What is the recommended size of a Volume of Interest for cancellous bone? A skeleton-based study

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Cancellous bone; size effect; architecture; skeleton

1. Introduction

The study of the bone fracture is an important issue for osteoporosis and car safety. The behavior of cancellous bone is strongly linked to the micro-architecture, the strain rate (Prot et al. 2015), and the specimen size (Harrison & McHugh 2010).

Numerical models are used in order to simulate the viscoelastic behavior up to the point of fracture propagation in cancellous bone. Finite element method (FEM) models based on micro-CT scans are currently the most popular approach. However, the results are dependent on the specimen size and the mesh density, in addition to which the fracture analysis is time-consuming (Hambli 2013). Moreover, the variable architecture within a typical specimen limits the minimum sample size that will still provide reasonable architectural parameter values in comparison with the full specimen size. Indeed, a BV/TV variation up to 20% was found in the same specimen ($\phi = 7.85$ mm) (Stauber et al. 2014). Skeleton-based models have already shown a great potential for the efficient simulation of bone behavior and fracture. Cancellous bone geometry is based on nodes, beams, and plates (Stauber & Müller 2006), which is straightforward to implement from a skeleton.

In this study, the effect of the Volume of Interest (VOI) size, within a sample, on the evaluation of cancellous bone architectural parameters from the skeletonized model will be presented. The aim was to furnish recommendations for the sample size for further numerical simulations.

2. Methods

2.1. Specimens

In total, 126 non-defatted cylindrical cancellous bone specimens ($\phi = 10.5$ mm, $H = 7.5$ mm) were extracted from the proximal part of 6 bovine femurs in the three principal planes (sagittal, frontal, and transversal).

2.2. Architecture acquisition

A micro-CT scanner (Phoenix, voxel size 80^3 μm^3) was used to acquire the bone architecture. The cancellous bone was automatically segmented from marrow using the Otsu multi-threshold method. Then, the skeleton was thinned from the surface using Avizo software and the following architecture parameters were computed (Table 1).

2.3. VOI extraction

From the original specimen models, 11 VOI samples were extracted: 10 were equally radially distributed by maximizing the distance between the VOI centers while one was centered. The vertical positions were randomly generated. The VOI fraction varied from 20% up to 90% of the original specimen.

2.4. Statistical analysis

For each parameter, the difference between a sample and the original specimen was computed. The mean values of 1386 sample differences (126 specimens × 11 VOIs) were computed for each volume fraction.

3. Results and discussion

The influence of the volume fraction on the geometry, morphology, and connectivity is illustrated in Figure 1. A decrease was observed for all parameters with a decrease of the VOI ($p < 0.001$). Tb.Th, Conn.D, and Nd.Nd were the least affected parameters with a mean difference between −5 and 5%. For N.Tp and N.Qp, a mean difference lower than −5% was obtained for a minimum volume fraction lower than 40%. This is because the sampling procedure requires the removal of the beams transgressing the VOI boundary. Thus, the number of connections is reduced at the nodes close to the VOI surface. Taking into account the creation of termini during sampling may overcome this bias.

The volume fraction influence on the anisotropy is presented in Figure 2. The value associated with the main direction of the trabeculae, MIL1, was well conserved when the volume fraction

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Table 1. Computed parameters.

Family	Parameter	Description
Geometry and morphology	Tb.Th (mm)	Mean thickness of trabeculae
	Conn.D (mm^{-3})	Number of trabeculae per unit volume
	Nd.Nd (mm^{-3})	Average branch length per unit volume
Connectivity	N.Tp (mm^{-3})	Number of triple per unit volume
	N.Qp (mm^{-3})	Number of quadruple per unit volume
Anisotropy	MIL (mm)	Mean intercept length

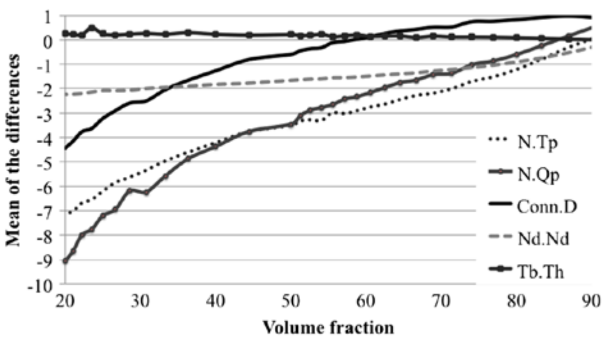

Figure 1. Effect of volume fraction on N.Tp, N.Qp, Conn.D, Nd.Nd, and Tb.Th.

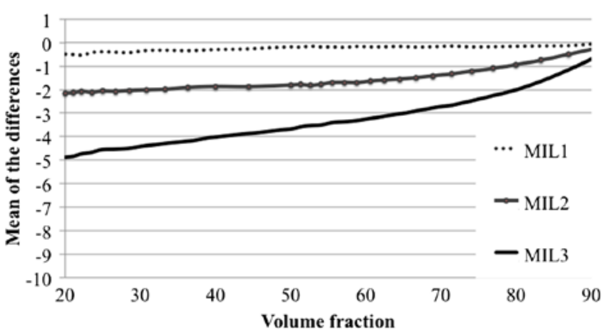

Figure 2. Effect of volume fraction on the mean intercept length.

decreased, with a difference less than 1%. The changes in each MIL are very similar, but they appeared bigger because of the difference in the original MIL values (MIL1 > MIL2 > MIL3).

Harrison and McHugh (2010) have shown a significant decrease of BV/TV when the sample diameter decreased with a constant aspect ratio. In particular, for a volume fraction of 53%, BV/TV decreased to 10%. In a first approximation, a decrease of BV/TV should be reflected in a decrease of Conn.D rather than Tb.Th due its small variation (<0.5%). However, Figure 1 shows a decrease of Conn.D of only 1%. The inhomogeneity of the limited set of 8 uniaxial specimens used by Harrison and McHugh 2010 may be responsible of the observed difference.

An accurate evaluation of BV/TV is important because it is strongly linked to the apparent Young's modulus (E_{app}) as evaluated using FEM simulations (Stauber et al. 2014). Thus, a small variation of BV/TV (and Conn.D) could adversely affect the simulation results. In order to reduce the effect of the volume of the sample on simulations, we assume a maximum mean difference of ±5% between the VOI and the original specimen. Thus, a volume fraction of 40% of the original specimen is representative of its skeleton architecture. For cancellous samples from bovine femurs, this implies a minimum representative size of $\phi = 7.7$ mm and $H = 5.5$ mm. This result concurs with a minimum specimen diameter of 7.5 mm recommended by (Linde et al. 1992) for experiments.

4. Conclusions

The VOI sample size has a significant effect on the evaluation of bone architecture parameters. In order to reduce the effect on simulations, the results presented in this study indicate that a sample size of $\phi = 7.7$ mm and $H = 5.5$ mm is adequate for bovine femoral cancellous bone.

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