

Open trabecular bone microFE models from microCT images: Ciclope new release with higher

*Original*

Open trabecular bone microFE models from microCT images: Ciclope new release with higher performances and verified tetra mesh option / Fraterrigo, Giulia; Santamaria, Alfonso Dario; Pani, Martino; Crimi, Gianluigi; Taddei, Fulvia; Schileo, Enrico; Iori, Gianluca. - (2024), pp. 143-144. ( 24th International Workshop on Quantitative Musculoskeletal Imaging (QMSKI) Barossa Valley (AUSTRALIA) Novembre 3-8 2024).

*Availability:*

This version is available at: 11583/3000428 since: 2025-05-26T14:20:59Z

*Publisher:*

Organising Committee of the 24th International Workshop on Quantitative Musculoskeletal Imaging

*Published*

DOI:

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)

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

Giulia Fraterrigo (1,2), Dario Santamaria (1), Martino Pani (3), Gianluigi Crimi (1), Fulvia Taddei (1), Enrico Schileo (1), Gianluca Iori (4)

1. IRCCS Istituto Ortopedico Rizzoli, Italy; 2. Politecnico di Torino, Italy; 3. University of Portsmouth, UK; 4. Synchrotron-light for Experimental Science and Applications in the Middle East, Jordan

## Introduction

Finite Element (FE) models from micro-Computed Tomography ( $\mu$ 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  $\mu$ 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  $\mu$ 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  $h=10\text{mm}$ ,  $\mu$ 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  $\varepsilon$  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  $\mu$ 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.

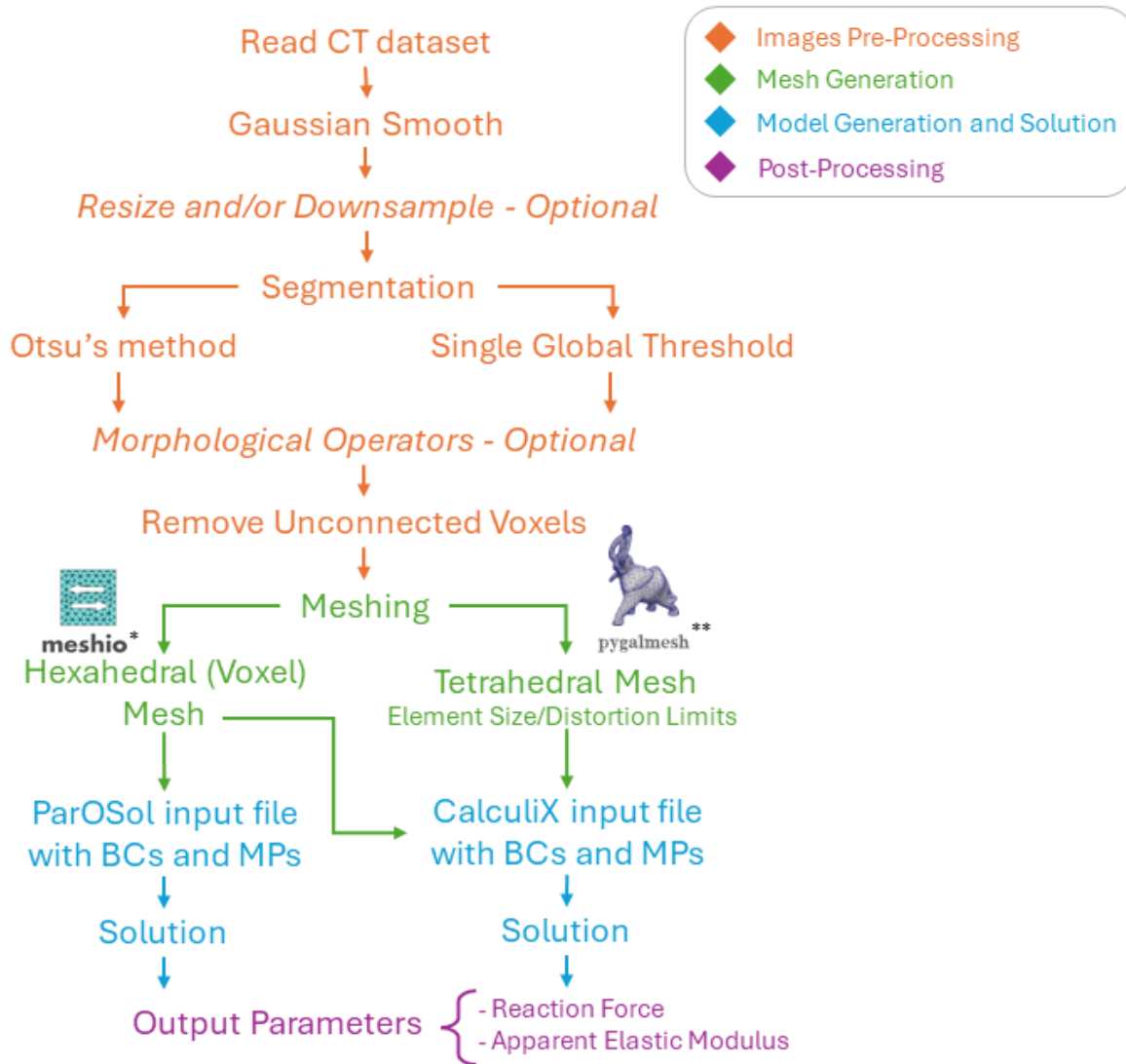
## **Acknowledgements**

Open and Reproducible Musculoskeletal Imaging Research community (ORMIR, [ormircommunity.github.io](https://ormircommunity.github.io))

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.

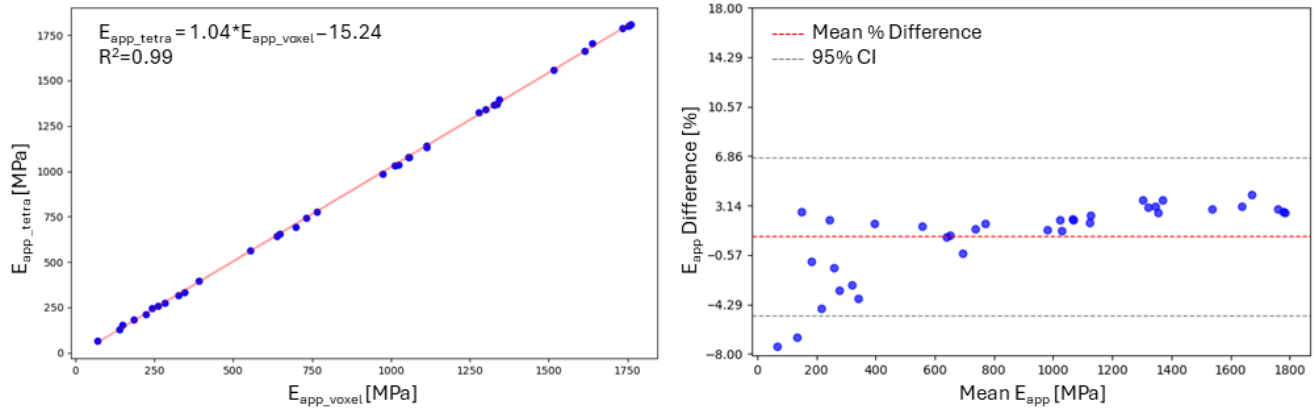


Figure 2- Apparent elastic modulus estimate. Left: linear regression of tetra10 vs. voxel. Right: Bland-Altman plot of tetra10 - voxel differences.