# CICLOPE: AN OPEN SOURCE PACKAGE TO BUILD FINITE ELEMENT MODELS FROM MICRO COMPUTED TOMOGRAPHY IMAGES

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## Introduction

Micro Finite Element (microFE) models are often derived from volumetric stacks of micro Computed Tomography (microCT) images to non-destructively assess mechanical properties of bone specimens. Specifically, microFE models of bone specimens are used to quantify the effect of pathologies and treatments (also over time, thus including remodelling) on the mechanical response of bone at the tissue level.

Different pipelines for the generation of microFE models of trabecular bone have been proposed in the past [1,2] and continue to appear [3,4]. However, as common in muscoloskeletal imaging research, the general absence of reproducible image-to-model pipelines and the use of proprietary or non-open-source software strongly limit validation and comparison of results across studies.

The aim of this communication is to present and describe the code package Ciclope. Ciclope is a fully open-source pipeline, written in Python to maximise availability, that can be used to preprocess microCT data to obtain a corresponding microFE model (with two mesh type options), solve and postprocess it.

## Methods

Ciclope implements a pretty standard pipeline to obtain microFE model results from microCT data, although several options are available in several pipeline steps.

### Example Pipeline

1. Loading and inspecting microCT data,
2. Image pre-processing
   - Apply Gaussian smooth and/or Resample (optional)
   - Segment tissue (Fixed threshold or Otsu method)
   - Remove unconnected clusters of voxels
3. Mesh generation
   - Create Unstructured Grid of voxels or tetrahedra
   - Generate FE model for simulation in CalculiX [5]
4. Analysis definition
   - Material properties (from template file)
   - Definition of linear static uniaxial compression test
5. Launch simulation in Calculix
6. Postprocessing
   - Convert Calculix output to .VTK for visualization
   - Calculate apparent elastic modulus from reaction forces

### Code design

Ciclope is composed of: (i) a core library of modules that generate the FE model; (ii) a library of utilities for pre- and postprocessing of images and FE models. The Python script generated during package installation can be used to launch analyses from the command line.

### Code ecosystem

Ciclope relies on other open source tools
- Mesh exports are performed with meshio [6]
- Tetrahedra meshes are generated with pygalmesh [7]
- Ciclope models can be solved with CalculiX [5]
- Visualization (data, results) relies on itkwidgets and Paraview.

## Results

The example in the Methods and in Figure 1 describes a linear static analysis of a trabecular bone specimens, which is being used by the authors to compare results between the voxel and tetra workflows, and to experimental Digital Image Correlation results. However, other use cases are already available in Ciclope, e.g. the analysis of a whole tooth or the elasto-plastic analysis of a steel foam. Ciclope is available at https://github.com/gianthk/ciclope
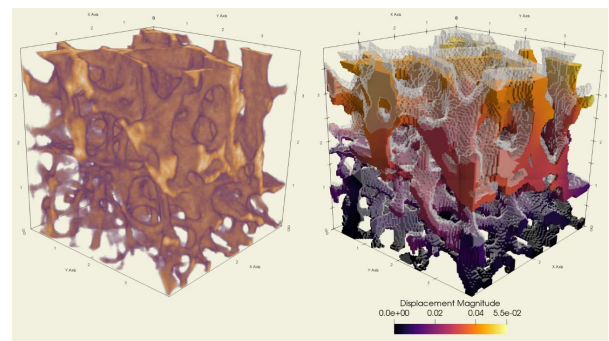


*Figure 1: microFE model and computed displacement field of a trabecular bone specimen from Ciclope*

## References

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