An Open and Accessible Application for the Simulation Bone Functional Adaptation

Timo van Leeuwen[1,2], Evie Vereecke[1], Jonas Rubenson[3], Chris Bradley[2], and Thor Besier[2]
[1]KULAK, KU Leuven, Kortrijk, Belgium
[2]The Auckland Bioengineering Institute, University of Auckland, Auckland, New Zealand
[2]Penn State, University of Pennsylvania, State College, US
[1] Email: timo.vanleeuwen@kuleuven.be

Summary

Here we present an application for the simulation of bone functional adaptation in response to complex loading regimes, specifically designed toward accessibility and usability in the field of biomechanics.

Introduction

Simulating bone functional adaptation is a challenging process that includes the discretization of intricate internal and external bone morphology, the implementation of complex loading conditions, and the often substantial computational demands required for accurate modeling. Finite Element (FE) analysis is the logical choice for the assessment of stress and strain in response to loading, and many accessible and user-friendly tools exist that have been built for this specific purpose (e.g. FEBio, Elmer, Abaqus). However, simulation of bone morphological adaptation requires methods that deal with the adaptation feedback loop, that allow for accurate application of nonhomogeneous boundary conditions, and which offer high resolution meshing and parallel numerical solving. Such tools are significantly more limited and typically exhibit low accessibility and usability.

To address these challenges, we have developed a fully open source, Python-based application for the simulation of bone strain and bone functional adaptation, specifically designed towards accessibility and usability.

Methods and testing

The application's main functionality is built upon OpenCMISS' [1] bespoke topology optimization module, integrated seamlessly into GUI based, (high resolution) FE pre/post-processsing modules that facilitate model building from image processing start to convergence. Bone surface meshes may be uploaded directly, or high-resolution medical image stacks (e.g., μCT .mhd files) can be programmatically segmented and reconstructed into high-resolution surface meshes or isosurfaces. Mmg3d [2] implicit domain meshing is integrated and used to generate robust, volumetric, tetrahedral meshes from surface model or isosurface contours. These meshes are optimized for morphological accuracy due to high refinement levels at the mesh boundaries. Boundary conditions can be selected manually or applied by means of integrated musculoskeletal modeling (MSM) through the OpenSim [3] API. Finally, the combined bone meshes and boundary conditions are passed to OpenCMISS's powerful numerical solver, equipped with inherent parallel solving. Its new bone optimization functionality executes a level-set-based linear elasticity topology optimization method, using a reaction diffusion equation and volume constraint to iteratively adapt the structural field [4, 5]. Ultimately, the optimization converges on a compliance solution, minimizing strain and material volume in response to the applied boundary conditions. In other words, it finds a morphological solution of optimized material volume in response to specific loads and, with carefully selected parameters, an accurate simulation of bone functional adaption.

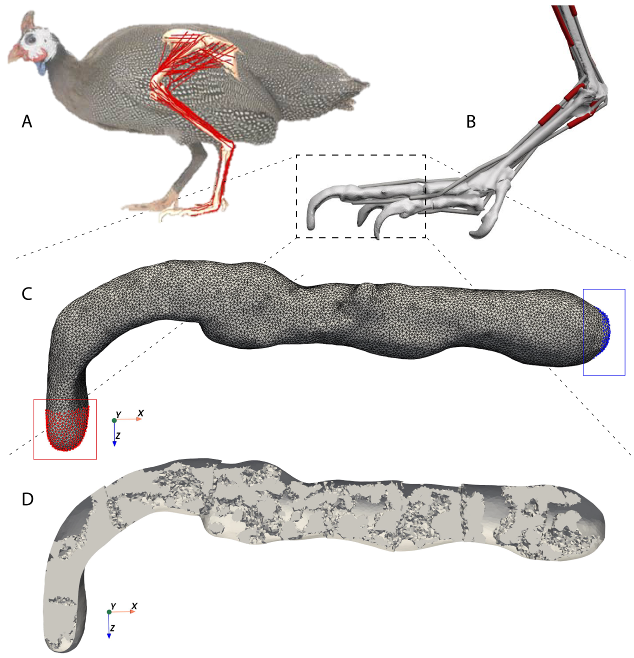

Figure 1: Test case of a Guinea Fowl (**A**) hind limb (**B**) third distal phalanx, which is a talon (**C**). Constrained (**C** blue) and z loaded (**C** red) nodes, applied with the manual boundary condition selection tool, result in the morphological response **D** at iteration 90.

The application is developed, tested, and validated by means of a Guinea Fowl (*Numida meleagris*) bipedal model species dataset (**Figure 1**), including anatomical data, loading biomechanics, and a MSM [6].

Conclusion

We have developed an accessible, modular, open-source application that integrates multiple components to simulate bone functional adaptation. Given its flexibility and focus on usability, we aim for broad scale, multidisciplinary employability in facilitating high-fidelity simulations.

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