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GIBBON: The Geometry and Image-Based Bioengineering add-On

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Software

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Summary

GIBBON, which loosely stands for Geometry and Image-Based Bioengineering add-ON, is a MATLAB® toolbox providing a single open-source framework for many aspects of computational (bio)mechanics such as: image segmentation, meshing, boundary conditions specification, finite element analysis (FEA), and visualization. A schematic of the core functionality of GIBBON is shown in the figure below.

Below is a more detailed discussion of the core functionality where reference is made to implementations in the documentation.

- **Image segmentation**: In patient-, or subject-specific biomechanics, the geometry information is often derived from image data (e.g. Magnetic Resonance Imaging (MRI)). GIBBON offers image filtering and smoothing methods, and has a graphical user interface for 3D image segmentation (`HELP_imx.m`). The segmented image data can be converted to 3D surface models (`DEMO_imx_levelset_surface_compare`) which can be meshed for FEA (`HELP_runTetGen`).
- **Computer Aided Design (CAD) tools**: Sometimes geometry is instead imported or designed. Using GIBBON, geometry can be imported from common mesh based CAD files (such as STL, `HELP_import_STL`). For generating geometries within MATLAB®, GIBBON also provides several CAD-style commands such as polygon rounding (`HELP_filletCurve`), revolution (`HELP_polyRevolve`), extrusion (`HELP_polyExtrude`), and sweeping and lofting (`HELP_polyLoftLinear` and `HELP_sweepLoft`). Simple geometries such as spheres (`HELP_geoSphere`), boxes (`HELP_quadBox`), platonic solids (`HELP_platonic_solid`), and rhombic dodecahedra (`HELP_rhombicDodecahedron`) can also be directly created using GIBBON.
- **Surface meshing tools**: 2D multi-region triangular meshing (e.g. `HELP_regionTriMesh2D` and `HELP_multiRegionTriMeshUneven2D`), resampling meshes geodesically (`DEMO_geodesic_remeshing`), smoothing (`DEMO_surface_smooth_methods`), and surface mesh refinement (e.g. `HELP_subtri`, `HELP_subTriDual` and `HELP_subQuad`), mesh type conversions (e.g. `HELP_tri2quad`, `HELP_quad2tri`), and mesh dual computation (`HELP_patch_dual`). Geometries can also be exported to the STL format e.g. for computer aided manufacture and 3D printing.
- **Volumetric meshing**: Tetrahedral meshing (and constrained Delaunay tessellation) of multi-region domains is enabled through an interface with the TetGen (Si 2015) package (`HELP_runTetGen` and `HELP_constrainedDelaunayTetGen`). Hexahedral meshes for some geometry types can be directly coded (e.g. spheres `HELP_hexMeshSphere`, boxes `HELP_hexMeshBox` and lattices `HELP_element2HexLattice`). For general input surfaces multi-region mixed tetrahedral-hexahedral meshing is also available (e.g. `DEMO_MixedTetHexMeshing`).
- **Lattice structures**: One method to generate surface geometry for lattices is the use of triply-periodic functions (`HELP_triplyPeriodicMinimal`). Functions to convert element descriptions, such as tetrahedral and hexahedral elements,

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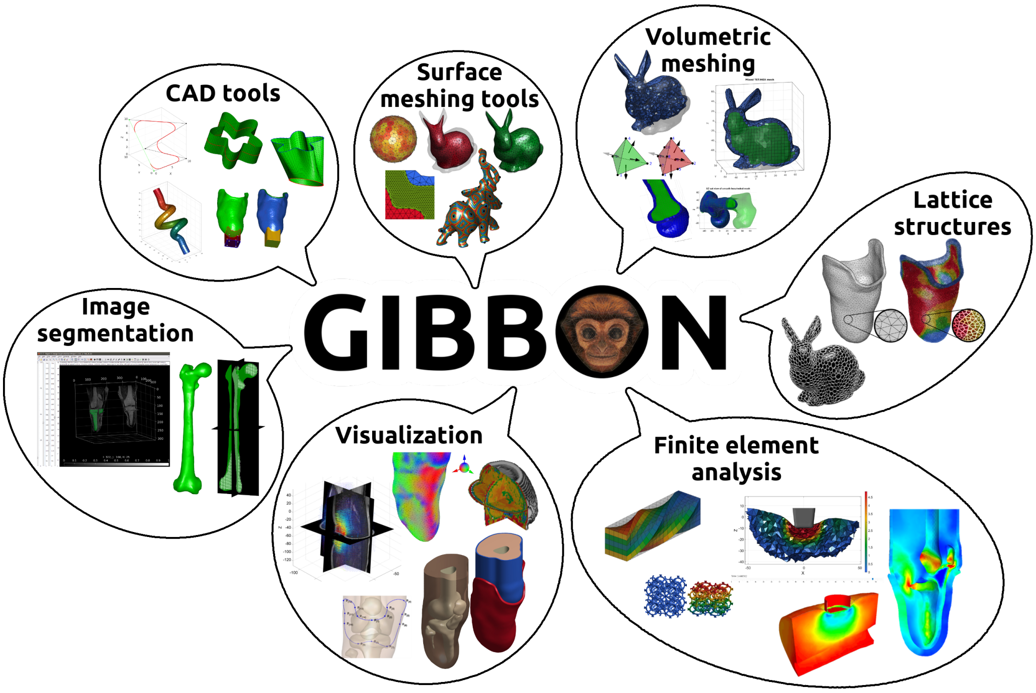

Figure 1: A Graphical summary of the GIBBON toolbox

to lattice structures have also been implemented (`HELP_element2lattice` and `HELP_element2HexLattice`). These allow for the creation of 3D boundary conforming lattice structures on arbitrary input geometry. Exporting of hexahedral elements is also supported allowing for FEA on the created lattice structures (`DEMO_FEBio_hexLattice_compression`).

- **Finite element analysis (FEA)**: GIBBON interfaces with the free software FEBio (Maas et al. 2012) for FEA (source code available on FEBio website). GIBBON can be used as a pre- and post- processor for FEBio as it enables code-based development of meshes, boundary conditions, and input files. FEBio files can be directly exported based on dedicated MATLAB® structures (`HELP_febioStruct2xml`). Furthermore, GIBBON can be used to start and control FEBio simulations. As such, iterative and inverse FEA (e.g. based on MATLAB® optimization routines) is also enabled. All `DEMO_febio_...` files are FEBio demos, e.g. `DEMO_febio_0001_cube_uniaxial` is a simple uniaxial loading example, and `DEMO_FEBio_iFEA_uniaxial_01` is an example of inverse FEA. Other demos cover tension, compression, shear, applied forces, applied pressures, applied displacements, bending, poroelasticity, dynamic and viscoelastic analysis, contact and indentation problems, multi-generational materials for pre-load analysis.
- **Visualization**: GIBBON expands the standard MATLAB® visualization capabilities by adding 3D image and voxel visualization (`HELP_im2patch` and `HELP_sliceViewer`), meshed geometries (`HELP_gpatch` and `HELP_meshView`), finite element models (`HELP_element2patch`), and colormapped vector data (`HELP_quiverVec`), and all visualization methods enable multiple colormaps to be used in each figure or axis window. Furthermore GIBBON offers a custom figure window `cFigure` containing 3D rotation options (`HELP_vcw`) that mimic CAD behavior of 3D scene rendering, and high quality figure exporting options (`HELP_efw`). Advanced graphics animation creation and exporting capabilities through a figure window based GUI are also enabled (`HELP_anim8`).

To date GIBBON has been used for image analysis and visualization (Moerman et al.

2012), continuum mechanics (Moerman, Simms, and Nagel 2016), soft tissue biomechanics (M. Takaza, Moerman, and Simms 2013) (Cooney et al. 2015), subject-specific and inverse FEA of soft biological soft tissue *in-vivo* (Moerman et al. 2017) (Sengeh et al. 2016), and automated generation of parametric scalable models of the lumbar spine (Lavecchia et al. 2018). The author's personal research with GIBBON is currently focused on subject-specific computational modeling for the automated generation of 3D printable prosthetic devices with optimized and spatially varying mechanical behavior (Moerman, Sengeh, and Herr 2016).

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