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Open trabecular bone microFE models from microCT images: Ciclope new release with higher performances and verified tetra mesh option

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Introduction

Finite Element (FE) models from micro-Computed Tomography (μ CT) images can non-destructively assess trabecular bone mechanics. To ensure reproducibility and foster cross-validation, we recently developed within the ORMIR[1] community an open-source μ CT-to-FE Python package, Ciclope [2].

Ciclope offers voxel-based and tetrahedral meshing options. Voxel-based meshing is the accepted gold standard but is usually computationally expensive and in the first Ciclope implementation had performance limitations, due to the direct sparse solver adopted [3]. Tetrahedral meshing is more efficient and flexible, but seldom used due to the lack of model verification, and validation against the gold standard.

We here propose to improve: (i) the efficiency of voxel-based models by enabling the integration of an iterative parallel solver (ii) verification of tetrahedral models by testing convergence to meshing parameters and comparability with voxel-based results in terms of apparent Young's modulus (E_{app}), a basic but important result of μ CT-based FE models of trabecular bone.

Materials and Methods

We introduced in the Ciclope pipeline ParOSol TU Wien [4], a parallel Octree-based solver, and implemented the conversion to HDF5 data format. Ciclope pipeline is briefly illustrated in Figure 1.

We processed in Ciclope forty-two cylindrical trabecular bone samples from excised human femurs ($d=5\text{mm}$ and $h=10\text{mm}$, μ CT pixel size= $19\mu\text{m}$). We generated eight-node hexahedral meshes by direct voxel-to-element conversion on binarized images. A convergence study for tetrahedral meshes (linear and quadratic) explored element size and distortion parameters. Axial compression boundary conditions were applied to all models to compute $E_{app} = (F_{tot}/A) / \varepsilon$, where F is the reaction force, A the cross-sectional area, and ε the axial strain. We used relative and absolute percentage variations in E_{app} as convergence metrics, and differences with voxel mesh results to assess tetra-to-voxel comparability.

Results

Integration of ParOSol in Ciclope improved the solution performance of voxel models by more than one order of magnitude (e.g. for a 6M nodes model, allocated RAM from 220 to 9 GB, solution time from > 2 h to 10 min) and enabled the solution of large models ($>50\text{M}$ nodes corresponding to e.g. a standard 10mm diameter, 20mm length specimen for mechanical tests, acquired in μ CT at $19\mu\text{m}$).

Tetrahedral models reached convergence at 2% of both relative and absolute E_{app} variations when setting the average element size to 1.5 times the voxel size and the maximum element circumradius to 3 times the voxel size (average trabecular thickness was 3 to 5 times the voxel size). Tetrahedral models DOF were on average 1/32 and 1/6 of voxel models for 4-node and 10-node tetrahedra respectively.

Results from 4-node tetrahedral models strongly correlated with voxel models ($R^2=0.99$), but systematically overestimated E_{app} by $11\pm 3\%$, coherently with the known stiffening effect of linear tetrahedra. In fact, the quadratic 10-node formulation reduced E_{app} difference to $1\pm 3\%$ Figure 2.

Discussion

We defined a set of tetrahedral mesh parameters that permit numerical convergence and full comparability of results with standard voxel models. The upcoming Ciclope release will include a parallel solver into the pipeline, enabling solution of large trabecular bone specimens.

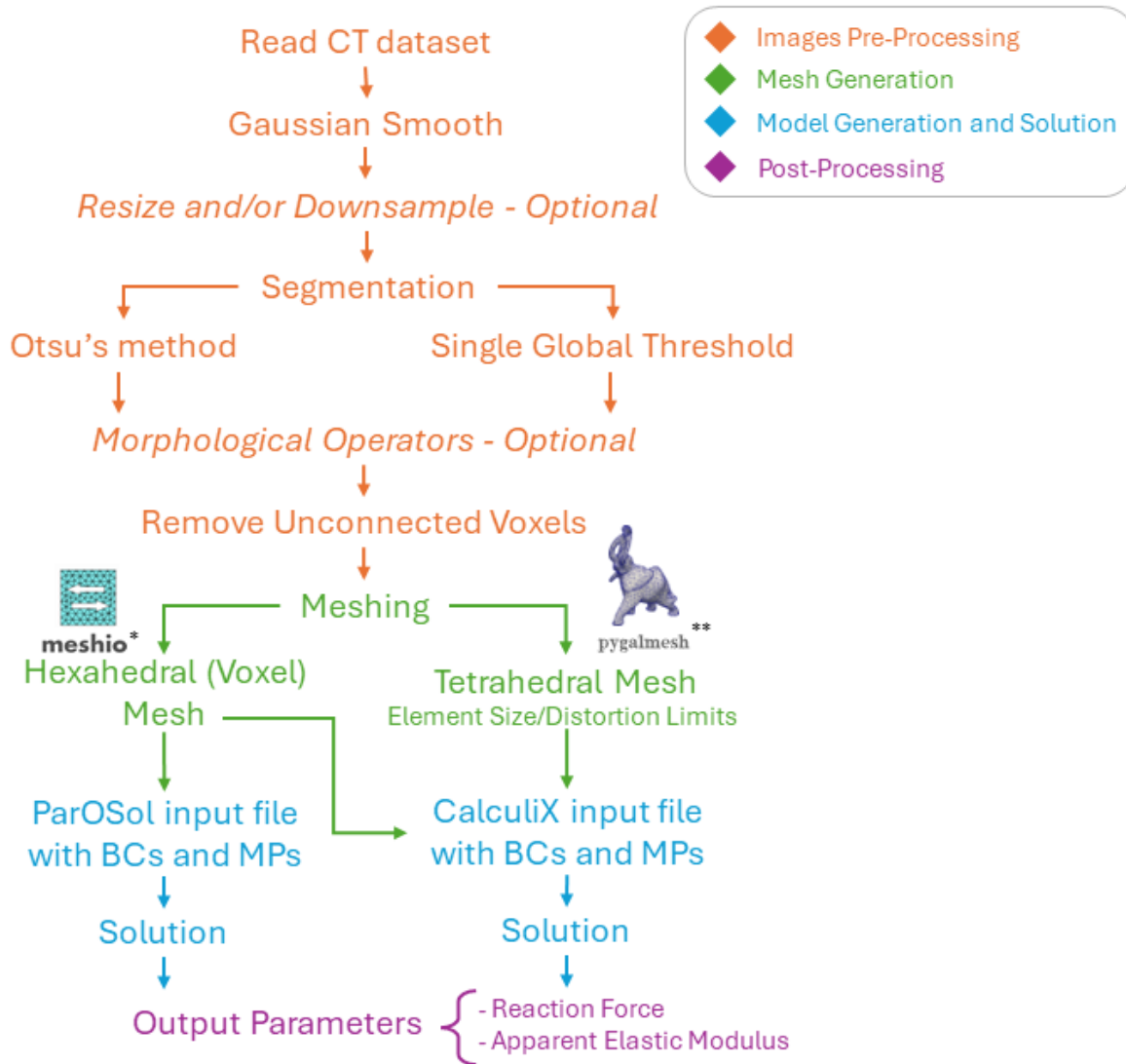
Acknowledgements

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Italian Ministry of Health 5x1000 project Year 2021

References

1. Iori et al., JOSS, 8:4952, 2023
2. Dhondt and Wittig, CalculiX (<http://www.calculix.de/>, <https://github.com/calculix>)
3. Bachmann, ParOSol TU Wien (<https://github.com/reox/parosol-tu-wien>)



* Schlömer, meshio: <https://pypi.org/project/meshio>

** Schlömer, pygalmesh: <https://pypi.org/project/pygalmesh>

Figure 1 - Ciclope pipeline.

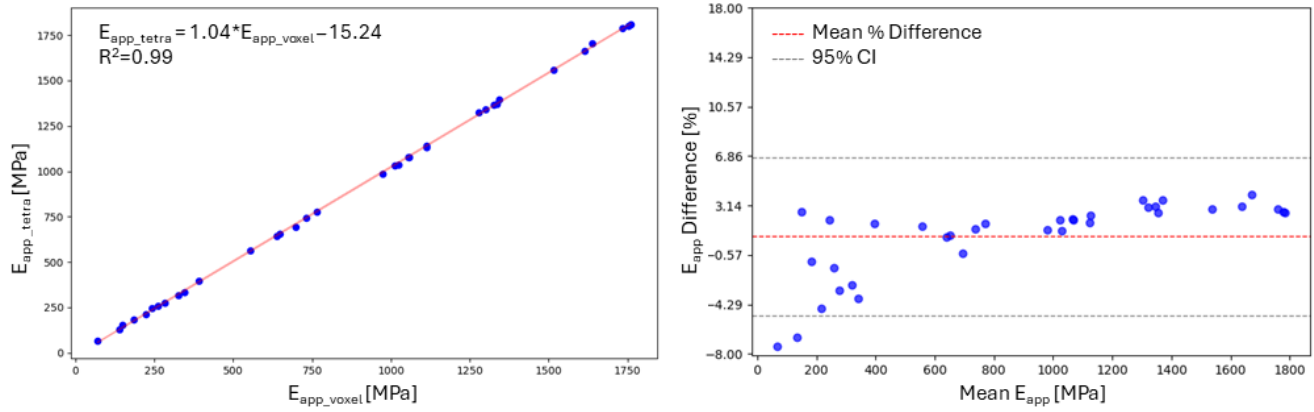


Figure 2- Apparent elastic modulus estimate. Left: linear regression of tetra10 vs. voxel. Right: Bland-Altman plot of tetra10 - voxel differences.