomographie aux rayons X au format 8 bits (256 niveaux de gris) réalisé à l'aide du logiciel Avizio Fire®. (a) Lissage à l'aide d'un filtre médian ; (b) Segmentation par seuillage ; (c) Génération d'un maillage surfacique 3D (4.10^7 faces) ; (d) Simplification du maillage surfacique 3D (400 000 faces) ; (e) Maillage tétraédrique 3D (250 000 nœuds and 800 000 éléments).

Figure 3 : Evolution des paramètres mécaniques macroscopiques en fonction de la fraction volumique BV/TV. $\mathbf{E_s^{exp}}$ correspond au module d'élasticité macroscopique et $\boldsymbol{\sigma_s^{exp}}$ à la limite d'élasticité.

Figure 4 : Module d'élasticité macroscopique $\mathbf{E_s}$ obtenue lors de l'essai expérimental et comparé à celui obtenu à l'aide de l'analyse par micro-éléments-finis $\mathbf{E_s^{num}}$ simulé avec un module d'élasticité local de 20 GPa.

Figure 5 : Evolution du module d'élasticité macroscopique $\mathbf{E_s^{num}}$ en fonction de la fraction volumique BV/TV.

Figure 6 : Module d'élasticité $\mathbf{E_{Tr}}$ et limite d'élasticité $\boldsymbol{\sigma_s}$ du tissu trabéculaire obtenu par la méthode inverse d'analyse par micro-éléments-finis.

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