Credible Image-Based Modeling and Simulation of Mitral Valve

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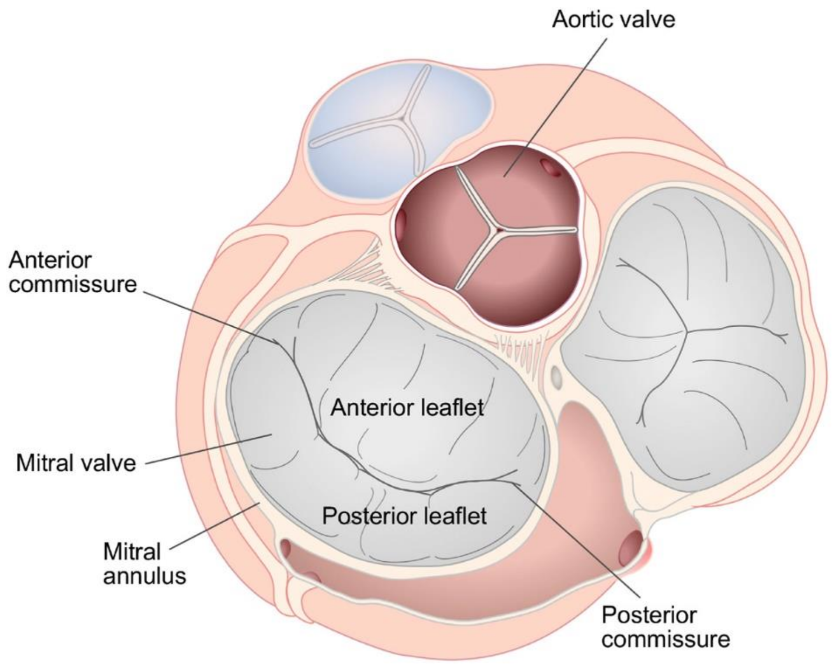
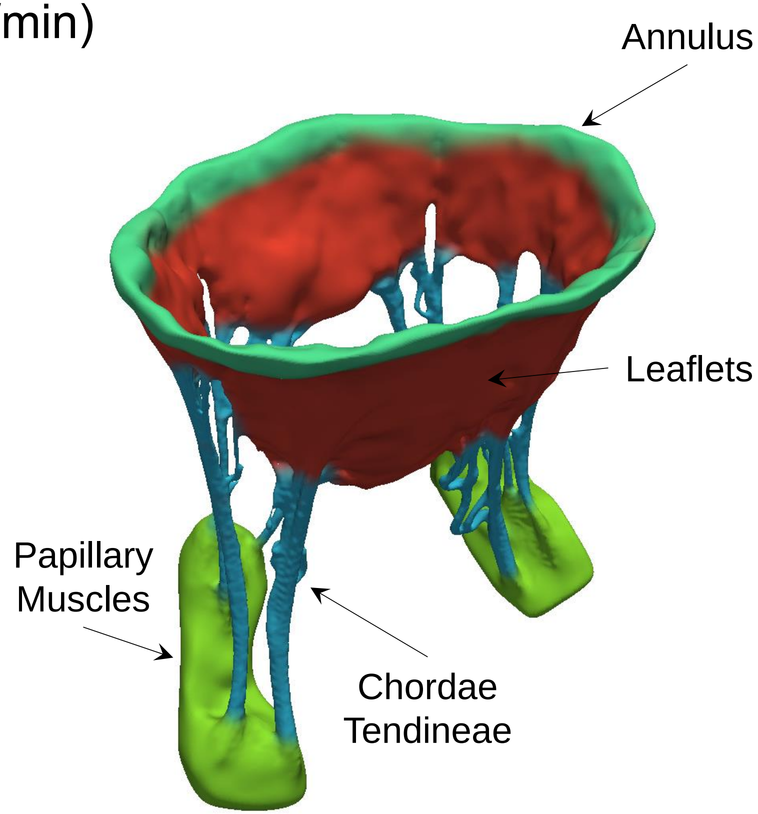
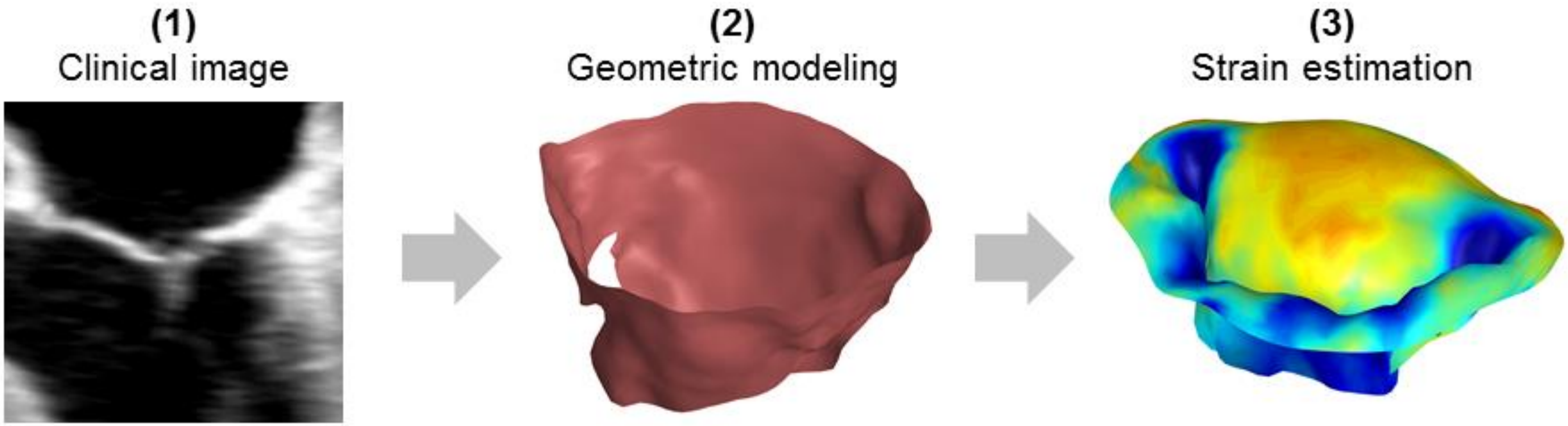
Mitral Valve (MV)

- 2 cusps (unique)
- 4~6 cm^2 orifice area (largest)
- Bearing >100 mmHg transvalvular pressure (healthy)
- “Beating” >100,000 a day (~80 beats/min)





R1: Define context clearly

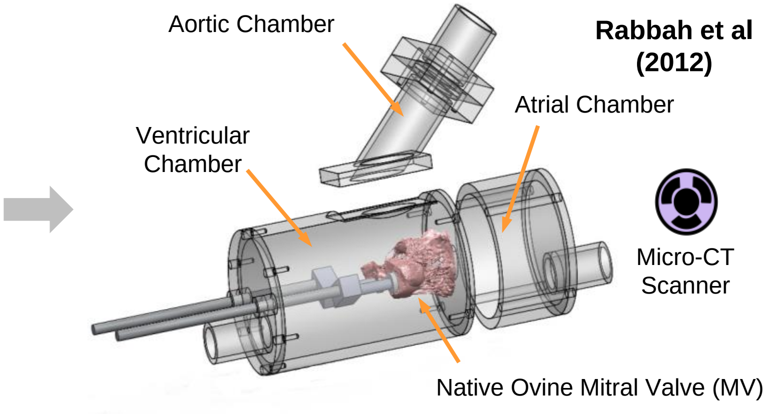


- Objectives
  - Provides local strain estimates across entire valve
  - Extendible to *in silico* perturbation studies
  - Non-invasive image-based method
- Physics-based morphing approach, calibrated using acquired imaging data
- Rely only on geometric data extractable *in vivo*

R2: Use appropriate data

Materials

- Five ovine MVs
- Dimensionally Compatible with the Georgia Tech Left Heart Simulator (GTLHS)



Methods

- In-vitro simulation of 9 states in GTLHS with tristate annulus holder
- Each MV was instrumented with ~100 fiducial markers
- Micro-CT imaging of MV geometry in each sate
- Collagen-fiber architecture imaging using SALS

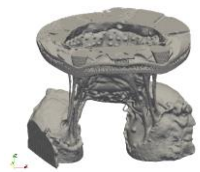
Normal / Healthy
healthy annulus
healthy PM positions

Dilated
dilated flat annulus
displaced PMs

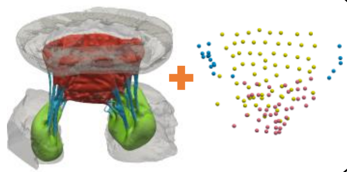
Surgically Modified
dilated flat annulus
displaced PMs

Major Data Processing Steps

End-diastolic (unloaded) state images

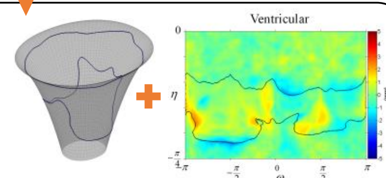


Filtering/Segmentation
Morphological labeling

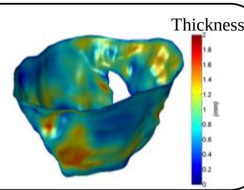


Trimming

Geometric modeling of leaflets:
Superquadric fitting + spectral analysis

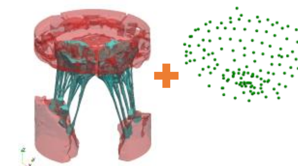


Reconstructed median surface with superimposed thickness field



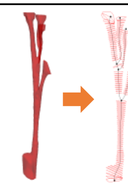
End-systolic (pressurized) state images

Filtering/Segmentation
Morphological labeling

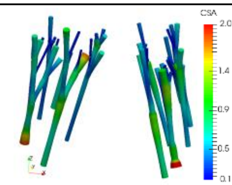


Trimming

Extraction of centerlines & pointwise CSA
(curve-skeleton representation)



Reconstructed Chordae Tendineae with superimposed CSA



python · FEniCS project · OPEN CASCADE · VTK · jupyter · ParaView
SciPy · matplotlib · NumPy · Fiji · ImageJ · MeshLab

simpleware ScanIP
ZBrush

R5: Use version control [GIT]

Bitbucket

Author	Commit	Message	Date
Andrew Drach	b0cd2bb	refactoring, minor fixes, add new features + Add [Leaflets] histogram fro...	2017-03-07
Andrew Drach	5e438c3	refactoring, minor fixes	2017-02-25
Andrew Drach	11400be	minor updates, refactoring	2017-02-20
Andrew Drach	eac5d2b	new features, bug fixes + [Abaqus]: added MVCT prestrain; 2D leaflet ou...	2017-01-25
Andrew Drach	ce4eba3	+ [Abaqus]: added Abaqus pre- and post-processing module + [BCS]: a...	2016-12-15
Andrew Drach	bf0da9d	+ [Chordae]: added a module to perform projection, flaring, and export ...	2016-10-08
Andrew Drach	c5f0826	+ Added a new module [BCS] for processing of boundary conditions data	2016-10-08
Andrew Drach	6660236	+ [Leaflets]: added thickness processing functionality + [CFA]: added affi...	2016-10-08
Andrew Drach	3c6ee58	- added the pipeline for processing of CFA data - minor update to the O...	2016-09-20
Andrew Drach	cf4bda6	updated the code for Chordae processing, added the meshing module	2016-09-20
Andrew Drach	191cbcd	- Added a script to design new marker locations - Minor update to the ...	2016-08-23
Andrew Drach	3d70a85	- Finished the morphing scripts [OpenClosed-02 and Open-Closed-03] -...	2016-08-18
Andrew Drach	f813266	- Added export of boundary curves to MAT file in [Leaflets-02-map_mar...	2016-08-15
Andrew Drach	f5a3918	finished working on [Leaflets-02-map_markers]	2016-08-12
Andrew Drach	26dc516 M	Merged in parameterize-env (pull request #1) added parameterization o...	2016-08-11
Andrew Drach	7fcb814	added parameterization of environmental variables in env.paths	2016-08-11
Andrew Drach	0e7cc51	Strippped down version	2016-08-10
Andrew Drach	91509ab	Initial commit	2016-08-10

Unfortunately, no version control for the documentation (user guides)

Bitbucket

jupyter

R6: Document adequately

Name	Last Modified	File size
env	10 months ago	
old	a year ago	
post-processing	8 months ago	
utils	a year ago	
Abaqus-01-input.ipynb	8 months ago	58.4 kB
Abaqus-02-post-chordae.ipynb	a year ago	7.78 kB
Abaqus-02-post-leaflets-Copy1.ipynb	a year ago	24.2 kB
Abaqus-02-post-leaflets.ipynb	a year ago	26.2 kB
Abaqus-03-post-leaflets-CAS.ipynb	8 months ago	13.7 kB
Abaqus-03-post-leaflets-histogram.ipynb	8 months ago	1.29 MB
Abaqus-03-post-leaflets-stats.ipynb	8 months ago	8.67 kB
Abaqus-04-marker-errors.ipynb	10 months ago	2.24 MB
Abaqus-04-post-leaflets-averaging.ipynb	8 months ago	15.9 kB
BCS-01-extract-data.ipynb	a year ago	11.7 kB
BCS-01-in-vivo-annulus.ipynb	a year ago	50.9 kB
BCS-02-annulus-disps.ipynb	a year ago	11.3 kB
BCS-03-origin-disps.ipynb	a year ago	6.57 kB
BCS-04-compare-annuli.ipynb	2 years ago	180 kB
CalcTriMeasures.ipynb	2 years ago	11 kB
CFA-01-readSALS.ipynb	a year ago	1.98 MB

R6: Document adequately

Import modules

```
#!/usr/bin/env python

###############################################################################
"""This script processes CSV file with boundary representation of the leaflets
   and generates finite element mesh with mapped markers"""
__author__     = "Andrew Drach"
__copyright__  = "(c) 2017 Andrew Drach"
__credits__    = "Andrew Drach"
__license__    = "<license>"
__version__    = "1.0.1"
__maintainer__ = "Andrew Drach"
__email__      = "andrew.drach@utexas.edu"
__status__     = "Development"
###############################################################################

import os, sys, itertools, math, copy
import logging
from time import clock
from functools import wraps
import numpy as np
import scipy.io as sio
import scipy.interpolate as sint

import triangle
import triangle.plot as triplot
import matplotlib.pyplot as plt
from mpl_toolkits.axes_grid1 import make_axes_locatable
%matplotlib inline

from env.paths import *
from utils.bSpline_utils import *
from utils.VTK_utils import *
from utils.SQfunctions import *
from utils.leaflets_utils import *
from utils.marker_utils import *

import vtk
```

```
# Define the function which performs 2D ball pivoting to build the curve connectivity from scatter data
# INPUT ARGUMENTS:
#     lim_a -- angle constraint
#     lim_d -- radius constraint
#     scl_y -- y scaling
# OUTPUT: sorted indices of a connected curve
def BallPivoting2D(data1,lim_a=120,lim_d=0.025,scl_y=5,duptol1=1e-9):

    vnorm = lambda x  : np.sum(x**2)**0.5
    vcos  = lambda x,y: np.sum(x*y)/vnorm(x)/vnorm(y)
    acosd = lambda x  : math.degrees( math.acos(x) )

    data        = np.copy(data1)
    data[:,1] *= scl_y

    len1      = len(data)
    pnt1      = data[0]
    dir1      = np.array([1.0,0.0,0.0])
    mask1     = np.ones(len1,dtype=bool)
    mask1[0] = False
    sort1     = [0]
```

Import modules

Initialize variables and setup logging

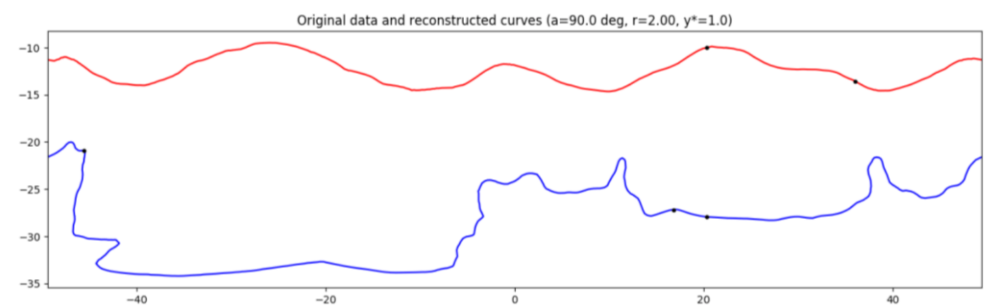
```
INFO     ----------  START OF Leaflets-02-map_markers  ----------
```

Read CSV and MAT files

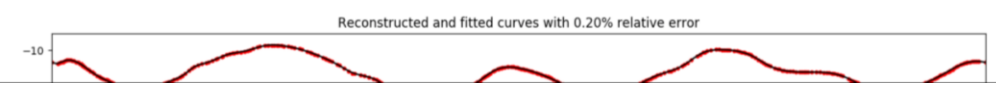
```
INFO     Opening [c:\Andrew\Academia\___MV\UT09\leaflets\input\UT09_atr_boundaries.csv]
INFO     The point cloud consists of 2800 vertices
INFO     X range: -1.000  1.002
INFO     Y range: -0.266 -0.074
INFO     Total of 1708 duplicates removed
INFO     Total of 142 edge points removed
INFO     Opening [c:\Andrew\Academia\___MV\UT09\leaflets\input\UT09_sq_fit_params.mat]
```

Reconstruct, visualize, and export the boundaries in AC coordinate system

```
INFO     Ball pivoting parameters: angle = 90.0 degrees, radius = 2.00, y scaling = 1.0
INFO     Reconstructing curve 1
INFO     [BallPivoting2D]: The pivoting step (10.730) is larger than the limit (2.0)
INFO     [BallPivoting2D]: Total number of points in the curve: 422
INFO     Reconstructing curve 2
INFO     [BallPivoting2D]: The pivoting step (15.300) is larger than the limit (2.0)
INFO     [BallPivoting2D]: Total number of points in the curve: 523
```




```
INFO     [Fit2Dcurve]: 0.2% with 58 coefficients. Status: 0
INFO     [Fit2Dcurve]: 0.2% with 85 coefficients. Status: 0
```



R1: Define context clearly

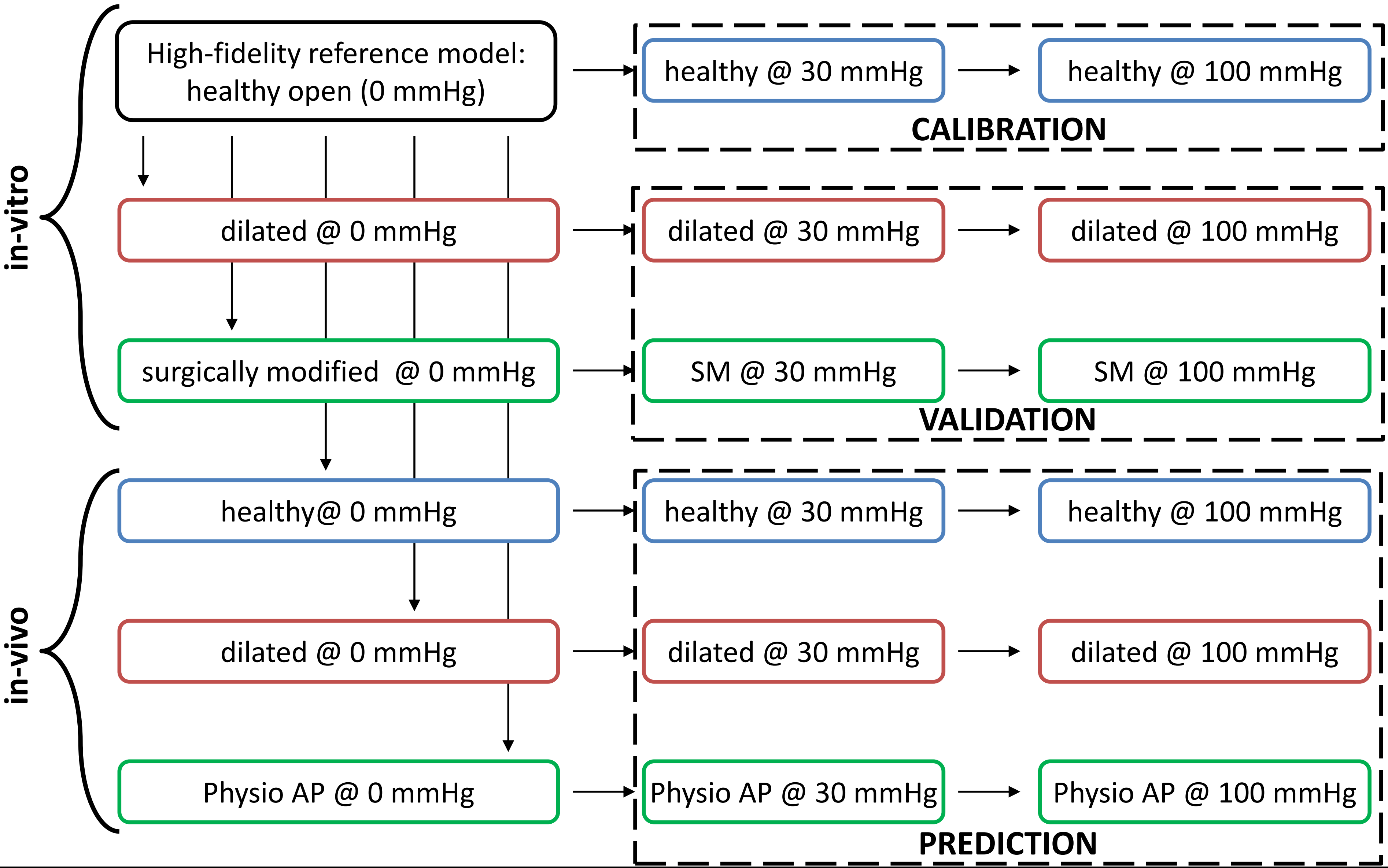
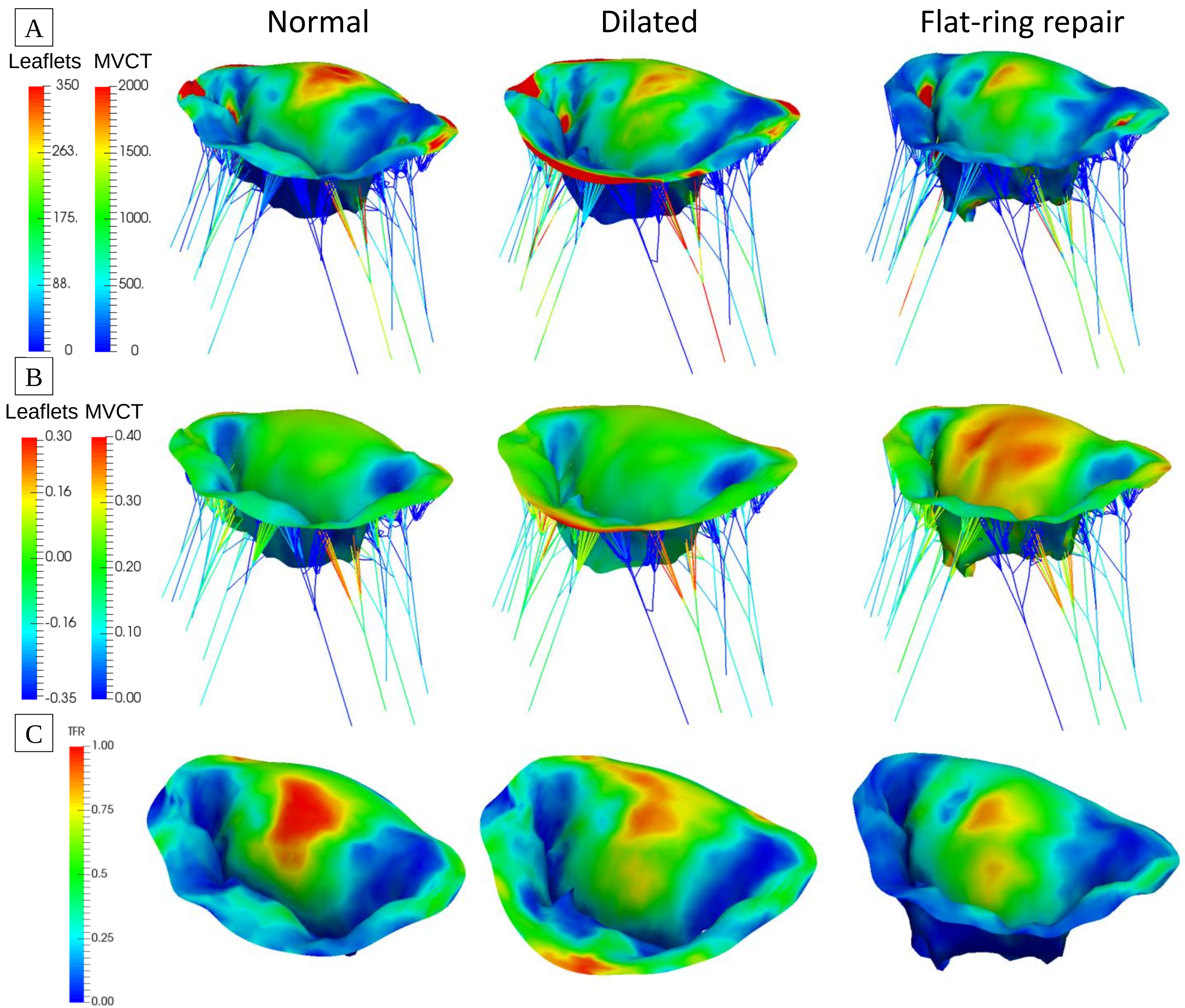


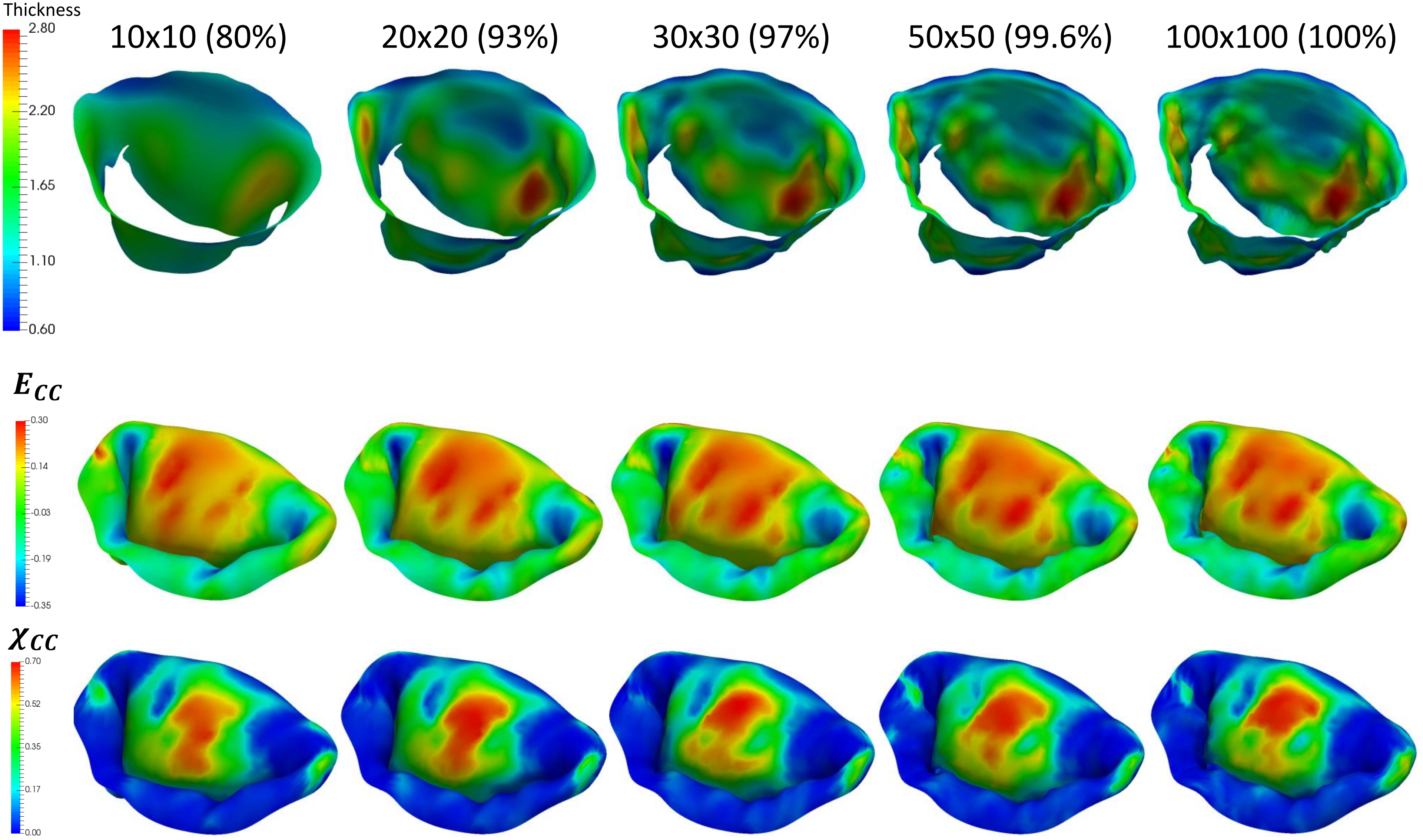
Illustration of Simulation Results



R9: Test competing implementations
R10: Conform to standards

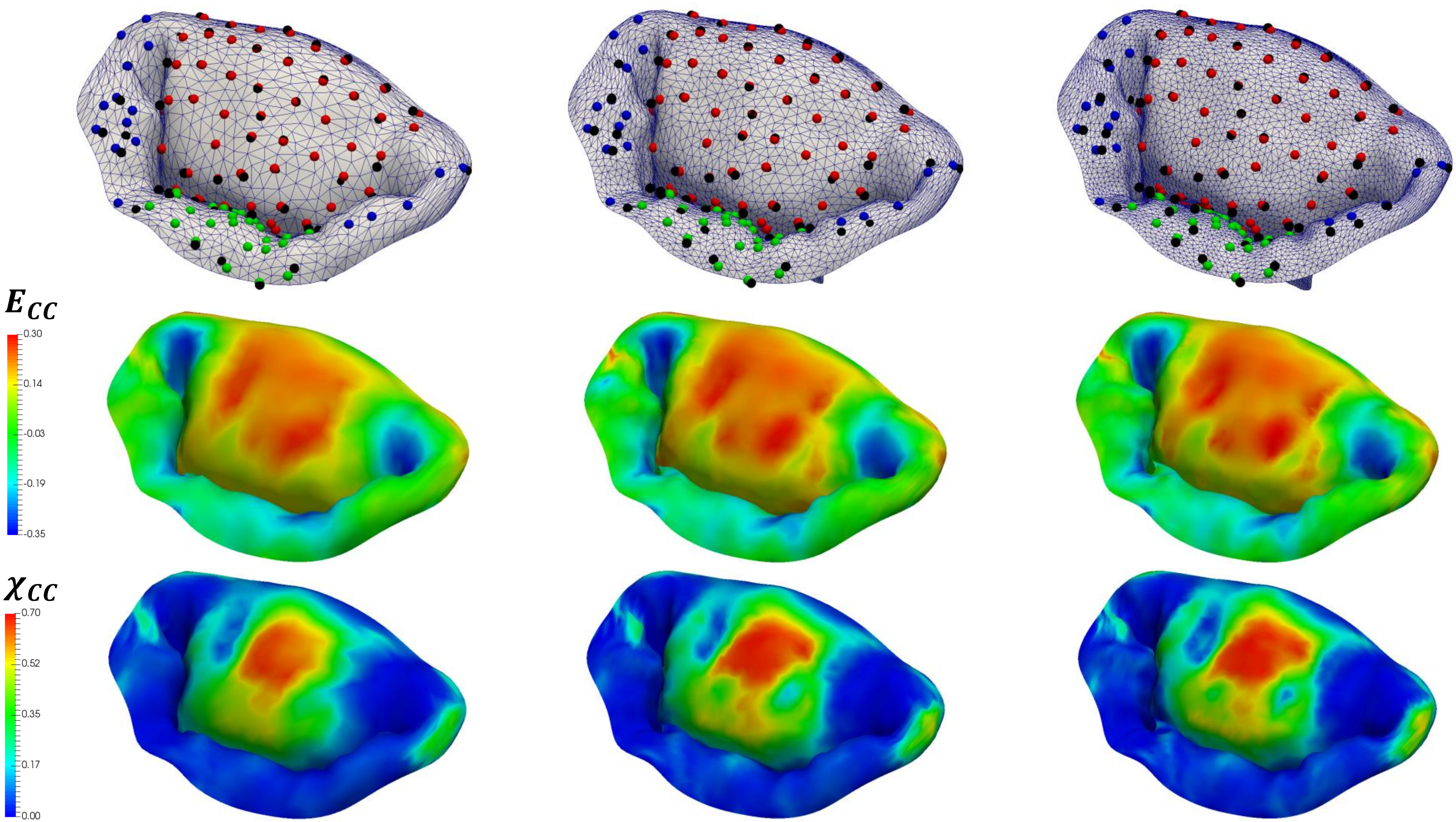
Unfortunately, no comparison to the external / independent models, approaches or standards

Sensitivity Studies: Resolution of Features



Sensitivity Studies: FE Discretization

N100 | N150 | N200



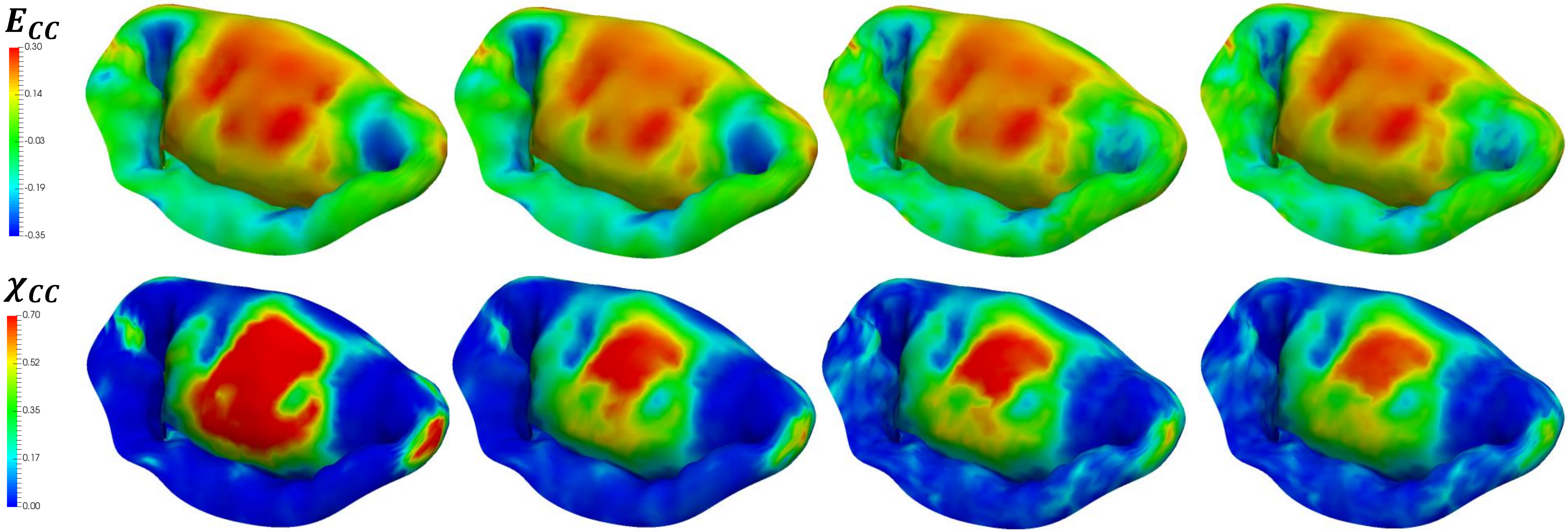
2,610 tri
elm.size ~0.94 mm

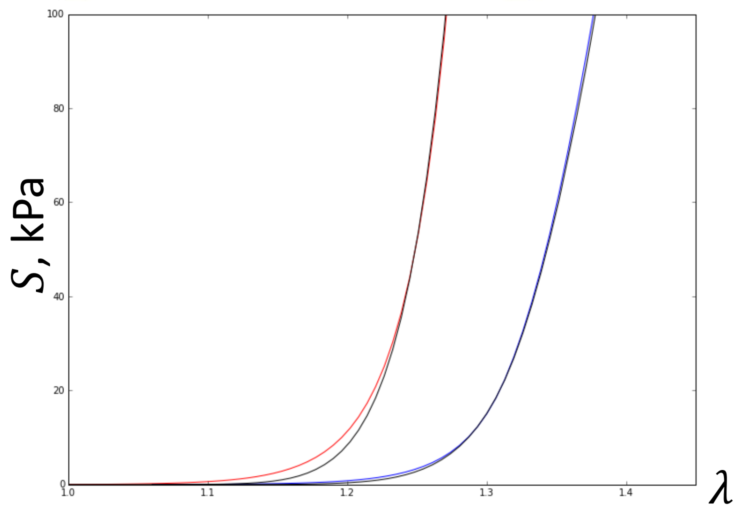
5,770 tri
elm.size ~0.63 mm

10,338 tri
elm.size ~0.47 mm

Sensitivity Studies: Material Model

Isotropic | PD = CC, σ=30° | PD = mapped, σ=30° | Fully mapped PD, σ



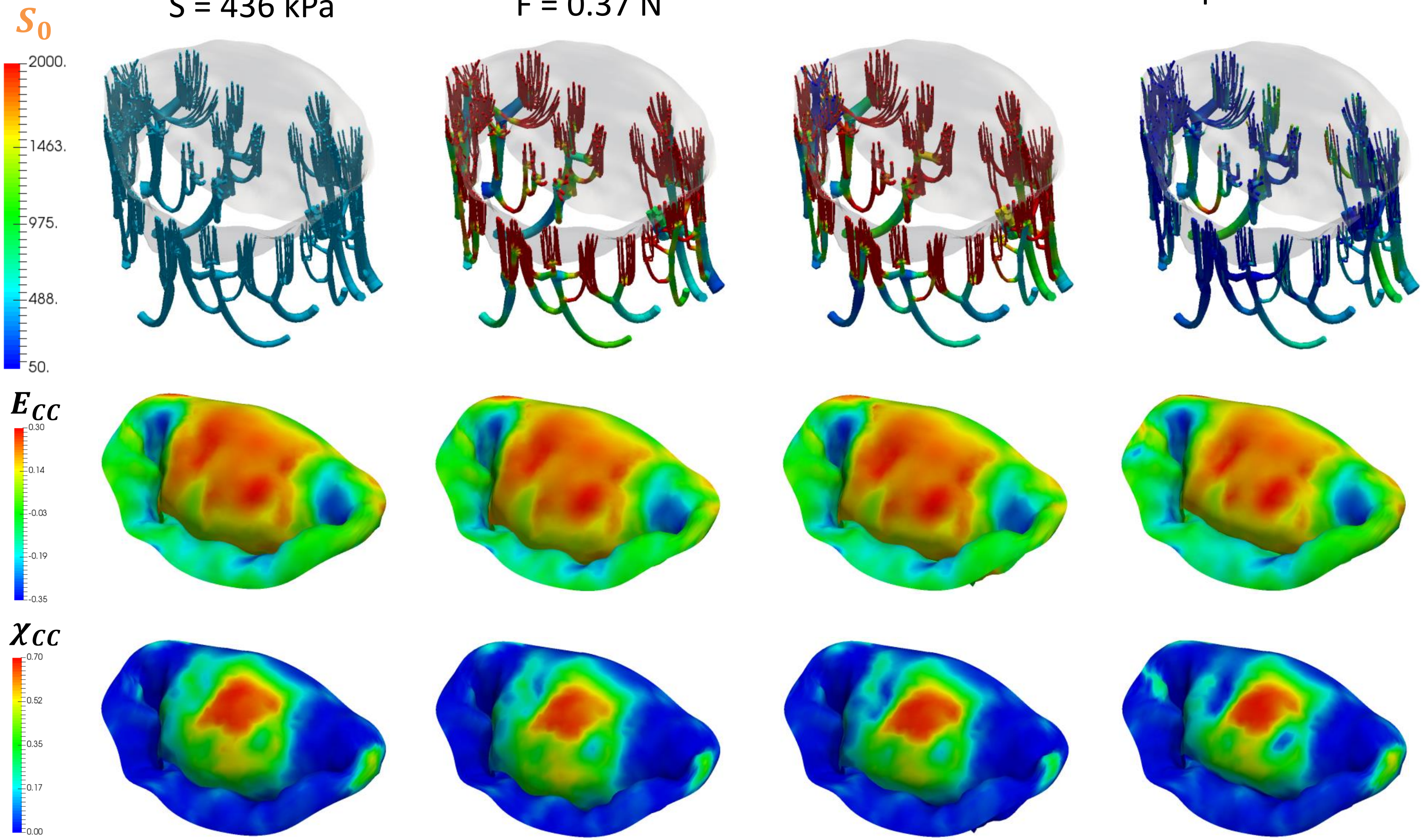


Simplified Structural Model (SSM)
by Fan&Sacks 2014

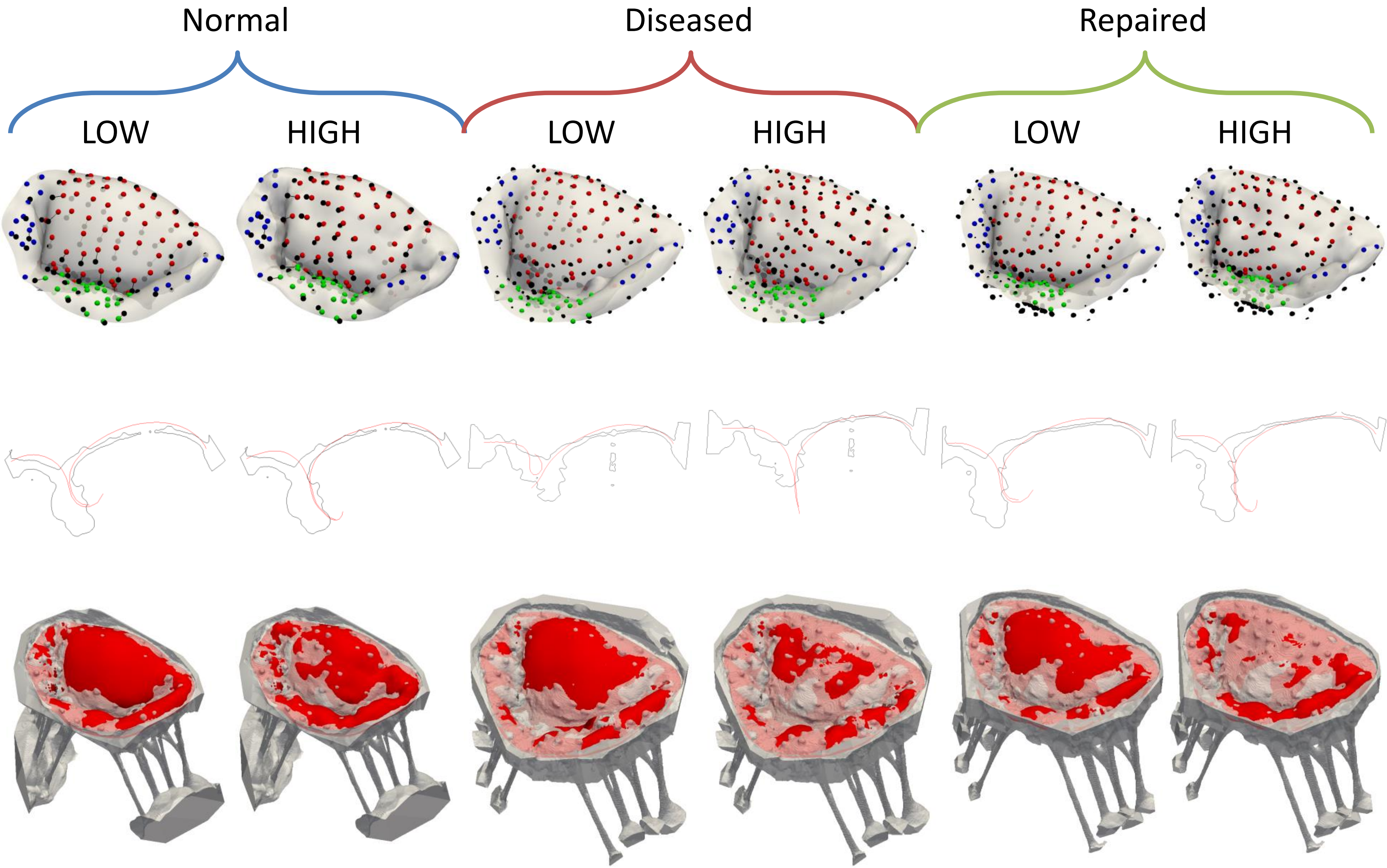
$\mu_m = 10.11$ kPa
$c_0 = 0.0485$ kPa
$c_1 = 24.26$
$\sigma = 22.94°$
$E_{ub} = 0.55$

Sensitivity Studies: Chordae Prestrain

avg S S = 436 kPa	avg F F = 0.37 N	F = Reaction	Fully mapped pre-strain

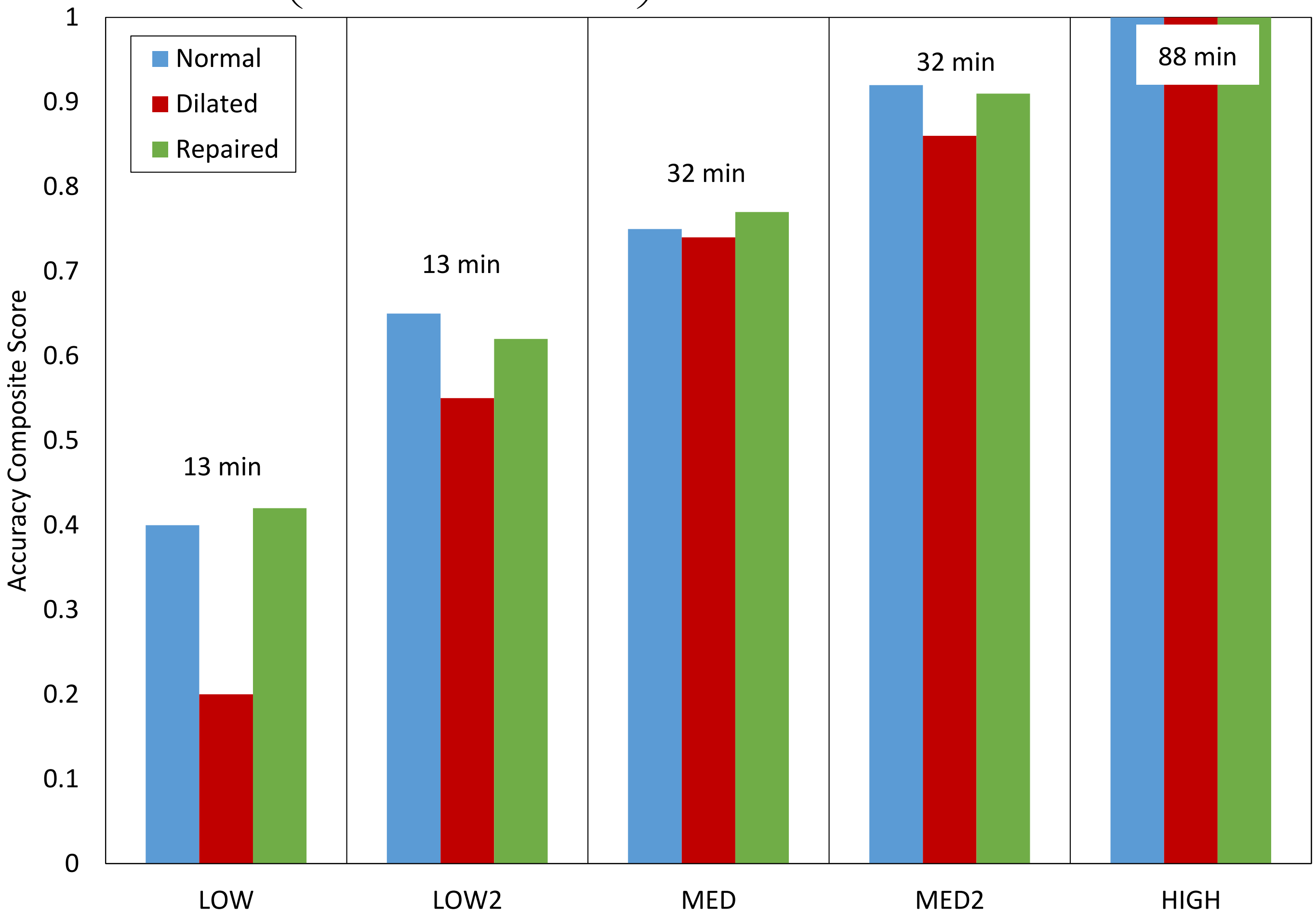


Simulation Results



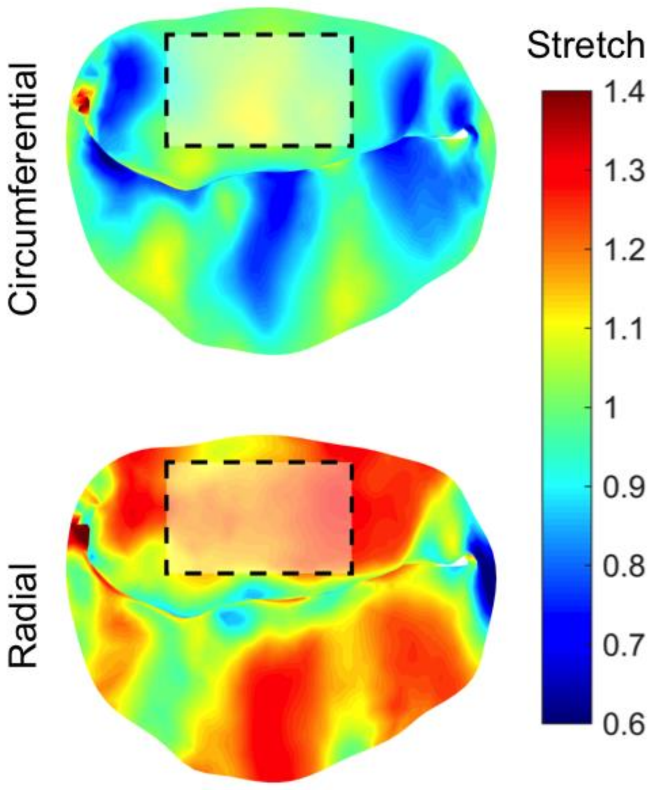
R3: Evaluate within context (in-vitro)

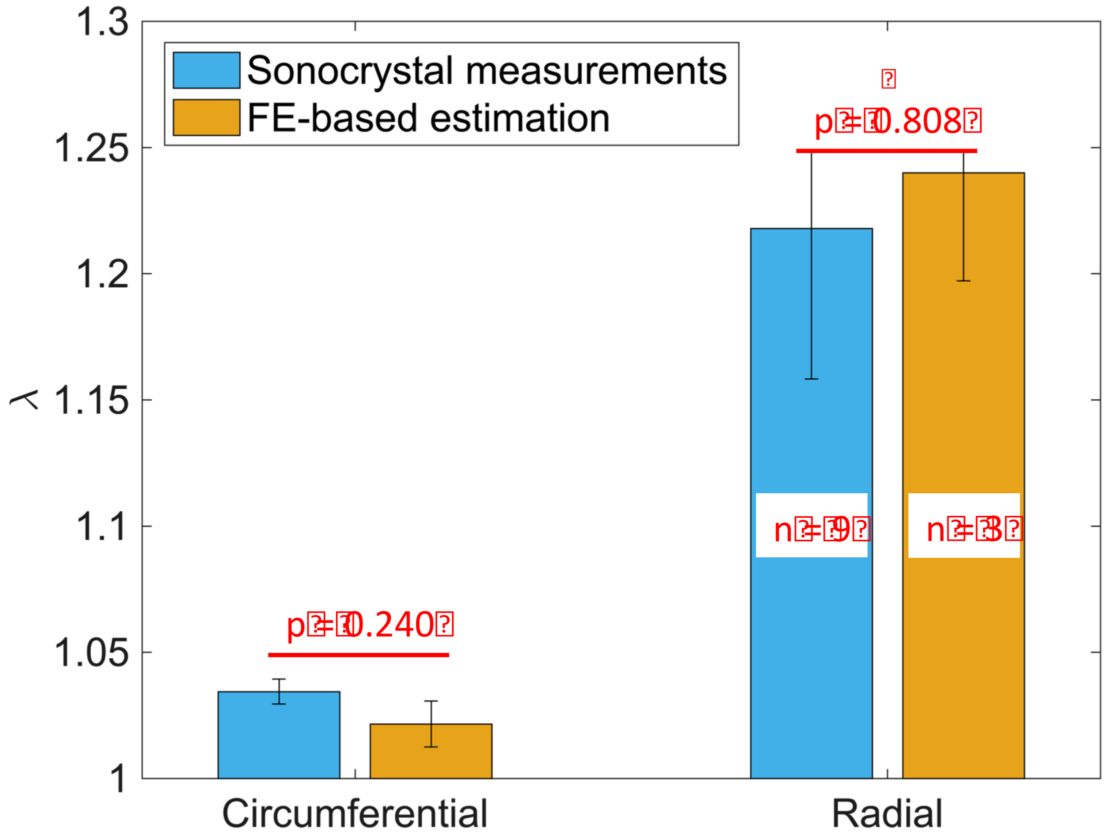
$$CAS = \sum_k \left(1 - \frac{\sqrt{\sum_i^N \left(q_{i,k} - \bar{q}_{i,k} \right)^2}}{\sigma_{i,k}} \right) / \dim(k) \qquad k = \{S_{CC}, S_{RR}, E_{CC}, E_{RR}, \mathbf{X}_{CC}, \mathbf{X}_{RR},\}$$



R3: Evaluate within context (in-vivo)

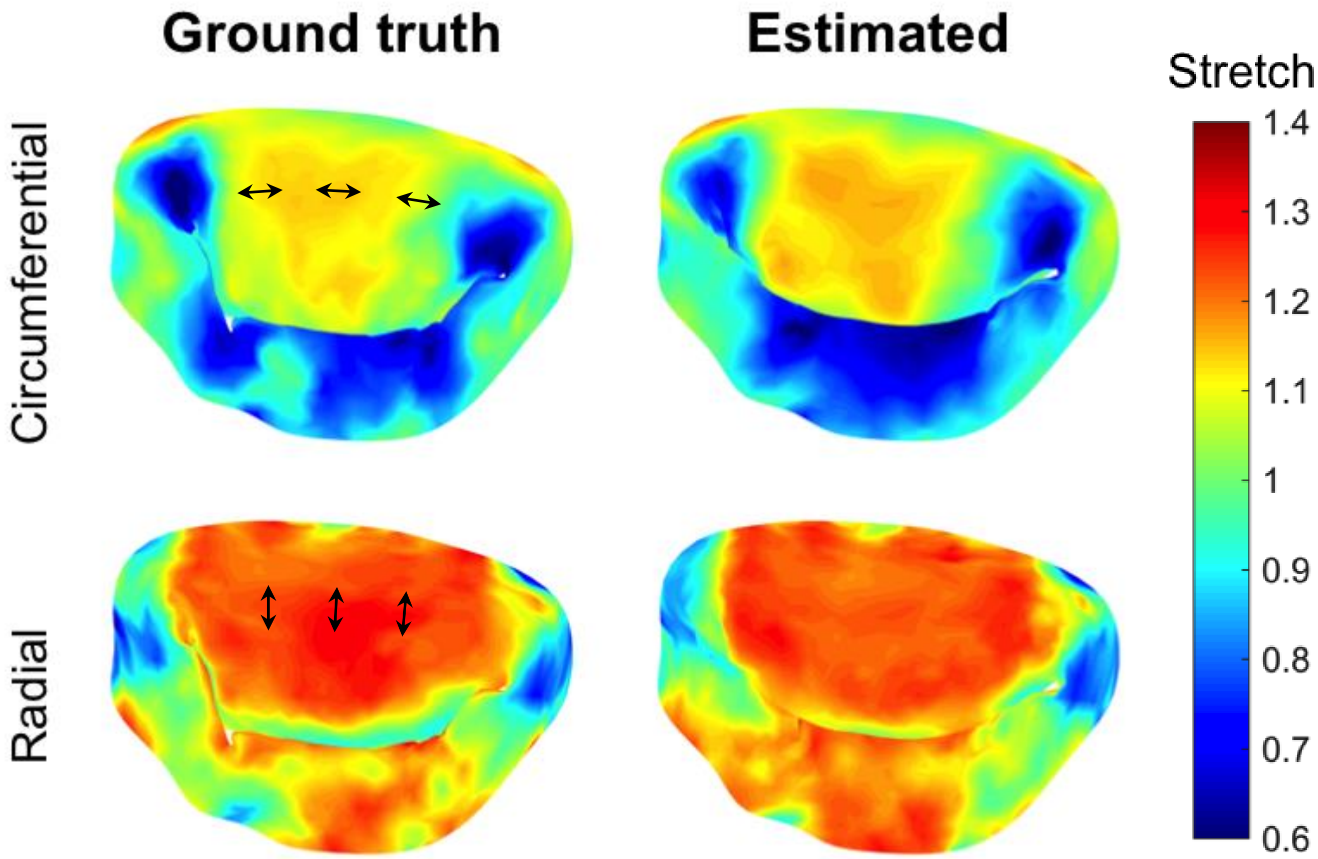
Accuracy of the Method





R4: List limitations explicitly

Accuracy of strain estimates



We have chosen to use a uniform thickness and uniform downward chord-mimicking force

R7: Disseminate broadly

R8: Get independent reviews

PEER-REVIEWED PUBLICATIONS

1. Khalighi AH, Rego BV, Drach A, Gorman RC, Gorman JH, Sacks MS. "Development of a Functionally Equivalent Model of the Mitral Valve Chordae Tendineae Through Topology Optimization" [Under Review] Annals of biomedical engineering. 2018
2. Rego BV, Khalighi AH, Drach A, Lai EK, Pouch AM, Gorman RC, Gorman JH, Sacks MS. "A non-invasive method for the determination of in vivo mitral valve leaflet strains" [Under Review]] International journal for numerical methods in biomedical engineering. 2018
3. Ayoub S. Tsai KC, Khalighi AH, Sacks MS. "The Three-Dimensional Microenvironment of the Mitral Valve: Insights into the Effects of Physiological Loads" [In press]. Cellular and Molecular Bioengineering
4. Sacks MS, Khalighi AH, Rego BV, Ayoub S, Drach A. "On the need for multi-scale geometric modelling of the mitral heart valve". Healthcare technology letters. 2017 Oct 25;4(5):150

…………

9. Drach A, Khalighi AH, ter Huurne FM, Lee CH, Bloodworth C, Pierce EL, Jensen MO, Yoganathan AP, Sacks MS. "Population-averaged geometric model of mitral valve from patient-specific imaging data". Journal of medical devices. 2015 Sep 1;9(3):030952.

PRESENTATIONS AT INTERNATIONAL CONFERENCES

2018: 9 presentations 2017: 16 presentations 2016: 6 presentations 2015: 7 presentations

Unfortunately, no external / independent users due to some limitations on dissemination

Acknowledgments

People:

- Charles H. Bloodworth IV (GeorgiaTech)
- Eric L. Pierce (GeorgiaTech)

Funding

- NHLBI NIH Grant R01HL119297

Summary

Rule	Status of Implementation
R1: Define context clearly	**GOOD**
R2: Use appropriate data	**GOOD**
R3: Evaluate within context	**GOOD**
R4: List limitations explicitly	**AVERAGE** (not comprehensive enough to be used immediately in the clinical applications)
R5: Use version control	**GOOD**
R6: Document adequately	**AVERAGE** (lack of tutorials, user guide)
R7: Disseminate broadly	**GOOD**
R8: Get independent reviews	**AVERAGE** (lack of review by independent users)
R9: Test competing implementations	**AVERAGE** (lack of comparison against independent models/approaches)
R10: Conform to standards	**BAD**