Ciclope: micro Computed Tomography to Finite Elements

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Summary

The Python package `ciclope` processes computed tomography images to generate finite element models. The aim of `ciclope` is to provide fully open-source, reproducible pipelines for simulating the mechanical properties of bone using the finite element method.

Statement of need

Tissue level micro Finite Element (microFE) models derived from laboratory or synchrotron micro Computed Tomography (microCT) volumetric data can provide non-destructive assessments of the bone mechanical properties. The technique is used to investigate the effect of pathologies, treatment and remodelling on the mechanical response of bone at the tissue level, and is applied both to human and animal samples. Linear elastic microFE simulations are implemented to back-calculate the tissue elastic modulus (Bayraktar et al., 2004), understand deformation mechanisms (Zauel et al., 2005), or predict failure (Pistoia et al., 2002) of trabecular bone, as well as to estimate the stiffness of whole bones from small animals (Oliviero et al., 2020). Different pipelines for the generation of microFE models of trabecular bone have been proposed (Cox et al., 2022; Fernández et al., 2022; Megías et al., 2022; Verhulp et al., 2008). Nevertheless, the validation and comparison of results across studies is hindered by the use of proprietary or non-open-source software, and by the general absence of reproducible FE pipelines. We present the Python package `ciclope`: a fully open-source pipeline from microCT data preprocessing to microFE model generation, solution and postprocessing.

Design

`Ciclope` is composed of a core library of modules for FE model generation (`ciclope.core`), and a library of utilities for image and FE model pre- and postprocessing (`ciclope.utils`) that can be imported and used within Python. Additionally, the `ciclope.py` script generated during package installation allows to launch microCT-to-FE pipelines directly from the commandline.

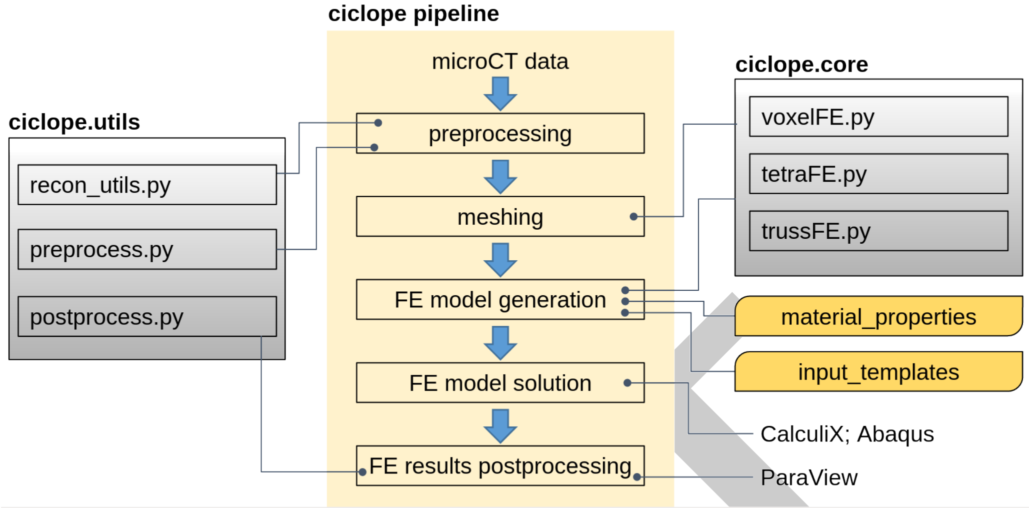

Figure 1: Design of ciclope, and application to a pipeline for FE model generation from microCT data.

A pipeline for the generation and solution of a FE model derived from 3D microCT data is shown in the central part of figure Figure 1. **Image preprocessing**: a microCT dataset is loaded in Python and segmented to isolate bone voxels and background. A connectivity check is performed to remove spurious unconnected structures. The 3D image can be smoothed, rotated, cropped and resampled to lower resolution. Embedding layers and steel caps can be added to simulate experimental conditions of mechanical testing. **Meshing**: `ciclope` allows to create several types of FE meshes. Image voxels can be directly converted to 8-node, hexahedral brick elements with the `voxelFE.py` module. Alternatively, meshes of 4-node tetrahedra can be generated calling `CGAL` (The CGAL Project, 2022) through the `tetraFE.py` module. Finally, the `trussFE.py` module allows to generate a mesh of 2-node beam elements, where each beam represents a single trabecula, and has a local trabecular thickness associated to it. **FE model generation**: the mesh is converted to an `.INP` input file for the FE solver. Within this process, the user can define the model material properties and the type of FE analysis (i.e. boundary conditions, analysis type and steps, requested outputs) through separate `.TMP` template files. Libraries of `material_properties` and `input_templates` are provided. Additional `CalculiX` user examples and templates are available online (*CalculiX Examples*, 2022). For voxel-FE model generation, different **material mapping** strategies can be used: uniform tissue material properties (elastic modulus and poisson ratio) can be applied to all bone voxels. Alternatively, the local image intensity (voxel grey values) can be converted to heterogeneous material properties using a mapping law defined by the user.

The ciclope ecosystem

`Ciclope` relies on several other tools for 3D image and FE processing:

- Voxel and tetrahedra mesh exports are performed with `meshio` (Schlömer, 2022a).
- Tetrahedra meshes are generated with `pygalmesh`, a Python frontend to `CGAL` (Schlömer, 2022b).
- High-resolution surface meshes for visualization are generated with `PyMCubes` (Neila, 2022).
- The FE input files (`.INP`) generated by `ciclope` can be solved using the free software `CalculiX` (Dhont, 2022) or Abaqus.
- For data and FE results visualization, `ciclope` relies on `itkwidgets` (*Itkwidgets*, 2022), `ParaView` (*ParaView*, 2022), and `ccx2paraview` (*CalculiX to Paraview Converter (Frd to Vtk/Vtu)*, 2022).

Examples

Ciclope contains a library of Jupyter notebooks of example applications in the field of computational biomechanics Figure 2. The main use case is a pipeline for the generation of microFE models from microCT scans of trabecular bone. The simulation (linear-elastic) of a mechanical compression test is used to back-calculate the apparent elastic modulus of trabecular bone. This procedure is demonstrated using hexahedra (voxel, Figure 2A), tetrahedra (Figure 2B), and beam finite elements (Figure 2C). Two approaches for the local mapping of material inhomogeneities are illustrated using voxel and tetrahedra FE. Each example can be run within Jupyter or executed from the commandline with the ciclope.py script. Ciclope can be applied to microCT scans other than trabecular bone, such as whole teeth (Figure 2D), or metal foams (Figure 2E).

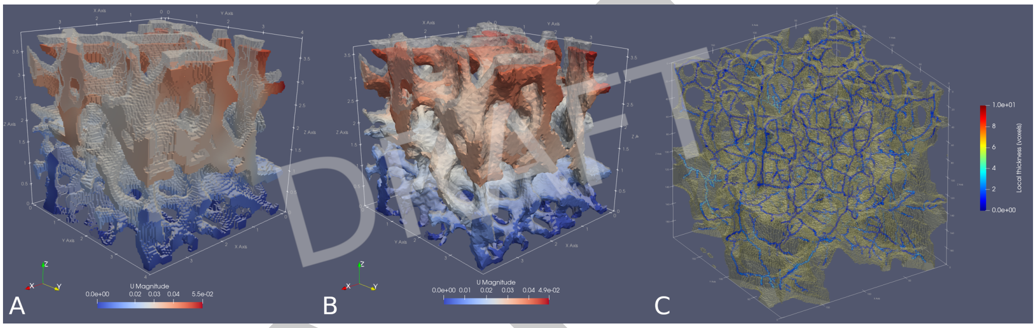

Figure 2: MicroFE models of trabecular bone generated from 3D microCT data with ciclope. Hexahedra (A), tetrahedra (B) and truss (C) finite element models generated with the voxelFE.py, tetraFE.py, and trussFE.py modules, respectively.

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