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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 (μ CT) images to assess mechanical properties non-destructively. The most common approach is voxel-based FE modeling, where 3D voxels from μ CT 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 μ CT 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 μ CT 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 $\nu = 0.3$. 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})

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

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.

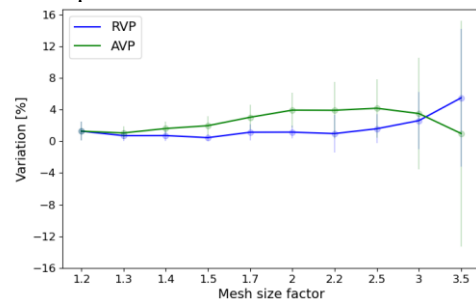


Figure 1: Convergence results of tetra models

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

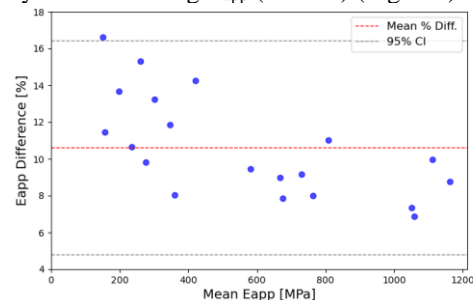


Figure 2: Bland-Altman plot of tetra-voxel variations

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 $E_{app-tetra}$.

References

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

