Robust Image-Based Modeling and Simulation in Biomechanics

By

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DISSERTATION

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DOCTOR OF PHILOSOPHY

in

CIVIL AND ENVIRONMENTAL ENGINEERING

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of the

UNIVERSITY OF CALIFORNIA

DAVIS

Approved:

Mark Rashid, Chair

Natarajan Sukumar

John Bolander

Committee in Charge

2018

To . . .

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Abstract

Robust Image-Based Modeling and Simulation in Biomechanics

The abstract submitted as part of your dissertation, in the introductory pages, does not have a word limit. It should follow the same format as the rest of your dissertation (1.5 inch left margin, double-spaced, consecutive page numbering, etc.).

Acknowledgments

Acknowledgements to those who helped you get to this point. They should be listed by chapter when appropriate.

Chapter 1

Overview

Fix UCD template based on formatting issues here: https://grad.ucdavis.edu/current-students/academic-services-information/filing-thesis-or-dissertation

[?] [?] [?, ?, ?, ?]

refer to Steve's thesis - get a copy if possible

Other software:

SOFA

Simvascular, Allison Marsden

Shadden Lab Berkeley

knee (Tammy Donahue)

hip (Dave Fhyrie)

heart

orthodontic

Chapter 2

Medical Imaging

Figure 2.1. A sample figure.

2.1 Magnetic Resonance Imaging

MRI is ideal for visually distinguishing soft tissues, but objects MUST contain hydrogen molecules (e.g. water). However it is possible to get around this problem and scan dry objects made of plastic, for example, by immersing them in jelly. The negative of the object is then visible in the MRI data. Segmentation can be threshold based in some cases. Unfortunately it is quite common for different objects to be easily distinguishable visually, by texture, but not by greyscale. In these cases some level of manual segmentation may be required. MRI images often suffer from signal attenuation and/or noise on the borders of the region of interest.

MRI, CT, ultrasound, others

2.1.1 Diffusion Tensor MRI

2.2 Computed Tomography

X-ray computed tomography (CT) $\rightarrow$ becoming more popular

2.3 Other Imaging Technologies

Ultrasound (3D), Elastography, etc.

Chapter 3

Image Segmentation

[?] – Mumford-Shah model

[?] threshold based segmentation edge based region based clustering matching

future - neural networks

3.1 Review of Image Segmentation Techniques

3.1.1 Level Sets

3.1.2 Flood Fill

3.1.3 Color Space Voronoi Partitioning

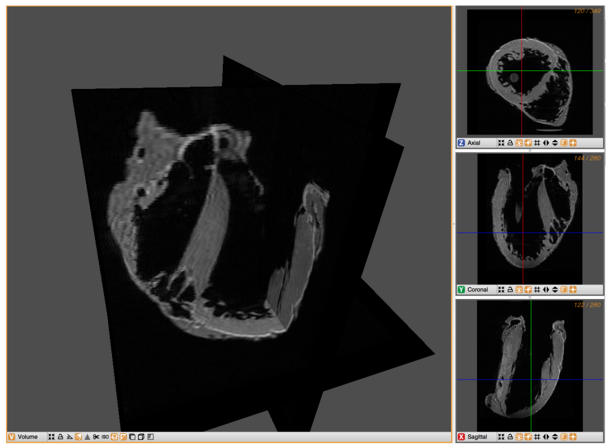
[?]

3.1.4 Adaptive Template-Moderated

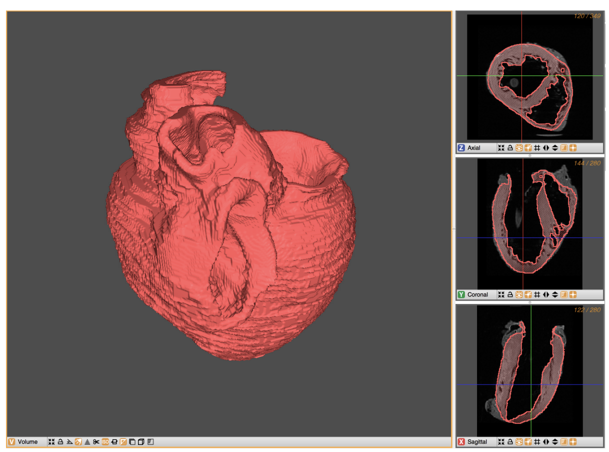
3.1.5 Manual Approaches

Seg3D, Simpleware, ITK-Snap

Invesalius



(a)

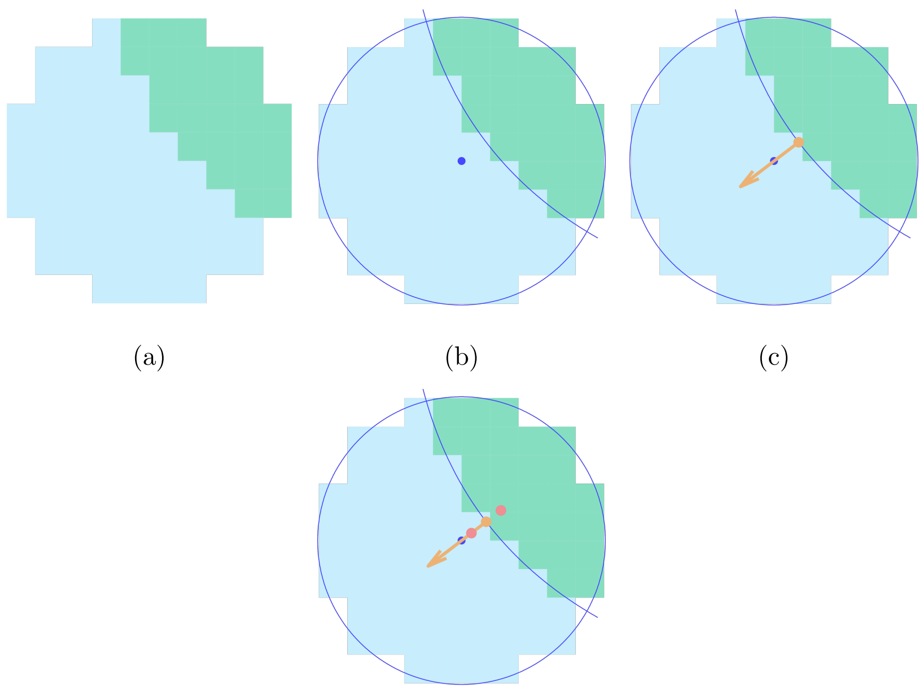


(b)

Figure 3.1. (a) MRI of *ex-vivo* human heart, and (b) resulting segmented image mask

Chapter 4

Mesh Generation



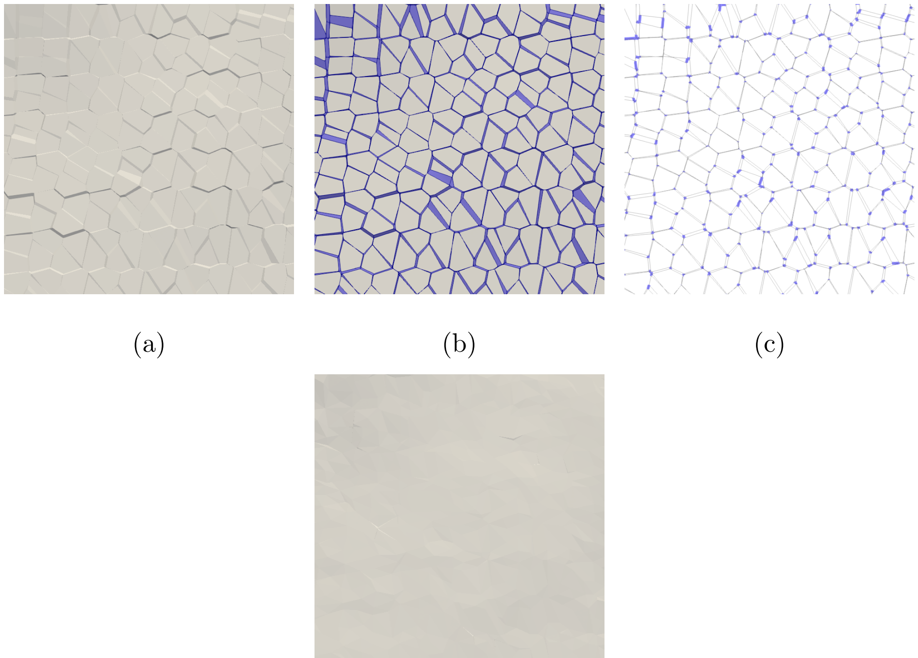
(a) (b) (c)

(d)

Figure 4.1. (a) Sample window of segmented image, (b) interface approximation, (c) point/normal placement, and d) Voronoi site placement

4.1 Review of Mesh Generation Techniques

Don't forget PhDResearch/doc/vorrecon



(a) (b) (c)

(d)

Figure 4.2. Clean-up of undesirable “cross-talk” facets for a surface patch: (a) initial surface following Voronoi-based surface reconstruction, (b) identification of “cross-talk” facets, (c) identification of edges to be collapsed, (d) final cleaned surface.

Hex meshing: sweep mesh thin sweep multizone

Universal meshes for smooth surfaces with no boundary in three dimensions

Search Voronoi meshing from medical imaging. Or from segmented medical imaging

vmtk: http://www.vmtk.org/tutorials/

http://www.robertschneiders.de/meshgeneration/software.html

$http : //homepage.usask.ca/\ ijm451/finite/fe_resources/mesh.html$

- simpleware webinar

- downsampling - poisson disk sampling

- smooth normals

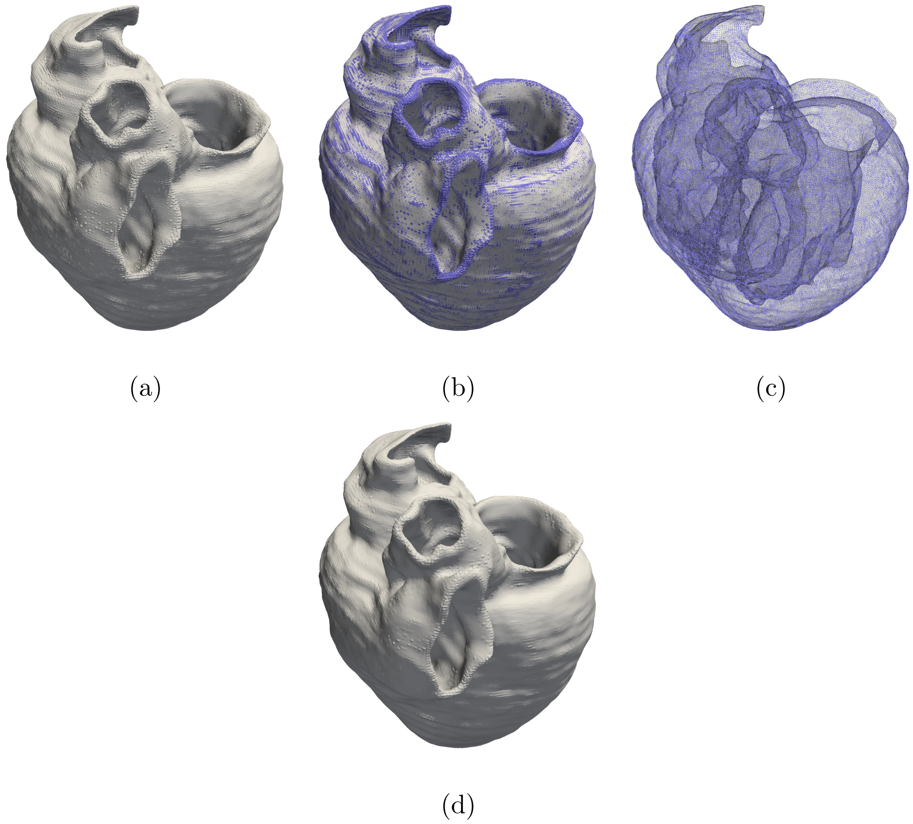


Figure 4.3. Clean-up of undesirable "cross-talk" facets for surface of *ex-vivo* human heart: (a) initial surface following Voronoi-based surface reconstruction, (b) identification of "cross-talk" facets, (c) identification of edges to be collapsed, (d) final cleaned surface.

- filtering

- watertight surface reconstruction

- vorocrust

- powercrust

- ball pivoting

- poisson surface reconstruction

- tight cocone

- meshing from CAD

- tetgen

- cubit/bolt

- direct meshing

- simpleware

- smoothing after the fact

- laplacian smooth

mesh simplification/decimation

cut cell approach

smoothing papers

noisy, oversampled point cloud

Simpleware webinar

- simpleware does not do CAD-based modeling, goes directly to the mesh - contact regarding technical work/papers for meshing export as STL, mesh, or NURBS - TWO BOTTLENECKS - image segmentation time - generating watertight and error free meshes - no gaps or overlaps - no inverted elements - no negative jacobian - segmentation -¿ stl -¿ smoothing -¿ nurbs -¿ meshing - cad geometry medical device -¿ export final model -¿ poor elements, gaps and overlap, non convergence, not watertight - manual corrections of stl, curbs, meshes

- generation of watertight STL - aspect ratio/mesh quality - image-based meshing

- BLENDR - graphics, STL - Rhino - STL generation, NURBS

Email Kerim, k.genc@simpleware.com

see you at WCCM Ross Cottons recently published paper Ross Cotton, r.cotton@simpleware.com

Simpleware paper: 1. marching cubes for surface mesh 2. Advancing front or Delaunay techniques for tet meshing –¿ produces slivers though 3. Extended EVoMacs

hex meshers:

truegrid

cubit

mask to mesh: dual contouring

"state of the art" papers

Sculpt Sandia - grid based meshing, volume fraction

"Parallel hex meshing from volume fractions"

For each voxel, sample a bunch of points, decide if inside or outside

Look at neighboring cells, do least squares to approximate gradient and throw down normal

Netgen advancing front. Mimix hex mesher

Truegrid hex mesher

CUBIT

Mimix

automated hex meshing at uconn: http://im.engr.uconn.edu/downloads.php

SURFACE RECONSTRUCTION: show results from Poison surf recon, powercrust, tight cocone

SimVascular: 2D segmentations followed by lofting

DECIMATION/SURFACE COARSENING:

ACVD papers Quadric Edge-Collapse Decimation

4.2 Voronoi Partitioning

Voro++

4.3 Tolerance-Aware Voronoi Partitioning

4.4 Voronoi-Based Mesh Generation

4.5 Boundary Representation (B-rep) Generation

4.6 Robust Polyhedral Mesh Generation from B-reps

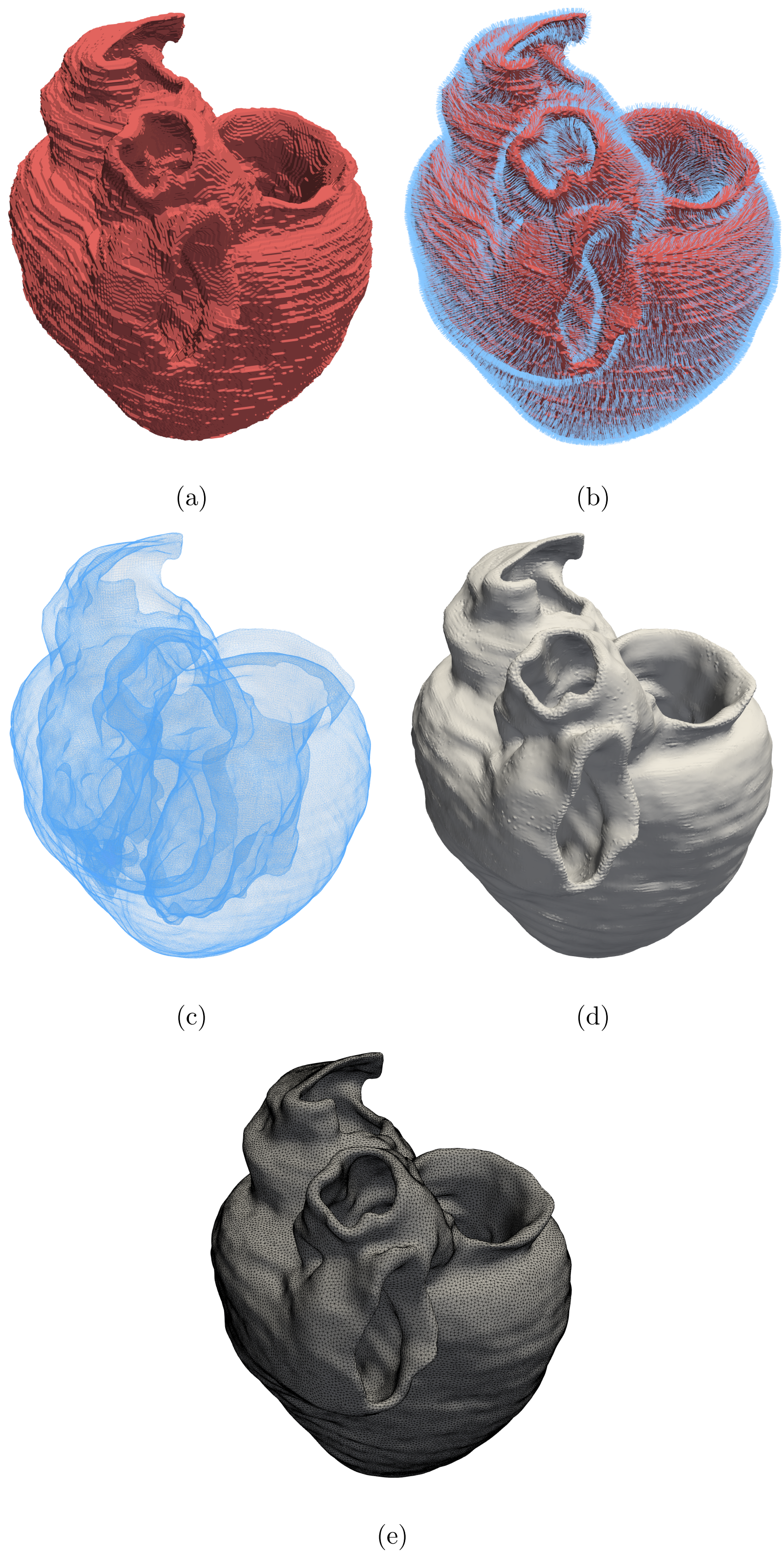


Figure 4.4. (a) Segmented image, (b) point/normal placement, (c) oriented point cloud (normals not shown), c) cleaned surface mesh generated from Voronoi partition (edges not shown), and d) final decimated surface

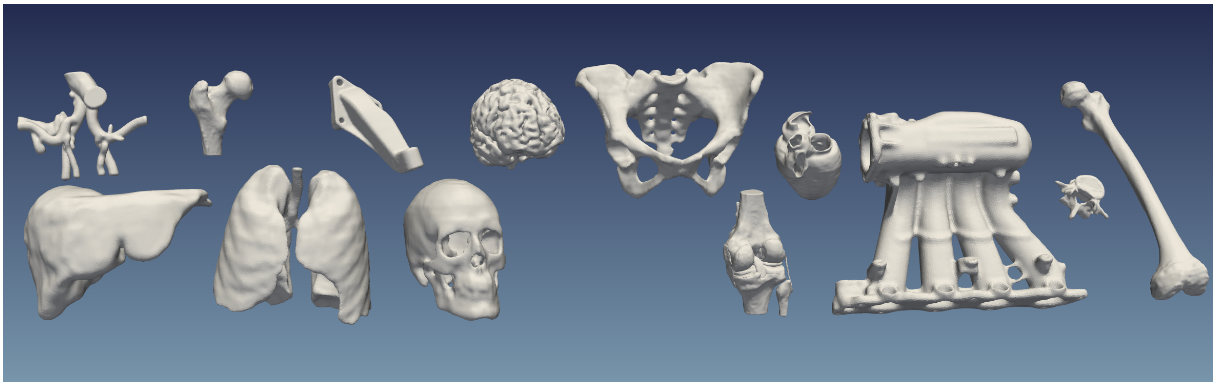
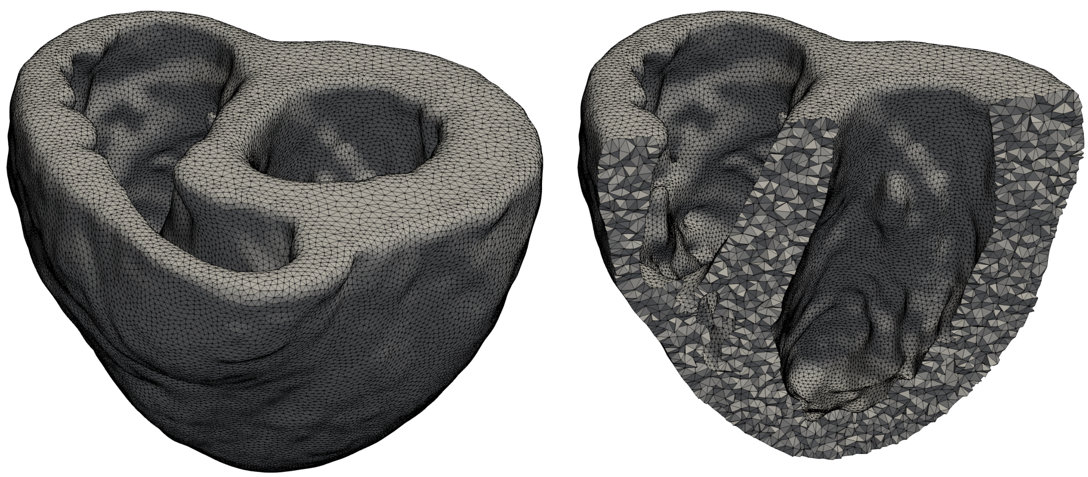


Figure 4.5. Suite of example surfaces generated from image data.

Figure 4.6. Screenshot of Github repo



(a) (b)

Figure 4.7. Bi-ventricular mesh: (a) surface mesh, and (b) clipped view of quadratic tetrahedral mesh used in Cardioid simulations

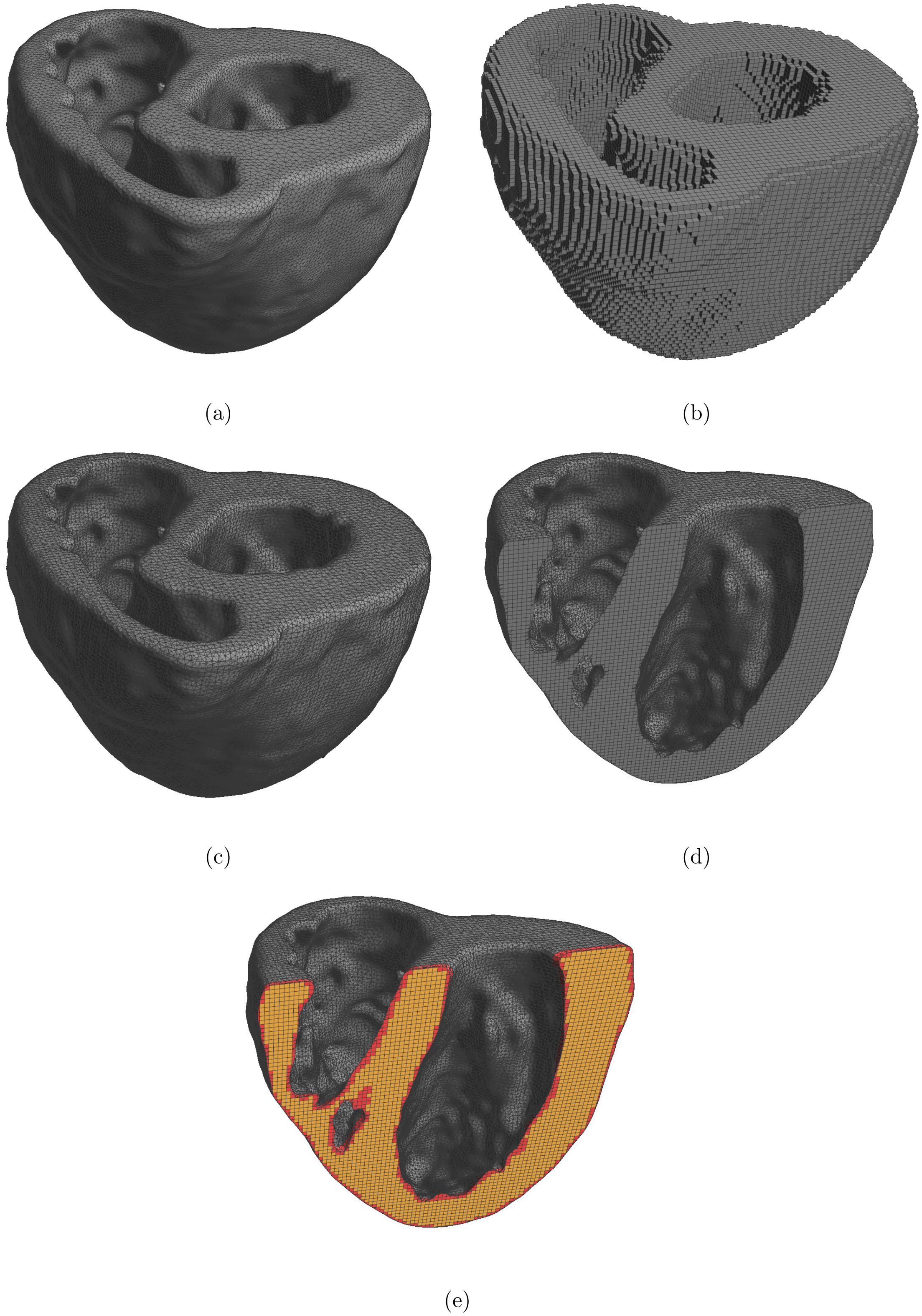
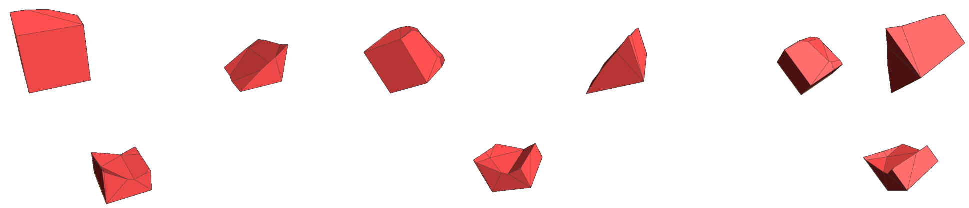
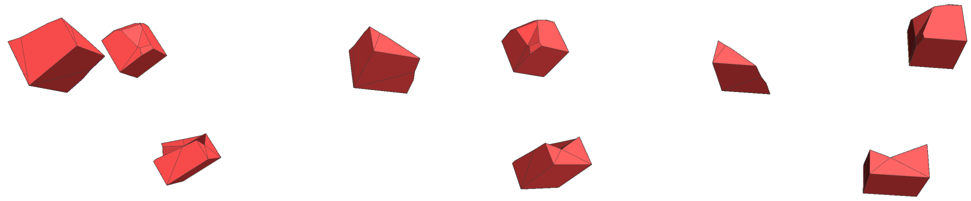


Figure 4.8. Generation of polyhedral mesh: (a) input surface mesh, (b) bounding hex mesh, (c) resulting polyhedral mesh, (d) clipped mesh, and (e) highlight of elements with cuboidal vs. general polyhedral shape.



(a) (b) (c)



(d) (e) (f)

Figure 4.9. Three example arbitrary polyhedral elements presented at different angles

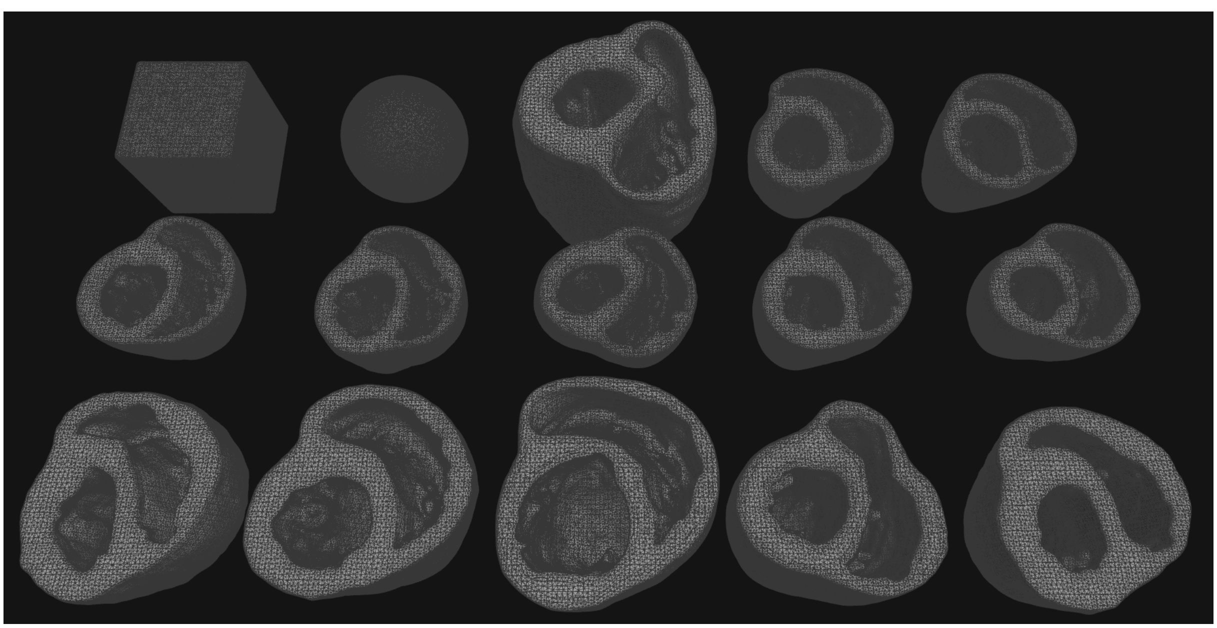


Figure 4.10. Suite of polyhedral finite element meshes generated from image data

Chapter 5

Numerical Methods

5.1 Continuum Mechanics

5.2 The Finite Element Method

(refer also to Jeremic and Felippa lecture notes, and Tom Hughes book)

5.3 Incremental Kinematics

see celeris/doc/NLmat.pdf

5.4 Hyperelastic Materials

5.5 The Partitioned Element Method

https://gaoxifeng.github.io/research.html $https://github.com/gaoxifeng/robust\_hex\_dominant\_meshi$

Chapter 6

Application: Cardiac Mechanics

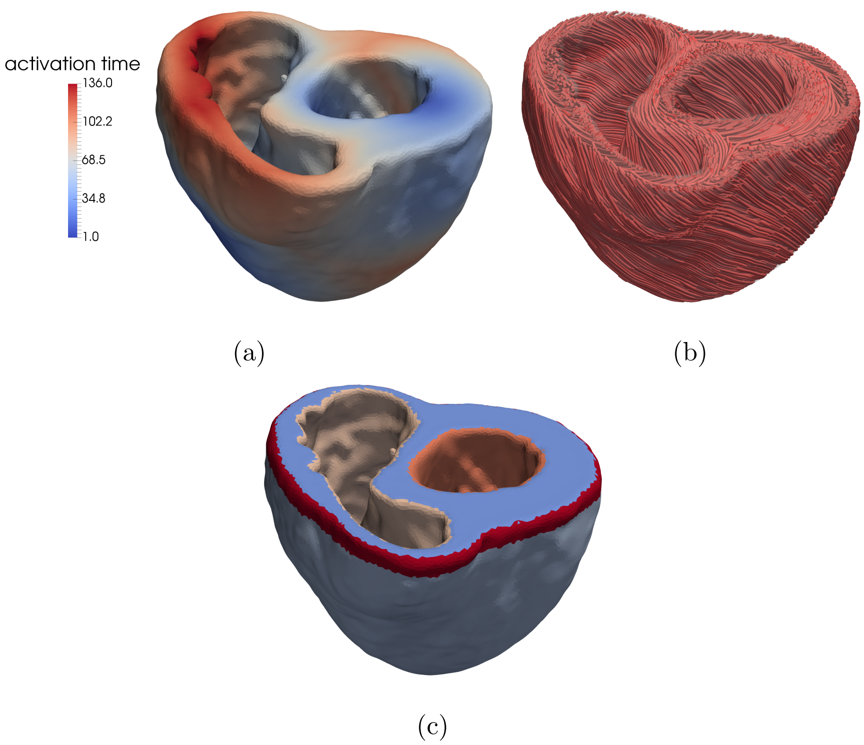
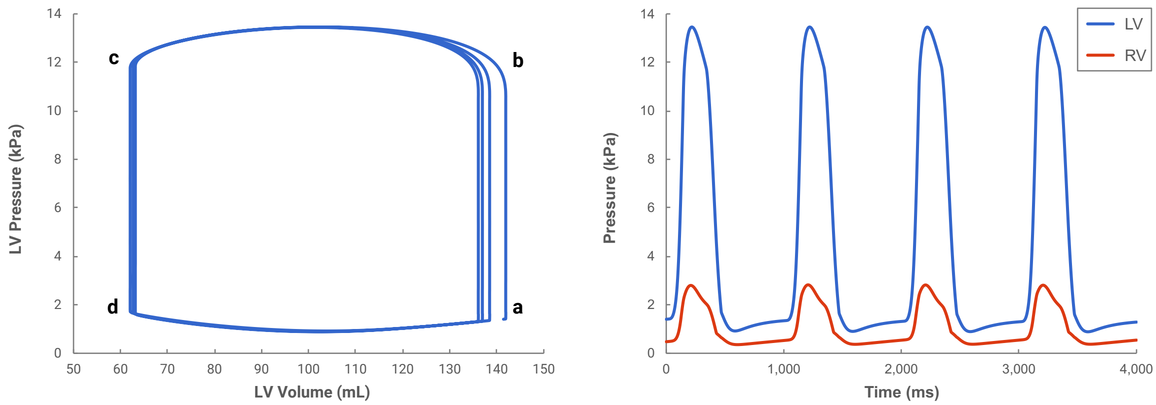


Figure 6.1. Mechanics modeling considerations: (a) muscle fiber orientations, (b) electrical activation times, and c) surface tagging and prescription of corresponding boundary conditions.

Cardioid science on saturday Youtube $heart_{p}apers$ papers Mark mentions in SOW



(a) (b)

Figure 6.2. Results from Cardioid simulation: (a) P-V loop of left ventricle, (b) pressure time history in left and right ventricles.

6.1 Description of Cardioid

6.2 Material Property Characterization

6.3 Fiber Generation

6.4 Boundary Conditions

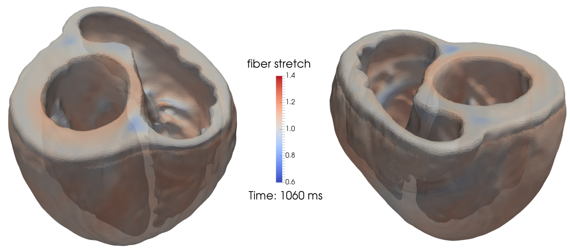
6.5 Simulation/Results

Questions to ask with available model Effect of smoothing/trabeculae Do trabeculae affect the solution How sensitive are the results from paraview smoothing? Effect of resolution make multiple meshes of same geometry Number of iterations do they depend on mesh resolution? Would like it not to Does V cycle work for my geometry? Fiber generation vs fibers from raw data + interp + smoothing Verification/validation Stress/strain plots Initial cycle is faster than others: first frame but also first cycle all together is faster Mesh quality/aspect ratio Potential plots: Volumetric strain Deviatoric strain C11, c22, c33 Maximal principal eigenvalue C11 from fiber orientation Hysteresis plot of position

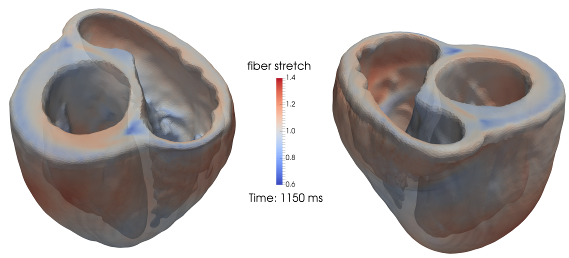
structure/trabeculae fibergen vs DTI Jeremy drug studies, a lot didnt match whole range of sensitivity studies

Preliminary Ideas

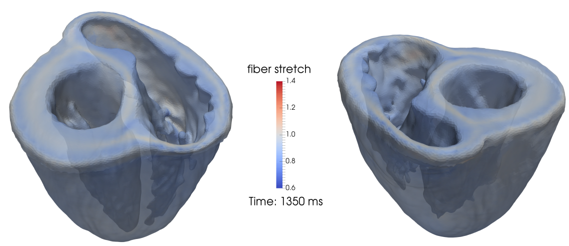
How does fiber orientation impact lengthening of heart How does mesh resolution



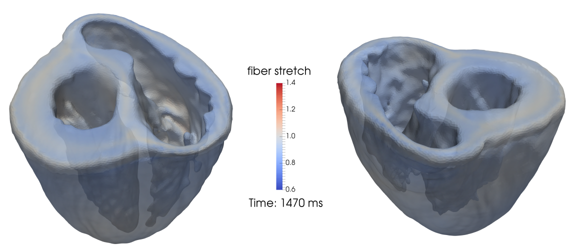
(a)



(b)



(c)



(d)

Figure 6.3. Deformed mesh from Cardioid simulation at different stages of cardiac cycle. Panels (a), (b), (c), and (d) correspond to the stages in the P-V loop denoted in FIGREF ???.

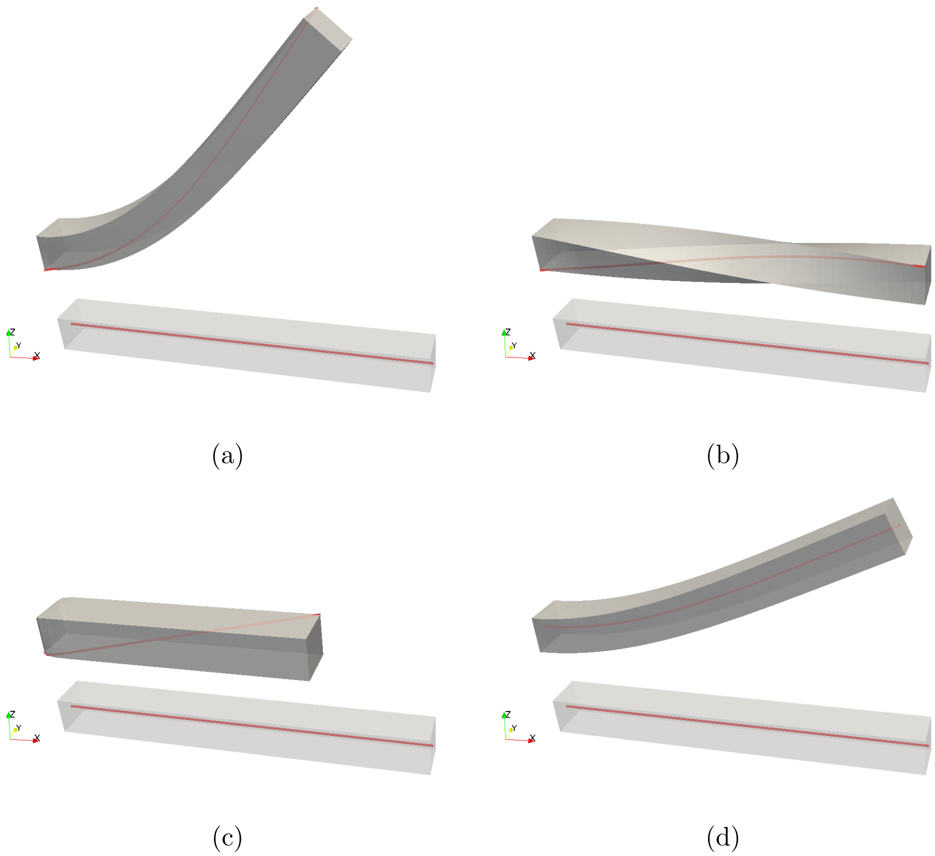
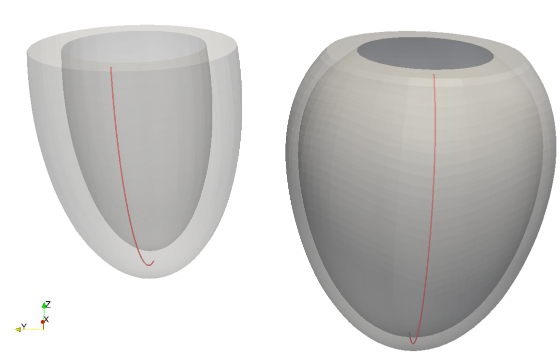


Figure 6.4. Undeformed (bottom) and deformed (top) configurations for cantilever beam verification problems: (a) Gurev P2: bending, (b) Gurev P3: torsion, c) Gurev P4: active contraction, and (d) Land P1: bending. The red curve denotes the curve over which displacements and positions are recorded for comparison of results.

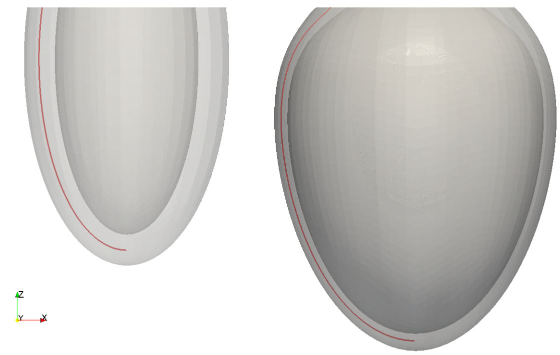
affect solution Explore exotic solvers Complete tool chain How does constitutive and active properties of heart affect solution

Nearly incompressible material leads to poor condition number in stiffness matrix Want to study how large scale, iterative solvers can be formulated to deal with poor condition number, as well as interact with element shape and mesh quality Want to couple electrophysiology model with mechanics model Want to understand the impact of mesh quality on solver performance, and help tune mesh generation procedures to generate meshes that are free of features that cause problems for the solver Why is full model not performing as well? Active tension, anisotropy, geometry. Which is the one that makes it hard?

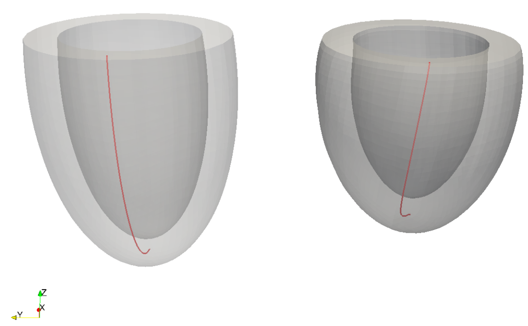
Solver may struggle due to a few elements that have a weird shape (Mesquite), mesh-



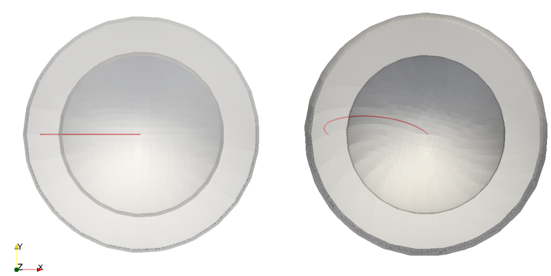
(a)



(b)



(c)

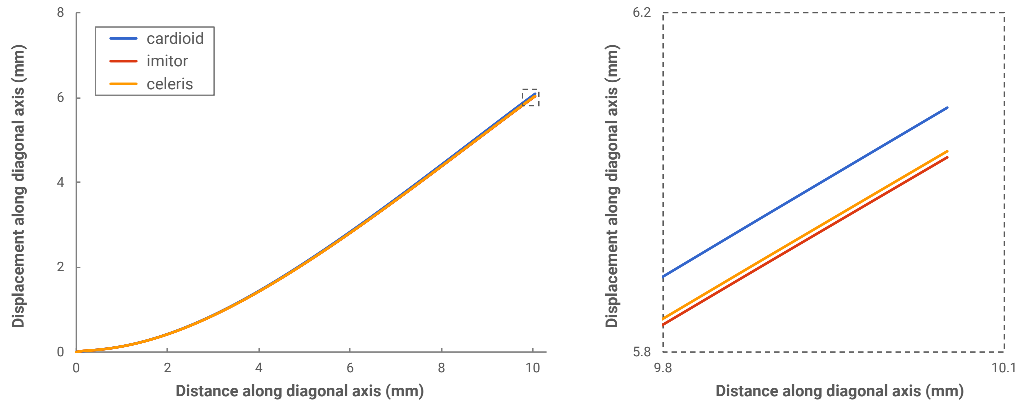


(d)

Figure 6.5. Undeformed (left) and deformed (right) configurations for single ventricle verification problems: (a,b) Land P2: inflation, and (c,d) Land P3: inflation and active contraction. The red curve denotes the curve over which displacements and positions are recorded for comparison of results.

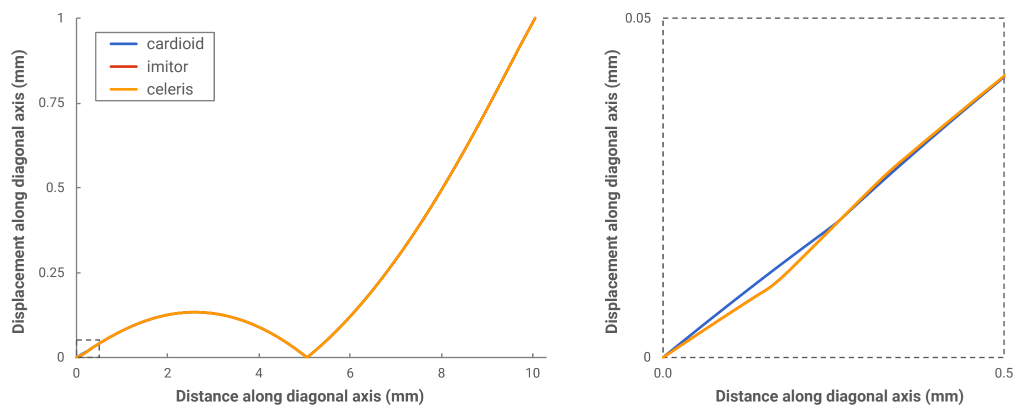
ing is a problem Activation model Coupling of electrophysiological and mechanical model (feedback may not be important) Electrophysiology model scales much larger than mechanical model, and can be solved almost real time Couple electrophysiology to ECG code finite element locations fed into ECG (same code base as FEM code) What parameters are affecting the result? Develop tool chain sensitivity analysis

What does it mean exactly to have an active component of stress? basically just a body force The ventricles are coupled to a lumped circulatory model? Volume as a function of time Direct solvers used because of active force component (?) Direct solvers limit number of DOF This method suggested is a Krylov subpace iterative solver, increases number of DOF, much larger scale problem Why quasi-static?? Elastic portion reacts very



(a) (b)

Figure 6.6. Results for Gurev P2 verification problem: (a) Displacement magnitude along diagonal axis, with (b) details for the free end of the beam



(a) (b)

Figure 6.7. Results for Gurev P3 verification problem: (a) Displacement magnitude along diagonal axis, with (b) details for the fixed end of the beam. The results for imitor and Celeris are indistinguishable in these plots.

quickly Any reason why quadratic elements chosen as opposed to linear elements? Avoid volumetric locking The main reason why the mixed displacement-pressure formulation for incompressible large deformation problems is often avoided is the difficulty in solving such saddle-point linear systems, and this difficulty is increased by the presence of active stress. problems with pyramid element why problems? Even after 15 node element introduced?

winslow canine diffusion tensor segmentation

Mark Rashid meeting

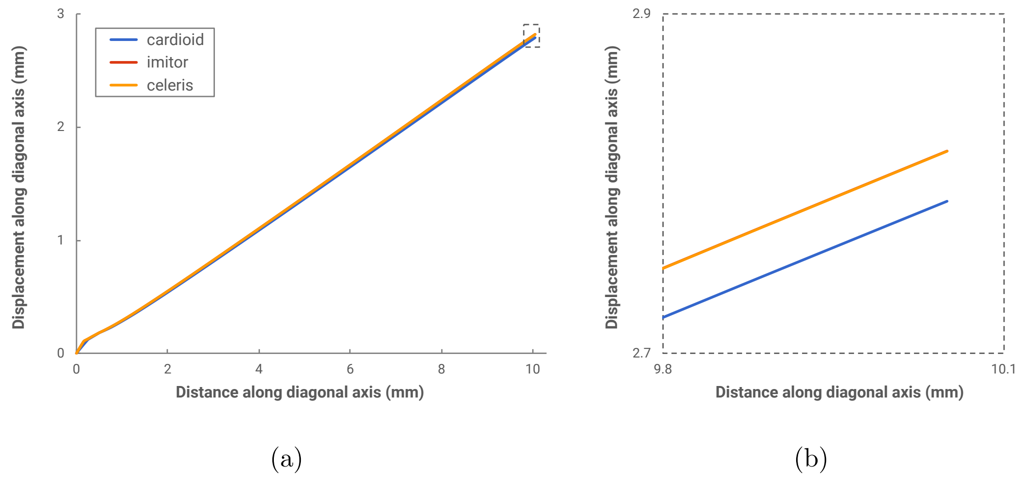


Figure 6.8. Results for Gurev P4 verification problem: (a) Displacement magnitude along diagonal axis, with (b) details for the free end of the beam. The results for imitor and Celeris are indistinguishable in these plots.

important to have every day workhorse stable analysis tool available

may be getting oscillations in pressure field that are hard to avoid in current formulation

oscillations in displacement from bending in beam is concerning - issue with constitutive model

near-incompressibility instead of fully incompressible

instead of pressure formulation, all displacement, only nearly enforce incompressibility element-wide average of element dilatation, essentially reduced-integration, a remedy for locking enhanced assumed strain / enhanced kinematics much more common to do all displacement, enhance kinematics instead of pressure formulation

BCs: projecting out rigid body translations and rotations

before today, the three options were fully tet, fully hex, and mixed. can we reiterate why you wouldnt recommend any of those three and why you would instead recommend polyhedral FEM laid out today

in the same way you have biological and electrophysiology experts, only makes sense to have an expert in computational solid mechanics

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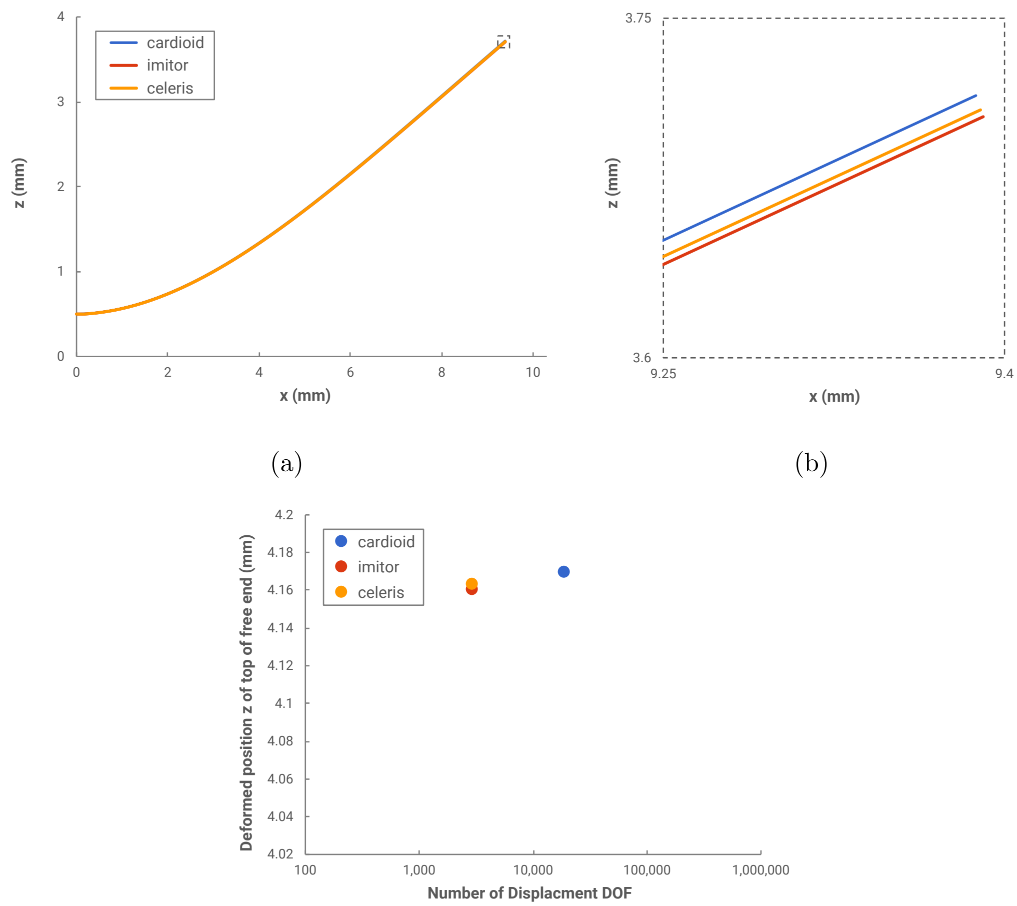
tets not okay - too many DOFs, accuracy potentially worse, even for higher order



(a) (b)

(c)

Figure 6.9. Results for Land P1 verification problem: (a) Deformed position of midline, with (b) details for the free end of the beam. Panel (c) shows the deformed position of the point $\mathbf{X} = (10, 0.5, 1)$ for each of the simulation codes.

full hex mesh nearly impossible mixed element: somewhere in between. prisms and pyramids are algorithmically difficult. Also, issues with convergence

Prof Rashids suggestions

direct solver instead of iterative solver is fiber discontinuity interacting with incompressibility constraint? 1 for experimentation, play with compressible passive formulation 2 take incompressibility off the table three main differences: geometry, continuous fiber orientations, purely tet mixture of elements could cause problems with convergence

WHAT CAN WE BE SLOPPY ABOUT? WHICH PARAMETERS MOST IMPORTANTLY AFFECT THE RESULT?

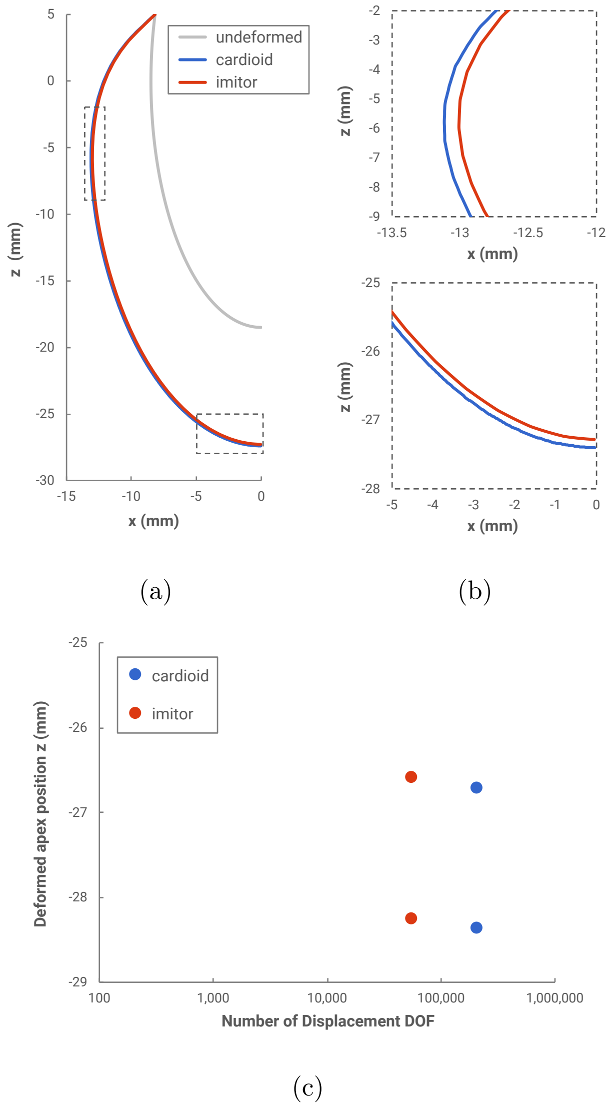


Figure 6.10. Results for Land P2 verification problem: (a) Deformed position of middle of the ventricle wall, with (b) details at the inflection point (top right) and the apical region (bottom right). Panel (c) shows the deformed position of the apex at the endo- and epicardium for each of the simulation codes.

—

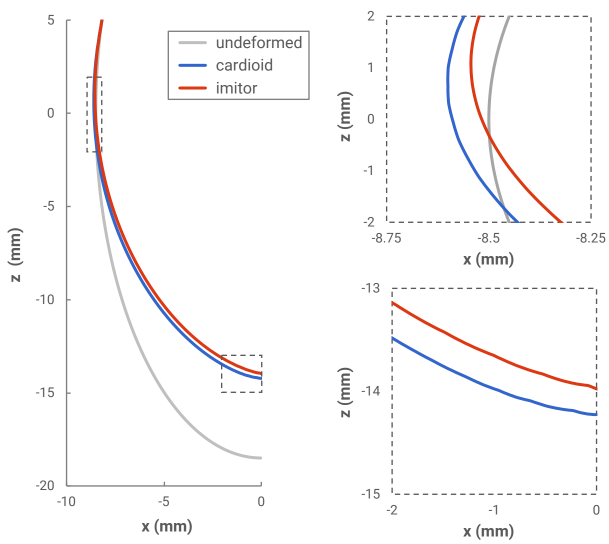
Natalia Trayanova is not the only one simulating beating hearts.

Some other profs that simulate beating hearts ...

Andrew McCulloch: http://cmrg.ucsd.edu/AndrewMcCulloch

Steve Niederer kclpure.kcl.ac.uk/portal/steven.niederer.html

Blanca Rodriguez www.cs.ox.ac.uk/people/blanca.rodriguez



(a) (b)

Figure 6.11. Results for Land P3 verification problem: (a) Deformed position of middle of the ventricle wall, with (b) details at the inflection point (top right) and the apical region (bottom right).

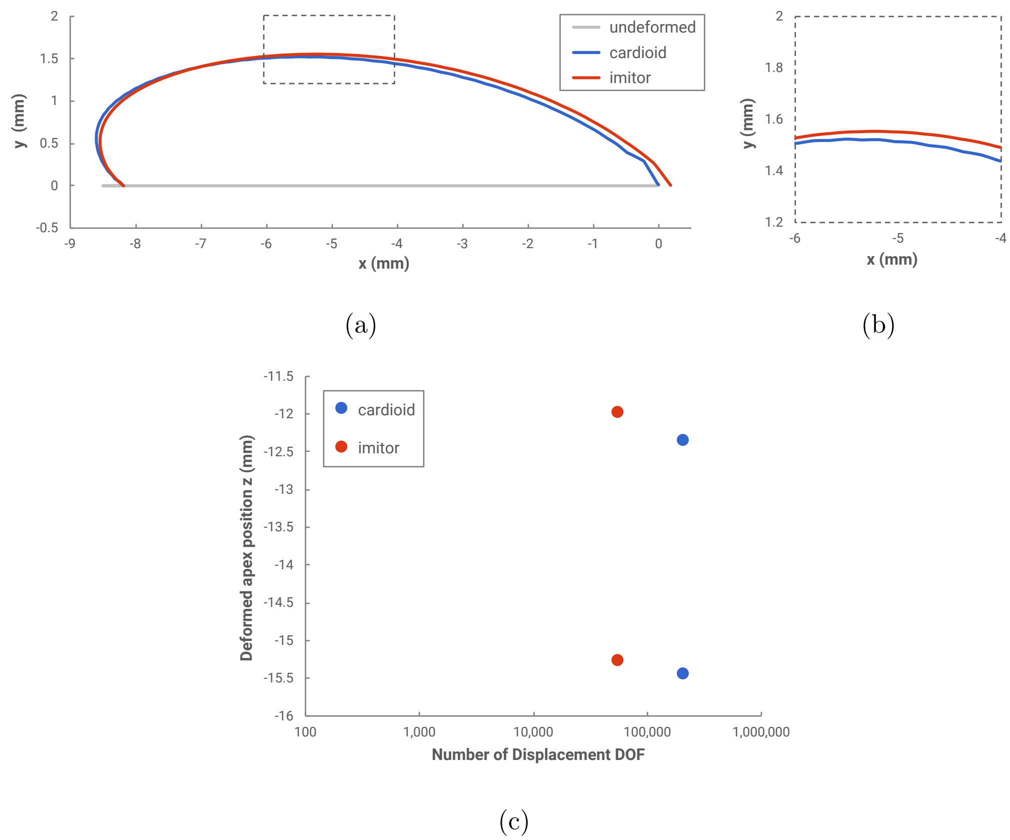


Figure 6.12. Results for Land P3 verification problem: (a) The same deformed position of middle of the ventricle wall, shown in the $x-y$ plane, with (b) details at the inflection point. Panel (c) shows the deformed position of the apex at the endo- and epicardium for each of the simulation codes.

Chapter 7

Future Work

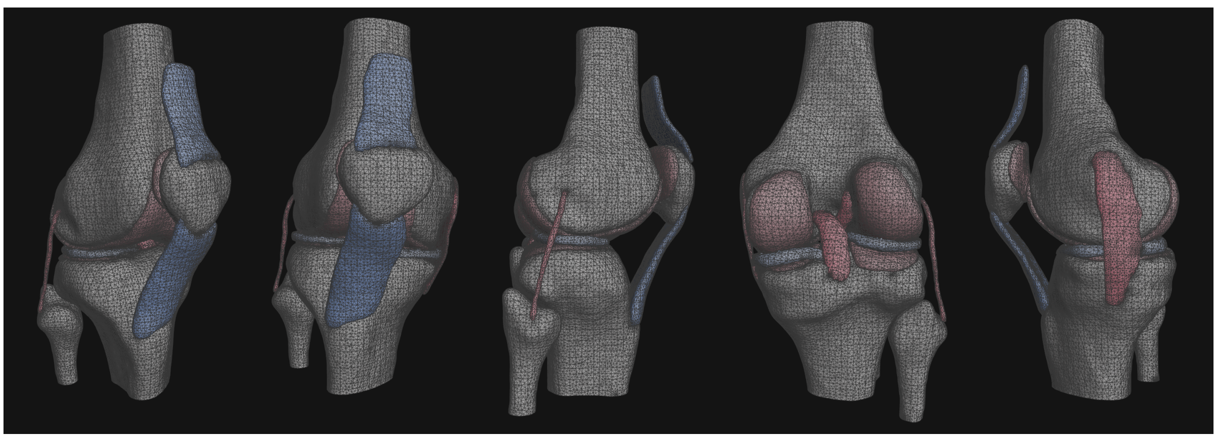


Figure 7.1. Polyhedral mesh of human knee from input surfaces generated from OpenKnee image masks

Active stress as function of eulerian fiber direction, not lagrangian

Global strain measures

full fledged heart sim

DTMRI

hemodynamics model

coupling with electrophysiology

contact with pericardium

FSI

coupling with cardiovascular simulation tools

coupling electrical, fluida

Figure 7.2. Suite of 3D-printed organs using surface meshes generated from novel image-based meshing tools

(a) (b) (c)

Figure 7.3. Comparison of meshes: (a) linear polyhedral mesh from Celeris, (b) quadratic tetrahedral mesh from Tetgen, (c) and quadratic tetrahedral mesh from Simpleware.

improvements to BCs, inside elastic medium

Lumens/SSA/active stress

7.1 Towards Automating the Image-to-Analysis Pipeline

7.1.1 Multiple Materials and Inhomogeneous Materials

7.1.2 Uncertainty Quantification, Verification, and Validation

Material properties, boundary conditions

7.1.3 High Performance Computing

7.2 Clinical Implications

(haptics, Simpleware stuff)

Center for Cardiovascular simulation (Texas) Heartflow, Inc., Charles Taylor

ASME V&V10 and V&V40

dental applications - 1) for implant placement and crown design, 2) for 3D printing, aesthetic try-in

tolerance-aware voronoi-partitioning

multiple material interfaces (see paper)

Abaqus: ability to deal with initial over-closures? A strain-free adjustment perhaps? Like if you were to mesh the femur and the femoral cartilage separately, say, and there is a tiny bit of overlap between them..are you able to fix this without going back to the meshing software?

Future Work

Comparison of surface reconstruction results to other methods

image-based meshing

Simplware

Cleaver

surface reconstruction

Poisson surf recon

vorocrust

tight cocone

compare volumes of segs to meshes

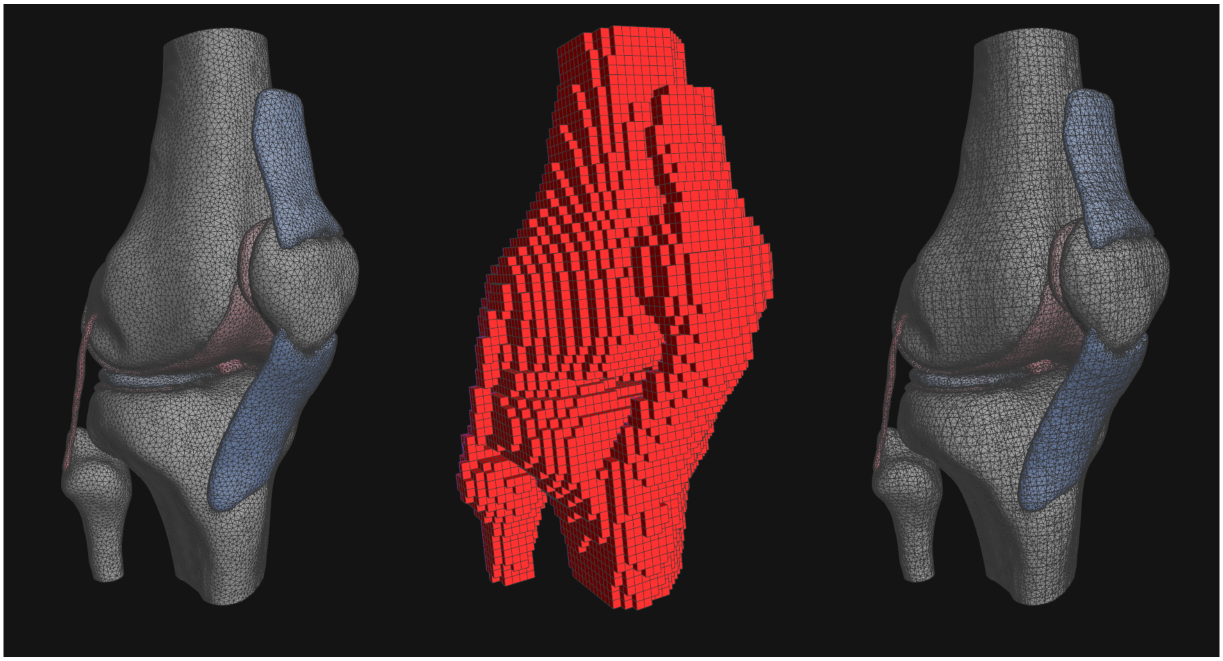


Figure 7.4. Polyhedral meshing sequence performed on knee mesh.

blender computes volume in 3D printing tab

One	Two
Three	Four

Table 7.1. An example of a table. Notice the caption is centered except when it runs longer than a single line on the page.

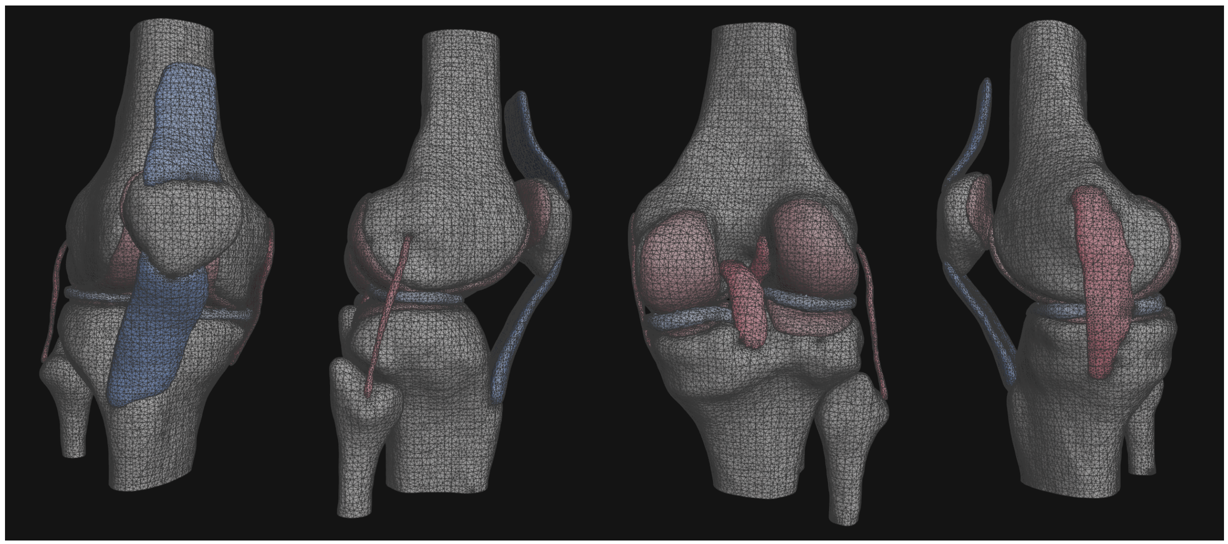


Figure 7.5. Resulting polyhedral mesh of knee.

Chapter 8

Conclusions

Omar Mohamed Hafez
March 2018
Civil and Environmental Engineering

Robust Image-Based Modeling and Simulation in Biomechanics

Abstract

The abstract that is submitted to UMI must be formatted as shown in the example here. The body of the abstract cannot exceed 350 words. It should be in typewritten form, double-spaced, and on bond paper. It is important to write an abstract that gives a clear description of the content and major divisions of the dissertation, since UMI will publish the abstract exactly as submitted. Students completing their requirements under Plan A should provide extra copies of the typed summary for use by the dissertation committee during the examination.

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