TETRAHEDRAL MICRO-FE MODELS OF HUMAN TRABECULAR BONE: A COMPUTATIONALLY EFFICIENT ALTERNATIVE TO VOXEL MODELS?

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Introduction

Finite Element (FE) models of trabecular bone are often generated from micro-Computed Tomography (µCT) images to assess mechanical properties non-destructively. The most common approach is voxel-based FE modeling, where 3D voxels from µCT images are directly converted into hexahedral elements, with the drawback of a high computational cost for the FE solution. A more computationally efficient approach is tetrahedral FE modeling [1], less used due to the need of specifying meshing parameters and to the risk of elements distortion.

Ciclope is a fully open-source pipeline, written in Python, that can be used to preprocess µCT data to obtain a corresponding voxel or tetrahedral FE model (https://ormircommunity.github.io/packages.html) [2].

This study aims to corroborate with a convergence test the robustness of the tetrahedral meshing approach, and to test its comparability with the voxel approach.

Methods

From the core of 21 cylindrical trabecular bone samples (d=10 mm, h=20 mm) extracted from the femoral head of human subjects and imaged with µCT at 19.5 voxel size, we cropped 42 cylindrical sub-samples (d=5 mm, h=10 mm, BV/TV [8%-38%]).

Using the Ciclope workflow, we (i) inverted the images greyscale, (ii) segmented bone using a fixed threshold, and (iii) removed unconnected voxel clusters. Voxel meshes with 8-node hexahedral elements were generated at full resolution and solved.

The convergence test for 4-node tetrahedral meshes explored the effect of element edge size and element distortion through two parameters:

- max facet size = *mesh size factor* * voxel size
- max element circumradius = *a* * max facet size

in two steps: first an optimal *mesh size factor* was defined, keeping the max cell circumradius constant to a low value (*a* = 2); then, *a* was let vary from 4 to 2.

Bone was considered linear elastic and homogeneous: E = 18000 MPa and ν = 0.3. A static compressive condition was simulated, fixing all the bottom nodes of the samples and imposing a vertical displacement of 0.04 mm on the top.

The target result was Apparent Young's Modulus (E_{app})

- $E_{app} = (F_{tot}/A) / \varepsilon$

where F is the total reaction force, A the cross-sectional area, and ε the strain.

For each sub-sample, relative (i.e. with respect to the next finer mesh) and absolute (i.e. with respect to the most refined mesh) percentage of variation (RPV and APV, respectively) in E_{app} were used as convergence metrics, while differences with voxel mesh results were used to assess tetra-to-voxel comparability.

Results

Convergence study: pooling data from all samples, a maximum facet size of 1.5*voxel size showed a relative and absolute E_{app} variation < 2% (Figure1). To achieve a similar variation (< 2% in both RPV and APV) the '*a*' distortion parameter had to be set to 2.

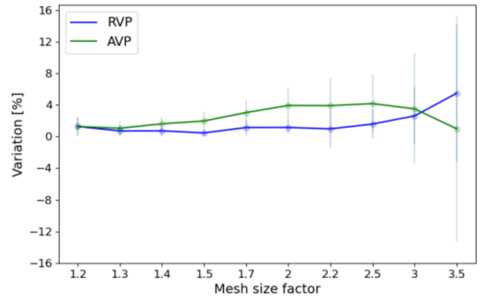

Figure 1: Convergence results of tetra models

Tetra-voxel comparison: Preliminary results on 20 subsamples indicate a strong correlation ($E_{app\text{-}tetra} = 1.07 * E_{app\text{-}voxel} + 13.47$, $R^2 = 0.99$), with tetrahedral models slightly overestimating E_{app} (11±3%) (Figure2).

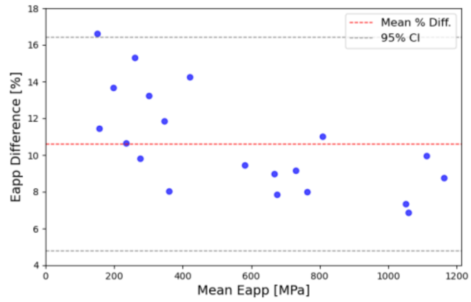

Figure 2: Bland-Altman plot of tetra-voxel variations

Discussion

Tetrahedral models built with mesh settings at 2% convergence drastically reduce computational cost (1/30 of nodes and 1/6 of elements) and are highly correlated with voxel models in E_{app} calculation. Future studies may explain the slight but consistent overestimation of $E_{app\text{-}tetra}$.

References

1. Megìas et al, CMPB, 219:106764, 2022
2. Iori et al., JOSS, 8:4952, 2023