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The effective elastic properties of human trabecular bone may be approximated using micro-finite element analyses of embedded volume elements

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Abstract Boundary conditions (BCs) and sample size affect the measured elastic properties of cancellous bone. Samples too small to be representative appear stiffer under kinematic uniform BCs (KUBCs) than under periodicity-compatible mixed uniform BCs (PMUBCs). To avoid those effects, we propose to determine the effective properties of trabecular bone using an embedded configuration. Cubic samples of various sizes (2.63, 5.29, 7.96, 10.58 and 15.87 mm) were cropped from μCT scans of femoral heads and vertebral bodies. They were converted into μFE models and their stiffness tensor was established via six uniaxial and shear load cases. PMUBCs- and KUBCs-based tensors were determined for each sample. "In situ" stiffness tensors were also evaluated for the embedded configuration, i.e. when the loads were transmitted to the samples via a layer of trabecular bone. The Zysset–Curnier model accounting for bone volume fraction and fabric anisotropy was fitted to those stiffness tensors, and model parameters ν_0 (Poisson's ratio) E_0 and μ_0 (elastic and shear moduli) were compared between sizes. BCs and sample size had little impact on ν_0. However, KUBCs- and PMUBCs-based E_0 and μ_0, respectively, decreased and increased with growing size, though convergence was not reached even for our largest samples. Both BCs produced upper and lower bounds for the in situ values that were almost constant across samples dimensions, thus appearing as an approximation of the effective properties. PMUBCs seem also appropriate for mimicking the trabecular core, but they still underestimate its elastic properties (especially in shear) even for nearly orthotropic samples.

Keywords Trabecular bone · Elastic properties · Boundary conditions · Micro-finite elements · In situ · Embedded configuration

1 Introduction

Osteoporosis is a widespread skeleton disease responsible for deleterious fractures in the elderly population (e.g. Hadji et al. 2013). Substantial direct and indirect social and economic costs are associated with those fractures, which emphasise the need for prevention and treatment of the osteoporotic disease. In this context, *in silico* medicine may prove an asset (Viceconti 2015). After all, homogenised FE (hFE) models can be used for diverse clinical applications such as the prediction of bone strength (Zysset et al. 2013), the evaluation of drug therapies (Keaveny et al. 2014), the optimisation of osteosynthesis procedures (Synek et al. 2015) or the prediction of the mechanical impact of osteoplasty (Maquer et al. 2016). In contrast to micro-finite element (μFE) analysis based on micro-computed tomography (μCT) images, hFE analysis—the current option to exploit clinical CT images—relies on averaged material properties of trabecular bone elements.

The elastic properties of representative volume elements (RVE) of trabecular bone may in turn be computed from μFE analyses using a homogenisation procedure (Hollister et al. 1991). The technique requires μCT data and sufficient computational resources, but allows multiple loading scenarios per sample without being affected by experimental damage artefacts. Homogenisation theory is more accurate for periodic porous composites than

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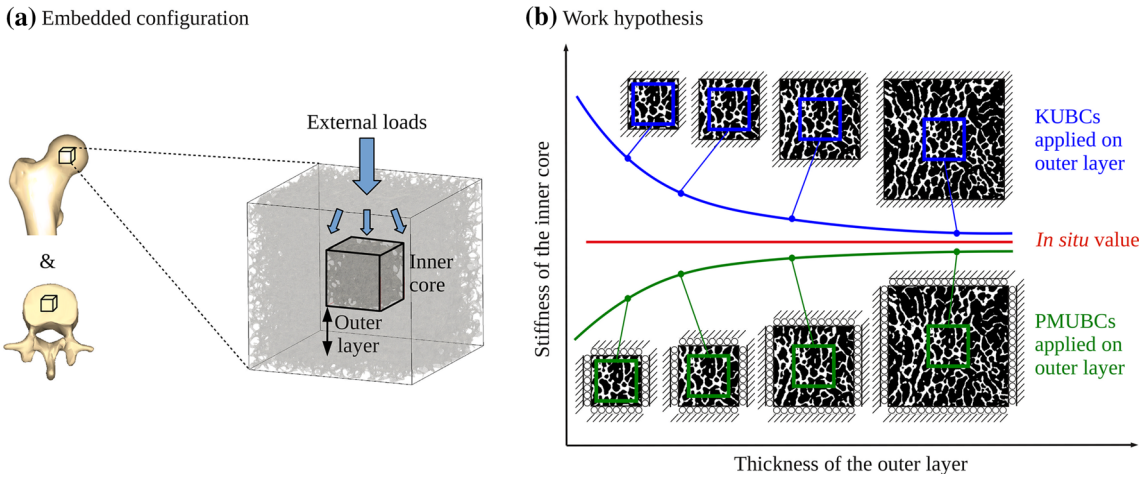

Fig. 1 **a** A large trabecular volume is cropped from the μCT scan of a vertebral body or a femoral head. It is turned into a μFE model on which loads are applied. The apparent stiffness of the inner core is then measured, the outer layer acting as a buffer transmitting the loads. **b** The boundary conditions (here KUBCs and PMUBCs) applied on the outer region still influence the stiffness of the core region. Our assumption is that the KUBCs- and PMUBCs-based stiffness of the core would converge towards the constant "in situ" value if the outer region were sufficiently large

standard approaches (Hollister and Kikuchi 1992). For non-periodic composites as trabecular bone, the Hill condition, equivalence between strain energy at macro- and micro-levels (Hill 1963), is only fulfilled for kinematic uniform (KUBCs: uniform displacements at the boundaries), static uniform (SUBCs: uniform tractions) and mixed uniform boundary conditions (MUBCs: combination of uniform tractions and displacements) (Hazanov and Amieur 1995; Ostoja-Starzewski 2006). More recently, Pahr and Zysset (2008) also proposed the periodicity-compatible MUBCs (PMUBCs) to mimic periodic BCs on nearly orthotropic structures.

The dimension of human bones often prevents the creation of RVEs and only apparent properties can be calculated for volumes of a non-periodic material that are too small to be representative (Hazanov and Huet 1994). Unlike the effective properties, the apparent ones are affected by the boundary conditions. Yet, a multitude of embedding approaches can smoothen this impact and relax the periodicity constraints (Böhm 2016). The idea is to measure the properties of a core region embedded in larger outer region on which loads are applied. The outer region acts as a buffer transferring the loads to the core in a more "natural" way. Although such analyses are commonly done for composites, we are not aware of its application to bone.

A size-dependent behaviour was also noted experimentally for foams (Lakes 1983; Hütter 2016), concrete (Syroka-Korol et al. 2013) and biological tissues (Choi et al. 1990) and also numerically for random matrix-inclusion composites (Ostoja-Starzewski 1998), periodic composites (Pecullan et al. 1999; Wang et al. 2009) and unidirectional fibre-reinforced composites (Jiang et al. 2001). This behaviour may be described by the micro-polar (or Cosserat) elasticity (Eringen 1999) as a dependence on the ratio of the dimension of the volume element to the characteristic length of its inner micro-structure (Wheel et al. 2015). Yet, it remains difficult to dissociate the influence of BCs and size on the apparent properties.

Using a randomly generated structure mimicking cancellous bone, Blöß and Welsch (2015) showed that KUBCs and SUBCs provided upper and lower bounds to PMUBCs-based elastic modulus. These bounds slowly converged towards the PMUBCs value with increasing sample size. In this work, the PMUBCs-based modulus was relatively unaffected by the sample size and was considered as a possible approximation of the effective modulus. However, this result might not hold for real bone morphologies.

We propose to use an embedding approach to determine the elastic properties of a trabecular region when loads are transmitted to the volume of interest via an outer layer of bone (Fig. 1a). Our hypothesis is that these apparent elastic properties actually converge towards "in situ" values if the outer layer gets sufficiently large (Fig. 1b). Then, using samples of different dimensions, the present study aims to establish the size dependency of the in situ, KUBCs- and PMUBCs-based elastic properties.

2 Materials and methods

2.1 Preparation of the samples

Micro-computed tomography (μCT) images (37 μm voxel size) performed on femoral heads and vertebral bodies were

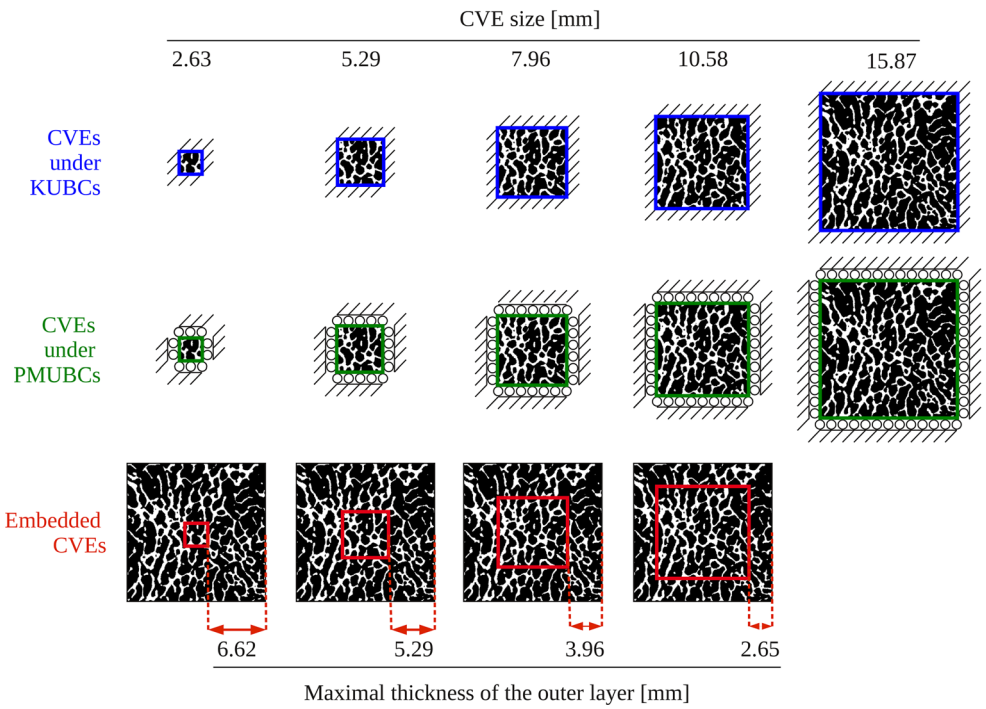

Fig. 2 One goal of the study is to verify our hypothesis for different CVE sizes. In situ, KUBCs- and PMUBCs-based apparent elastic properties were thus determined for four CVE sizes. In situ properties were in fact derived for CVEs embedded in larger and larger CVEs loaded under KUBCs and PMUBCs. The thickness of the outer layer of trabecular bone is thus progressively increased as described in Fig. 1. The maximal thickness reached for each CVE is also provided

obtained from two previous studies (Lochmüller et al. 2008; Marangalou et al. 2013). The donors had dedicated their body by testament to the Institute of Anatomy of the LMU in Munich or the Institute of Anatomy of the Amsterdam Medical Center (AMC) during life after ethics approval for the purpose of teaching and research. Seven trabecular biopsies were extracted from the vertebral scans (4 male and 2 female donors, 70 ± 6.5 years) and thirteen from the femoral ones (2 female donors, 81 and 95 years). Those twenty trabecular regions were segmented using a single-level threshold (Riedler and Calvard 1978) and the mean intercept length (MIL) (Whitehouse 1974; Harrigan and Mann 1984) was used to determine their fabric tensor. The images were then rotated to align the eigenvectors of the fabric tensor with the loading directions, as needed for PMUBCs (Pahr and Zysset 2008). After rotation, 20 cubic volumes of each size (2.63, 5.29, 7.96, 10.58 and 15.87 mm side length) were cropped and cleaned from unconnected bone regions (Fig. 2). BV/TV and degree of anisotropy (DA as ratio of the largest and the smallest eigenvalues of the fabric tensor) of each cube were finally evaluated. Because of morphological dissimilarities between samples extracted from vertebrae and femurs, two data sets were defined: the femur data set composed of 65 cubes (13 scans $\times$ 5 sizes) and the complete data set including 100 cubes from both vertebral and femoral sites. Please note that since some of our cubes are too small to be called RVEs, we rather used the term "CVE" for cubic volume element.

2.2 Computation of the KUBCs- and PMUBCs-based stiffness tensors

The first step was to conduct μFE analyses on the different sizes of CVE using KUBCs and PMUBCs (Fig. 2). To do so, we generated μFE models by converting bone voxels into linear hexahedral elements with isotropic elastic properties (elastic modulus $E = 10$ GPa, Poisson's ratio ν=0.3) (Pistoia et al. 2002). Marrow elements were not included in the μFE models to reduce the computing time and avoid convergence issues due to a high contrast of their stiffness to the stiffness of bone. Linear μFE analyses were performed via the ParOSol solver (Flaig 2012) with three uniaxial and three shear load cases conducted under KUBCs and PMUBCs as described in a previous study (Pahr and Zysset 2008), leading to 1200 simulations. The full stiffness tensors $\mathbf{S}^{\mathrm{KUBCs}}$ and $\mathbf{S}^{\mathrm{PMUBCs}}$ were derived from the μFE analyses via the apparent stresses and strains (Pahr and Zysset 2008) for each CVE.

2.3 Computation of the stiffness tensor of the CVEs in embedded configuration

The second step was to compute the stiffness tensors of the CVEs embedded in a larger volume. For that, we actually used μFE analyses performed on larger CVEs and simply focused on a region of the inner core (Fig. 2). This also

means that the loading in embedded configuration was not performed for our largest CVEs (15.87 mm).

Marrow was not included in the μFE analyses, although in principle, its deformation is necessary for the apparent strain calculation. This is a minor issue when BCs are applied directly on the boundary of the CVE as the a priori strains defined by the load case can be used in that case. However, we have no prior knowledge of the deformations occurring at the boundary of an embedded CVE (Fig. 1). Hence, we propose to estimate the deformation of a virtual marrow phase from those of the bone phase. The mean strains for a given CVE of side length L were determined as:

$$\begin{aligned}\langle\varepsilon_{ij}\rangle &= \frac{1}{V}\int_{\Omega}\frac{1}{2}\left(u_{i,j}+u_{j,i}\right)\mathrm{d}\Omega \\ &= \frac{1}{2V}\int_{\Gamma^*}\left(u_i n_j + u_j n_i\right)\mathrm{d}\Gamma^* \end{aligned} \tag{1}$$

where Γ^* is the boundary of the embedded CVE. The displacements (u) of a specified face (east, west, bottom, top, south and north, see Fig. 3a) were calculated as the mean displacements of the equally distributed existing bone nodes and virtual marrow points. The displacements for the marrow points $\bar{u}$ were interpolated based on the values from the closest bone nodes in each direction (Fig. 3b).

$$\bar{u} = \frac{1}{\sum N_i}\sum_{i=1}^{6} N_i u^i,\ N_i = \frac{1}{l_i} \tag{2}$$

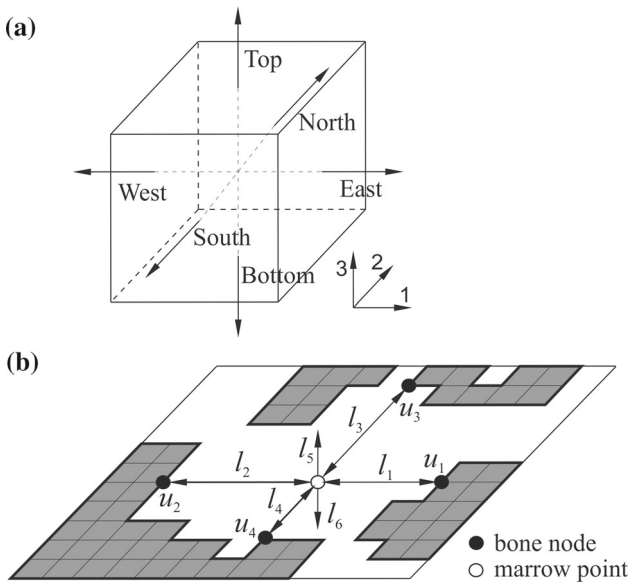

Fig. 3 Computation of the strains in the virtual marrow. **a** Faces of the CVE as described in Pahr and Zysset (2008), **b** the displacement $\bar{u}$ of the virtual marrow point are interpolated from the closest neighbouring bone nodes in east, west, north, south, top and bottom directions

In the eventuality of a missing bone node in a given direction, the a priori displacements of the point located on the outer face were used in the interpolation. If the a priori displacement component was not specified on the outer face either, the value in the opposite direction was then neglected.

For example, the average shear strain $\langle\varepsilon_{12}\rangle$ was derived as follow:

$$\begin{aligned}\langle\varepsilon_{12}\rangle &= \frac{1}{2V}\left[\int_{\mathrm{E+W}}\left({}^{\mathrm{E}}u_2 - {}^{\mathrm{W}}u_2\right)\mathrm{d}A\right. \\ &\quad \left. + \int_{\mathrm{N+S}}\left({}^{\mathrm{N}}u_1 - {}^{\mathrm{S}}u_1\right)\mathrm{d}A\right] \\ &= \frac{1}{2V}\left[\sum_{k=1}^{N}\left({}^{\mathrm{E}}u_2^k - {}^{\mathrm{W}}u_2^k\right)\Delta A\right. \\ &\quad \left. + \sum_{k=1}^{N}\left({}^{\mathrm{N}}u_1^k - {}^{\mathrm{S}}u_1^k\right)\Delta A\right] \end{aligned} \tag{3}$$

where $\int_{\mathrm{N+S}}\ldots$ is the integral of the displacements of the N square areas ΔA on the north and south face of the CVE. The displacements u^k of the kth square area were calculated as average from corner values of bone nodes and virtual marrow points. Finally, $\langle\varepsilon_{12}\rangle$ were computed based on the average displacements of the face $\langle u_k\rangle$:

$$\begin{aligned}\langle\varepsilon_{12}\rangle &= \frac{1}{2V}\left[\sum_{k=1}^{N}\left(\frac{{}^{\mathrm{E}}u_2^k}{N} - \frac{{}^{\mathrm{W}}u_2^k}{N}\right)N\Delta A\right. \\ &\quad \left. + \sum_{k=1}^{N}\left(\frac{{}^{\mathrm{N}}u_1^k}{N} - \frac{{}^{\mathrm{S}}u_1^k}{N}\right)N\Delta A\right] \\ &= \frac{1}{2L}\left[\sum_{k=1}^{N}\left(\frac{{}^{\mathrm{E}}u_2^k}{N} - \frac{{}^{\mathrm{W}}u_2^k}{N}\right) + \sum_{k=1}^{N}\left(\frac{{}^{\mathrm{N}}u_1^k}{N} - \frac{{}^{\mathrm{S}}u_1^k}{N}\right)\right] \\ &= \frac{1}{2L}\left(\left\langle{}^{\mathrm{E}}u_2\right\rangle - \left\langle{}^{\mathrm{W}}u_2\right\rangle + \left\langle{}^{\mathrm{N}}u_1\right\rangle - \left\langle{}^{\mathrm{S}}u_1\right\rangle\right) \end{aligned} \tag{4}$$

We conducted a verification analysis for twenty 3.44 mm CVEs embedded in 5.29 mm regions. For those, the marrow was explicitly modelled ($E_{\mathrm{marrow}} = 1\,\mathrm{MPa}$, $\nu_{\mathrm{marrow}} = 0.3$). The strain components resulting from volume average (two-material approach) and the virtual marrow method introduced in this section (only bone nodes were taken into account) were compared.

A stiffness tensor was computed for each embedded CVE using this new strain information and the elements' stresses resulting from the μFE analyses. However, those stiffness tensors still depend on the BCs applied on the outer boundaries ($\mathbf{S}_{\mathrm{embed}}^{\mathrm{KUBCs}}$ and $\mathbf{S}_{\mathrm{embed}}^{\mathrm{PMUBCs}}$). To understand and cancel this influence, we evaluated $\mathbf{S}_{\mathrm{embed}}^{\mathrm{KUBCs}}$ and $\mathbf{S}_{\mathrm{embed}}^{\mathrm{PMUBCs}}$ for various thicknesses of the outer region.

Table 1 Bone volume fraction (BV/TV) and degree of anisotropy (DA) for the different CVE sizes for the complete and femur data sets

CVE size (mm)	Complete data set		Femur data set	
	BV/TV	DA	BV/TV	DA
2.63	0.204 (±0.101)	1.63 (±0.20)	0.253 (±0.077)	1.59 (±0.15)
5.29	0.202 (±0.097)	1.60 (±0.19)	0.256 (±0.069)	1.61 (±0.19)
7.96	0.198 (±0.088)	1.59 (±0.18)	0.248 (±0.057)	1.62 (±0.19)
10.58	0.192 (±0.082)	1.58 (±0.17)	0.240 (±0.048)	1.62 (±0.18)
15.87	0.175 (±0.068)	1.53 (±0.14)	0.215 (±0.030)	1.56 (±0.13)

Average BV/TV and DA and their standard deviations decrease with increasing size

2.4 Computation of the in situ stiffness tensor

The third step was thus to relate each of the 9 independent components of $\mathbf{S}_{\text{embed}}^{\text{KUBCs}}$ and $\mathbf{S}_{\text{embed}}^{\text{PMUBCs}}$ to the thickness of the outer bony layer via two power laws (one for $\mathbf{S}_{\text{embed}}^{\text{KUBCs}}$, another for $\mathbf{S}_{\text{embed}}^{\text{PMUBCs}}$). These two laws were forced to converge towards a common value for a 30-mm-thick layer, which was assumed sufficient to suppress the impact of the outer BCs. This common value constituted the corresponding component of the in situ stiffness tensor ($\mathbf{S}^{\text{in situ}}$) that was then rotated according to the coordinate system of the fabric tensor (Gross et al. 2013).

2.5 Fitting of the Zysset–Curnier model to the stiffness tensors

At this point, it should be clear that $\mathbf{S}^{\text{KUBCs}}$, $\mathbf{S}^{\text{PMUBCs}}$ and $\mathbf{S}^{\text{in situ}}$ were computed for all the CVEs smaller than 15.87 mm (Fig. 2). In a last effort, we thus compared the dependency of those stiffness tensors on the CVE size.

A number of theoretical models were proposed to predict the elastic behaviour of trabecular bone from its morphology (Zysset 2003). Among them, the Zysset–Curnier model (Zysset and Curnier 1995) relates efficiently the stiffness tensor of a CVE to its best determinants: bone volume fraction (BV/TV) literally the amount of bone and fabric anisotropy reflecting its overall orientation distribution (Maquer et al. 2015). The parameters of the Zysset–Curnier model λ_0, λ_0', μ_0(shear modulus), k, l were fitted to the orthotropic representation of each stiffness tensor ($\mathbf{S}^{\text{KUBCs}}$, $\mathbf{S}^{\text{PMUBCs}}$, $\mathbf{S}^{\text{in situ}}$) via a multi-linear regression after log transformation (Gross et al. 2013; Panyasantisuk et al. 2015). The exponents k and l control the influence of BV/TV and fabric anisotropy, respectively. The values of E_0(elastic modulus) and ν_0 (Poisson's ratio) may be calculated based on λ_0, λ_0', μ_0. In the process, k and l were first determined simultaneously for all CVE sizes (2.63, 5.29, 7.96, 10.58 mm side length) and stiffness tensors ($\mathbf{S}^{\text{KUBCs}}$, $\mathbf{S}^{\text{PMUBCs}}$, $\mathbf{S}^{\text{in situ}}$) and then fixed to allow the direct comparison of λ_0, λ_0', μ_0, $E_0$and ν_0 across sizes and tensors. The confidence intervals of the parameters were also calculated.

For further use of the model, parameter sets were also determined individually for each size and stiffness tensor ("Appendix 1"). Comparisons with the literature are also presented in "Appendix 2". Convergence analyses were finally conducted after reducing the original finite element size from 37 to 18.5 µm to evaluate its impact on the fitted parameters and the Hill condition ("Appendix 3").

3 Results

3.1 Morphological information

A broad range of BV/TV [0.043-0.406] and DA [1.14-2.07] was obtained. The complete data set (BV/TV $= 0.194 \pm 0.089$) was less dense than the femur data set (BV/TV $= 0.242 \pm 0.060$), because it contains vertebral samples with low BV/TV. The complete group was slightly more isotropic (DA $= 1.59 \pm 0.018$) compared to the femur data set (DA $= 1.60 \pm 0.017$). For comparison, our largest study on the topic included samples from femur, radius and vertebra locations and featured a BV/TV of 0.15 ± 0.084 and a DA of 1.57 ± 0.28 (Gross et al. 2013). As shown in Table 1, BV/TV and DA were consistent across VE sizes. The lowest values of morphological parameters were observed for the largest CVEs, because they are the most heterogeneous and contain regions with low BV/TV as well.

3.2 Computation of the in situ stiffness tensor components

The strains of the embedded CVEs computed following the method described in Sect. 2.4 are almost equivalent to the usual two-material approach. The average relative difference of all strain components between these two methods are only 0.08 % (±0.91 %) when KUBCs were directly applied on the CVE and 0.46 % (±2.53 %) when PMUBCs were applied. Accordingly, $\mathbf{S}^{\text{in situ}}$ was extrapolated from $\mathbf{S}_{\text{embed}}^{\text{KUBCs}}$ and $\mathbf{S}_{\text{embed}}^{\text{PMUBCs}}$ as presented in Fig. 4 for few representative components. The components of $\mathbf{S}_{\text{embed}}^{\text{KUBCs}}$ were larger than those of $\mathbf{S}_{\text{embed}}^{\text{PMUBCs}}$. Both stiffness tensors were affected by the thickness of the surrounding trabecular layer, but the rate

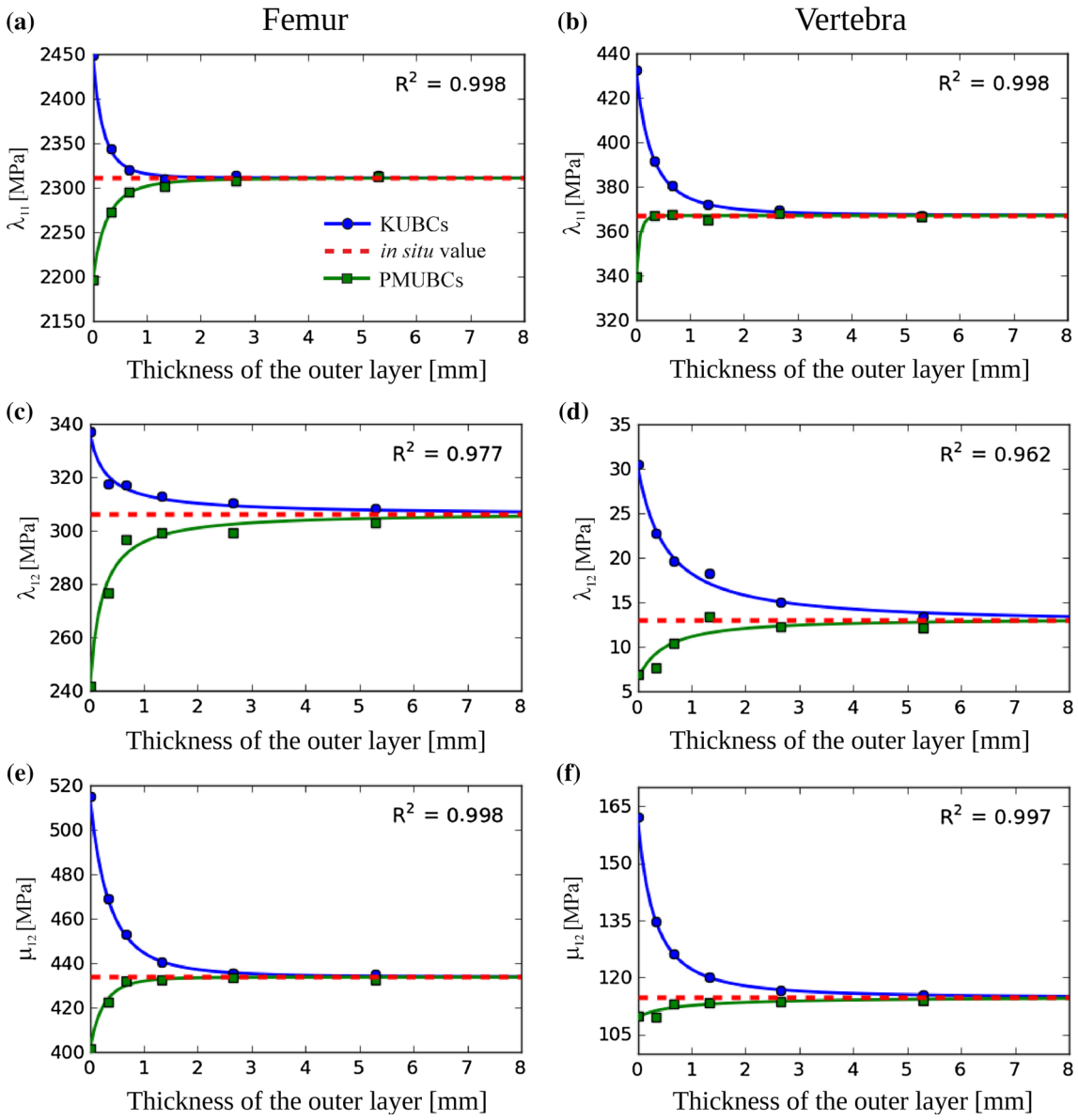

Fig. 4 Computation of the in situ stiffness tensor components. The in situ components of the stiffness tensor ($\mathbf{S}^{\text{in situ}}$) were computed as the asymptotic value towards which the components of the KUBCs ($\mathbf{S}^{\text{KUBCs}}_{\text{embed}}$)- and PMUBCs ($\mathbf{S}^{\text{PMUBCs}}_{\text{embed}}$)-based stiffness tensors converge. This example is displaying the convergence of the main normal component λ_{11} (**a**, **b**), the off-diagonal normal component λ_{12} (**c**, **d**) and the shear component μ_{12} (**e**, **f**) for 5.29 mm CVEs extracted from a vertebra and a femur

of decrease in the $\mathbf{S}^{\text{KUBCs}}_{\text{embed}}$ components was lower than the rate at which the $\mathbf{S}^{\text{PMUBCs}}_{\text{embed}}$ components increased. The power law curves describing the dependency of the stiffness to the layer's thickness fitted well the KUBCs and PMUBCs data ($R^2 > 0.95$).

3.3 Size dependency of the KUBCs, PMUBCs and in situ elastic properties

The exponents k (2.312) and l (1.313) were derived simultaneously for $\mathbf{S}^{\text{KUBCs}}$, $\mathbf{S}^{\text{PMUBCs}}$, $\mathbf{S}^{\text{in situ}}$ and all CVE sizes to evaluate their influence on the elasticity parameters (λ_0, λ_0', μ_0, E_0, ν_0). Despite this, the goodness of fit of the model to the μFE data was high for each size ($R^2_{\text{adj}} \sim 0.9$), even if lower R^2_{adj} were achieved with smallest CVEs (2.63 mm). The elasticity parameters under KUBCs, PMUBCs and in situ are provided for several CVE sizes in Table 2. Nevertheless, for both groups, all KUBCs and PMUBCs parameters (except ν_0) bounded the in situ values independently of the size. Except ν_0, KUBCs parameters decreased with growing size, while the PMUBCs ones (except λ_0) increased until 7.96 mm side length. Aside from the smallest CVEs, in situ

Table 2 Comparison of in situ, KUBCs- and PMUBCs-based elasticity parameters for different CVE sizes

CVE size (mm)	λ_0	λ_0'	μ_0	E_0	ν_0	R^2_{adj}
KUBCs, complete data set						
2.63	15,390	10,400	12,460	36,044	0.205	0.834
5.29	13,069	8028	9023	27,821	0.205	0.936
7.96	12,371	7504	8272	25,824	0.206	0.946
10.58	11,790	7066	7680	24,232	0.207	0.956
15.87	11,158	6808	7414	23,158	0.208	0.955
KUBCs, femur data set						
2.63	11,378	8605	9946	27,557	0.216	0.884
5.29	10,015	7337	8112	23,033	0.219	0.912
7.96	9753	7196	7783	22,135	0.221	0.914
10.58	9516	7121	7639	21,616	0.223	0.917
15.87	9301	7190	7760	2,1590	0.225	0.928
In situ, complete data set						
2.63	11,081	6283	5625	19,573	0.220	0.902
5.29	9957	5710	5389	18,269	0.216	0.942
7.96	10,011	5655	5321	18,221	0.215	0.940
10.58	10,091	5553	5170	18,057	0.214	0.940
In situ, femur data set						
2.63	8776	6594	6068	17,750	0.240	0.905
5.29	8380	6254	6000	17,443	0.235	0.923
7.96	8410	6169	6042	17,640	0.231	0.922
10.58	8593	6113	5926	17,632	0.230	0.932
PMUBCs, complete data set						
2.63	11,548	3944	3016	16,135	0.183	0.841
5.29	10,827	4414	3969	17,084	0.190	0.933
7.96	10,618	4591	4306	17,462	0.193	0.943
10.58	10,355	4468	4289	17,228	0.191	0.940
15.87	9819	4314	4226	16,623	0.191	0.928
PMUBCs, femur data set						
2.63	10,147	4537	4046	16,430	0.199	0.929
5.29	8898	4993	4794	16,361	0.213	0.948
7.96	8993	5176	5042	16,868	0.213	0.955
10.58	8982	5085	5072	16,989	0.210	0.950
15.87	8792	4891	5032	16,840	0.206	0.930

In this table, k (2.3116) and l (1.313) were fixed to allow the comparison

values were almost constant. Figure 5 better highlights the relative effects of the boundary condition and size on the parameters E_0, μ_0 and ν_0. The convergence of μ_0 and E_0 was relatively slow for KUBCs and not reached for the largest CVEs. The relative differences are greater for μ_0 than E_0, especially for PMUBCs. Boundary condition and size had, however, moderate influence on ν_0.

4 Discussion

The homogenisation procedure conducted on a sample too small to be representative provides apparent properties affected by boundary condition and sample size. In an attempt to better approximate the effective properties of cancellous bone, we proposed to load an inner volume via the surrounding trabecular bone.

Prior studies attempted to measure the properties of cancellous bone "in situ" (Un et al. 2006; Harrison and McHugh 2010), and the concept of "embedded configuration" is not new. However, to our knowledge, this is the first time such technique is used to determine the homogenised properties of trabecular bone. μFE analyses of six different loading scenarios were performed to obtain the in situ stiffness tensor instead of focusing only on the elastic modulus along a single loading direction. Consequently, our results are much

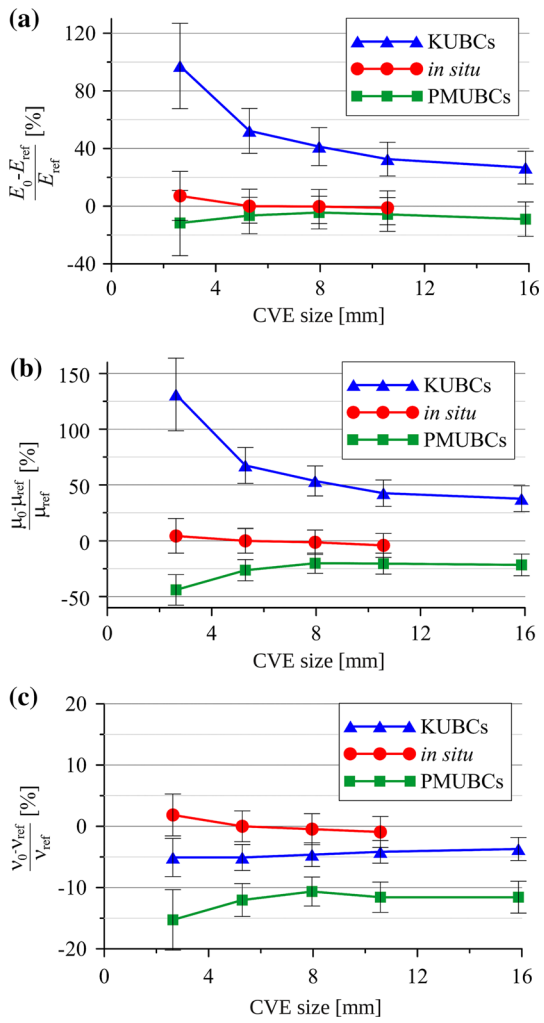

Fig. 5 Size dependency of the KUBCs, PMUBCs and in situ elastic properties. Elastic modulus (E_0), shear modulus (μ_0) and Poisson ratio (ν_0) computed for different CVE sizes on the complete data set are displayed relative to the in situ values of the 5.29 mm CVEs (E_{ref}, μ_{ref}, ν_{ref}). KUBCs- and PMUBCs-based E_0 and μ_0 bound the in situ values. BCs and CVE size have moderate impact on ν_0. The confidence intervals of the measures were also computed

more general and include the shear moduli, independently of BV/TV and anisotropy. Secondly, we proposed a technique to reduce the computation time and convergence issues during the calculation of the strains applied to the embedded CVEs by avoiding the explicit modelling of the marrow phase. This assumption should not affect our findings as marrow has low stiffness in comparison with bone, especially under quasi-static loading. Third, we ensured the robustness of our findings by using trabecular biopsies originated from two common fracture sites (femur, vertebral body) and featuring a broad range of density and morphology. Finally, we verified the consistency of our results with respect to the spatial discretisation of the solution by repeating a part of our analyses with a voxel mesh refined by a factor of two.

The size dependency of the apparent elastic properties was evaluated via four CVE sizes. Our results (Fig. 5; Table 2) confirm that in situ properties are essentially size independent beyond a minimum of 2 to 4 mm and that KUBCs-based properties converge slower with the CVE size than when PMUBCs are used (Jiang et al. 2001; Blöß and Welsch 2015). The size dependency of the KUBCs- and PMUBCs-based properties is a direct consequence of what happens at the boundary. Indeed, Fig. 4 shows that the effect of the boundary conditions is very localised and dissipates within 1 to 2 mm of bone. A similar effect (dubbed "side artefact" by the authors) was observed for cylindrical samples (Un et al. 2006; Bevill et al. 2007). Consequently, if the sample is smaller, the proportion of bone affected by the boundary conditions is larger and vice versa.

This work supports that PMUBCs are appropriate for mimicking the loading conditions of the trabecular core as suggested by Panyasantisuk et al. (2015). Other authors (Pahr and Zysset 2008; Blöß and Welsch 2015) inferred that PMUBCs were in fact the best boundary conditions for approximating the effective properties of cancellous bone regions. Nevertheless, PMUBCs-based properties slightly underestimate the in situ values even for our largest and nearly orthotropic CVEs. Furthermore, it is also worth noticing that the relative difference between the in situ and PMUBCs-based shear modulus is considerably larger than for elastic modulus. This finding is particularly important considering that bone yields more easily under shear. KUBCs, on the other hand, constrain the deformation of trabeculae near the faces of the RVE. This is somehow similar to the loading conditions near the cortical shell or a fully osseointegrated implant, except that a single face is usually constrained in those situations. "Real" elastic properties lay probably between in situ and KUBCs-based properties depending on both loading mode and stiffness of the surrounding tissue. This remains to be quantified in future works.

As we obtained the worst-fit and largest errors for the smallest 2.63 mm CVEs, our analysis concur with previous recommendations. Those should be of approximately 5 mm edge length to allow accurate calculation of the apparent elastic properties (van Rietbergen et al. 1995; Zysset et al. 1998). This size offers a good compromise between the computing resources needed for the μFE analyses and the relative homogeneity of the trabecular morphology (not achieved with smaller and much larger samples).

Several limitations should be highlighted. First, our complementary analyses ("Appendix 3") confirmed that the Hill condition is only approximately fulfilled for μFE analyses (Blöß and Welsch 2015). The lower difference between micro- and macro-level energy after mesh refinement indicates that this is mainly a discretisation issue of the FE

method, even if a dependence on BV/TV was also observed (Fig. 6). Nevertheless, the reduction in element size did not alter the relative influence of BCs and CVE size on the apparent elastic properties as all parameters were affected similarly (Table 6). Other shortcomings are related to our large CVEs. Those were extracted from real cancellous bone and there is no guarantee for the trabecular morphology to be analogous within the inner core and in the outer trabecular region (Harrison and McHugh 2010). As it is proved difficult to find large trabecular CVEs, only 20 biopsies were used, which is few compared to other studies (Gross et al. 2013; Panyasantisuk et al. 2015). Other relevant locations such as patella (Latypova et al. 2016) and distal radius (Gross et al. 2013) proved to be too small to extract sufficiently big volumes.

In this study, computational homogenisation of embedded trabecular regions was used to determine the in situ elastic properties of trabecular bone. Those were almost unaffected by the CVEs' dimensions and represent a close approximation of the effective properties. PMUBCs provide rather good, though lower, estimations of the in situ values, especially in shear. Similar analyses should be conducted beyond the linear range to provide more insights on the effective (BC-independent) yielding and failure behaviour of the trabecular structure.

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Compliance with ethical standards

Conflict of interest The authors have no conflict of interest to report.

Appendix 1

See Table 3.

Table 3 For further use of the Zysset–Curnier model, in situ, PMUBCs- and KUBCs-based elastic parameters were calculated independently for each CVE size on the complete data set

CVE size (mm)	λ_0	λ_0'	μ_0	k	l	R^2_{adj}
KUBCs						
2.63	4470	3021	3619	1.616	0.904	0.977
5.29	6351	3901	4384	1.903	1.093	0.972
7.96	6875	4170	4597	1.981	1.102	0.969
10.58	8413	5042	5480	2.126	1.124	0.963
15.87	10, 279	6272	6830	2.269	1.220	0.955
In situ						
2.63	9381	5318	4762	2.215	1.402	0.904
5.29	11, 318	6490	6126	2.385	1.336	0.943
7.96	11, 626	6567	6179	2.397	1.302	0.941
10.58	13, 238	7285	6783	2.465	1.289	0.943
PMUBCs						
2.63	29, 494	10, 074	7704	2.835	1.820	0.870
5.29	15, 692	6398	5753	2.519	1.543	0.940
7.96	15, 277	6606	6196	2.518	1.381	0.949
10.58	17, 623	7603	7300	2.609	1.369	0.950
15.87	18, 229	8009	7847	2.642	1.499	0.941

The high values of k and l were obtained for PMUBCs, confirming the large impact of BV/TV and anisotropy on elastic parameters for these BCs

Appendix 2

See Table 4.

Table 4 Zysset–Curnier model parameters computed under KUBCs and PMUBCs for 5.29 mm CVEs are compared with other works (Gross et al. 2013; Panyasantisuk et al. 2015)

Reference	Location	λ_0	λ_0'	μ_0	k	l	R^2_{adj}
KUBCs							
Present study	Femur, vertebra	3878	2382	2677	1.62	1.10	0.955
Gross et al. (2013)	Femur, vertebra, radius	4152	2932	2892	1.62	1.10	0.960
Present study	Femur	3649	2673	2956	1.60	0.99	0.967
Gross et al. (2013)	Femur	3841	3076	3115	1.60	0.99	0.983
Panyasantisuk et al. (2015)	Femur	3306	2736	2837	1.55	0.82	0.985
PMUBCs							
Present study	Femur	5027	2821	2708	1.91	1.10	0.935
Panyasantisuk et al. (2015)	Femur	5060	3353	3117	1.91	1.10	0.970

The values of k and l were taken from the corresponding literature to allow for direct comparisons. The good correspondence of our parameters with the literature data confirms the correctness of the applied methodology. The parameters λ_0, λ_0', μ_0 computed in this study are lower than values reported in the literature

Appendix 3

An extra analysis was performed on the complete data set after mesh refinement of the 2.63, 5.29, 7.96 and 10.58 mm CVEs. Each hexahedral finite element from the original mesh (37 μm size) was divided into eight smaller elements (18.5 μm size). The Zysset–Curnier model was then fitted to the KUBCs, PMUBCs and in situ stiffness tensors to evaluate the impact of the refinement (Tables 5, 6). To verify the impact of the mesh on the Hill condition, the average of the product of the stress and strain tensors for all elements (internal strain energy U_{micro}) and the product of the stress and strain averages (macro-level strain energy U_{macro}) were computed. The relative difference between U_{micro} and U_{macro} for 5.29 mm IVEs as a function of BV/TV is presented in Fig. 6.

Table 5 Zysset–Curnier model parameters calculated for 5.29 mm CVEs after mesh refinement

	λ_0	λ_0'	μ_0	k	l	R^2_{adj}
KUBCs	6462	3887	4407	1.943	1.120	0.972
In situ	11, 513	6431	6139	2.426	1.405	0.946
PMUBCs	16, 148	6448	5767	2.568	1.577	0.940

A small increase of k and l is noticeable

Table 6 Relative changes in the Zysset–Curnier model parameters after mesh refinement computed for constant $k = 2.3116$ and $l = 1.313$

CVE size (mm)	λ_0 (%)	λ_0' (%)	μ_0 (%)	E_0 (%)	ν_0 (%)
KUBCs					
2.63	−8.4	−10.1	−8.7	−8.2	−1.4
5.29	−7.7	−9.6	−8.8	−8.1	−1.1
7.96	−7.6	−9.5	−8.8	−8.1	−1.0
10.58	−7.6	−9.5	−8.9	−8.1	−1.0
In situ					
2.63	−5.8	−6.8	−7.6	−6.7	0.0
5.29	−5.7	−7.3	−7.5	−6.5	−0.6
PMUBCs					
2.63	−8.1	−8.0	−10.6	−9.1	0.8
5.29	−8.1	−10.0	−10.5	−8.9	−0.8
7.96	−8.0	−10.0	−10.3	−8.8	−0.8
10.58	−8.0	−10.0	−10.3	−8.8	−0.9

The relative difference is very consistent across CVE sizes and stiffness tensors

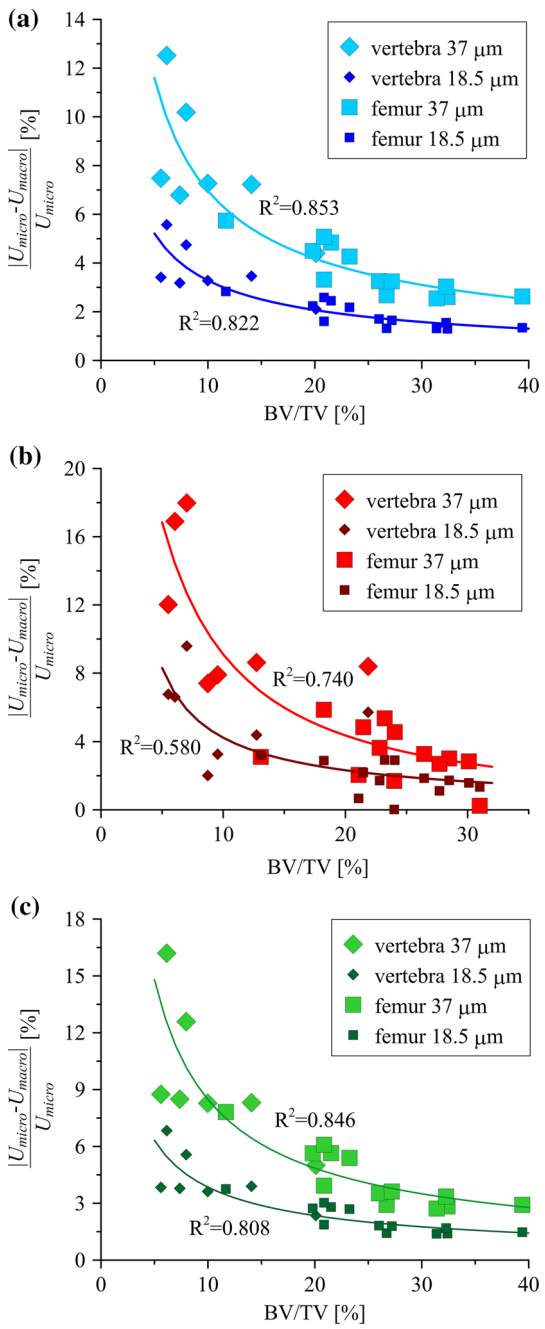

Fig. 6 Relative difference between internal strain energy U_{micro} and macro-level strain energy U_{macro} before and after mesh refinement as a function of BV/TV for **a** KUBCs, **b** in situ, **c** PMUBCs. The Hill condition is only approximately fulfilled. The difference between strain energy at macro- and micro-level decreases after mesh refinement and with increasing BV/TV

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