Computational heart mechanics

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Preface

The purpose of this book is to introduce students and researchers to the principles of computational soft tissue mechanics, and provide them with the necessary background to use, understand and potentially build computational software for heart mechanics. A brief general introduction to nonlinear solid mechanics is given, but the reader is referred to other books for a more detailed explanation of these topics. Obtaining one of these books is highly recommended, since the present tex is compact and may be difficult to read without any background in continuum mechanics. The book will include a number of relevant examples that give the reader both an idea of what the models can be used for, and a collection of "recipes" for using and solving the models.

From the doconce book setup:

1. Chapters can exist as stand-alone documents in different formats:
   - traditional LaTeX-style PDF report,
   - web pages with various fancy stylings (e.g., Sphinx, Bootstrap) and possibility for multi-media elements,
   - IPython notebooks,
   - blog posts (not exemplified here, but straightforward[1]),
   - wiki (if you do not need mathematical typesetting).
2. Chapters can be flexibly assembled into a traditional LaTeX-based PDF book for a traditional publisher, or a fancy ebook.

[1] http://hplgit.github.io/doconce/doc/pub/manual/html/manual.html#blog-posts

3. The book and the individual chapter documents may have different layouts.
4. Active use of preprocessors (Preprocess and Mako) makes it easy to have different versions of the chapters, e.g., a specialized version for a course and a general version for the world book market).
5. DocOnce has support for important elements in teaching material: eye-catching boxes (admonitions), quizzes, interactive code, videos, structured exercises, quotes.
6. Study guides or slides can easily be developed from the running text and stored along with the chapters. These can be published as LaTeX Beamer slides, reveal.js slides, and IPython notebooks.

These features have the great advantage that a book can evolve from small documents, thereby making the barrier for book writing much smaller. Also, several appealing ebook formats can be produced, both for the book and the individual chapter documents. The chances that your students read a chapter on the bus becomes larger if the chapter is available as attractive, screen-fit Bootstrap pages on the smart phone than if you just offer the classic LaTeX PDF which actually requires a big screen or a printer.

Implementation of point 1 and 2 is not trivial and requires some rules that might not feel natural at first sight in the setup. Writing a book soon becomes a technically and mentally complex task, just like developing a software system. For the latter people have invented a lot of sophisticated technologies and best practices to deal with the complexity. The present setup for books is a similar collection of my own technologies and best practices, developed from writing thousands of pages. In particular, the setup has been successfully used for the large-scale 900-page Springer book "A Primer on Scientific Programming with Python" [2] (individual chapters of this book, e.g. [1], can be examined online in various ebook formats) as well as for books in the works[2].

To use this setup, just clone the repository[3] and you have the directory structure, the scripts, and example files to get started with a book project at once! The source files for this book (especially in `doc/src/chapters/rules`) constitute nice demonstrations for learning about basic and advanced DocOnce writing techniques.

[2] `http://hplgit.github.io/num-methods-for-PDEs/doc/pub/index.html`
[3] `https://github.com/hplgit/setup4book-doconce`

April 2015 *Hans Petter Langtangen*

Contents

1 Introduction and Motivation

2 Introduction and motivation (appr. 10-15 pages)

2.1 Structure of the heart and cardiac muscle

2.1.1 Heart anatomy and mechanical function

Overview of heart anatomy and structure, focusing on the mechanical function

2.1.2 Structure of cardiac muscle tissue

Outline of muscle tissue organization;

- Overview of tissue structure
- Overview of cardiomyocyte structure, introducing the contractile proteins
- The extracellular matrix

2.2 The mechanics of heart contraction

Brief overview of the pumping function of the heart viewed as a mechanical multi-scale problem. A top-down view may be most illustrative, linking the different phases of the heart cycle (PV-loop, Wiggers diagram) to the mechanics of the tissue, the myocyte, and the sub-cellular structures.

2.3 Computational mechanics challenges

From a viewpoint of computational mechanics, outline the most important challenges of modeling heart mechanics.

2.3.1 Computational challenges of multiscale problems

Referring to the outline of heart mechanics as a multiscale problem in Section 2.2, outline current modeling paradigm and the general computational challenges related to solving multiscale, multiphysics problems.

2.3.2 Mechanics of soft tissues

Outline classical aspects known to be challenging in continuum mechanics, and describe how they are present in models of passive muscle tissue:

- large deformations
- Non-linear material behavior
- Incompressibility and related numerical problems
- High anisotropy
- Uncertainty and variability in material parameters

2.4 Heart disease and mechanical dysfunction

Some re-organization is possible here, maybe placing this part before the outline of the mechanical problem.

- Brief summary of heart disease in general
- Outline selected heart problems where mechanical dysfunction of the heart muscle is an important factor. Of course, the distinction is not entire clear, but this would exclude severe arrhytmia and direct effects of valve dysfunction, but include heart failure and remodeling driven by load imbalance caused by electrical dyssynchrony or valve problems.

2.5 Outline and scope of the book

Should possibly (probably) be moved to a preface. Outline the book's content, focus and intended audience, and, most importantly, list the many important topics that will not be covered by the book.

3 Introduction to Non-Linear Solid Mechanics

4 Introduction to non-linear solid mechanics (appr. 40 p)

A compact introduction to the necessary theory. Start the chapter with a brief ouline of its purpose, that we want to employ the laws of Newton to arrive at dynamic and static balance laws governing the relation between forces and deformation. Ths brief introduction will motivate the concepts of strain and stress to be introduced through the chapter.

4.1 Kinematics

Introduce the necessary framework for describing movement and deformation of soft tissues:

- Introduce the displacement field and mapping between the reference and undeformed configuration, also briefly mentioning the generalization to intermediate configurations as used in growth models and active strain models of contraction. Introduce the deformation gradient.
- Describe the distinction between Lagrangian and Eulerian description of field quantities.

4.2 The concept of strain

- Describe the purpose of and general requirements to deformation measures, i.e. the need for a precise measure of local deformations, excluding rigid body motion. Explain why neither the displacement field nor the deformation gradient are suitable measures of deformation.
- Introduce the most widely used deformation and strain tensors, including the linear strain tensor (for familiarity), the Green-Lagrange strain tensor, the left Cauchy-Green tensor. Possibly a couple more, but most likely just list these and cite other sources for details.
- Describe the concept of frame invariance, and introduce the primary strain invariants.

4.3 The concept of stress

- Basic intriduction to the stress vector and (Cauchy) stress tensor
- Explain the problems of using the Cauchy stress in large deformation mechanics
- Introduce the most commonly used stress tensors in soft tissue mechanics, i.e. the first and second Piola-Kirckhoff stress tensors.
- List alternative, potentially relevant stress tensors, cite other sources for details.

4.4 Balance equations

Present a compact derivation of the fundamental laws of motion, based on conservation of linear momentum.

- Euler description, Cauchy stress
- Lagrange description, Piola-Kirchoff stress
- Discuss the relative significance of the terms, motivate the quasi-static approach and the neglection of body forces
- Discuss the general nature of the equation, and relate this to the mismatch between number of equations and unknowns. This motivates the need for constitutive models.

4.5 Modeling material behavior

Give a general introduction to constitutive modeling, explicitly neglecting the complex behavior of the heart muscle and other soft tissues. For completeness and to increase the understanding of the balance equations presented above, describe the general behavior of fluids and solids, briefly list models for "advanced" solids (visco-elasticity, plasticity etc), and proceed to describe simpler elastic and hyperelastic models. This section has two purposes; (1) to give a soft introduction to material modeling before diving into the more complex and realistic case, and (2) to arrive at some fairly compact model problems that will be used to introduce the computational techniques in the next chapter.

5 Computational techniques for elasticity

6 Constitutive laws for passive heart tissue

7 Modeling cell and tissue contraction

8 Boundary conditions and whole heart models

9 Open problems in cardiac mechanics

Remark. Documents that contain raw Mako code in verbatim code blocks cannot also be processed by Mako, and this is the case with the `mako` chapter. Since we need Mako for processing the rest of this book document, we are forced to compile the `mako` chapter as a stand-alone document (with the `--no_mako` option) and let this appendix be just a link to the this stand-alone document[1].

[1] `http://hplgit.github.io/setup4book-doconce/doc/pub/mako/pdf/main_mako.pdf`

References

[1] H. P. Langtangen. Loops and lists. *http://hplgit.github.io/primer.html/doc/pub/looplist*.

[2] H. P. Langtangen. *A Primer on Scientific Programming With Python*. Texts in Computational Science and Engineering. Springer, fourth edition, 2014.