Credible Image-Based Modeling and Simulation of Mitral Valve

Andrew Drach ¹, Amir H. Khalighi ¹, Bruno V. Rego ¹, Michael S. Sacks ¹, Joseph H. Gorman III ², Robert C. Gorman ²

¹ Willerson Center for Cardiovascular Modeling & Simulation
Institute for Computational Engineering and Science
The University of Texas at Austin

² Gorman Cardiovascular Research Group
Perelman School of Medicine
University of Pennsylvania
Mitral Valve (MV)

- 2 cusps (unique)
- 4~6 cm² orifice area (largest)
- Bearing >100 mmHg transvalvular pressure (healthy)
- “Beating” >100,000 a day (~80 beats/min)
• 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*
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 state
• Collagen-fiber architecture imaging using SALS

Rabbah et al (2012)

Native Ovine Mitral Valve (MV)

Micro-CT Scanner

Aortic Chamber

Ventricular Chamber

Atrial Chamber

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

Trimming

Geometric modeling of leaflets:
Superquadric fitting + spectral analysis

Reconstructed median surface with superimposed thickness field

End-systolic (pressurized) state images

Trimming

Filtering/Segmentation
Morphological labeling

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

Reconstructed Chordae Tendineae with superimposed CSA

Python
Fenics Project
CASCADe
ViTK
Jupyter
ParaView
ScanIP
Simpleware
ZBrush
SciPy
Matplotlib
NumPy
Fiji
ImageJ
MeshLab

The University of Texas at Austin
R5: Use version control [GIT]

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<th>Date</th>
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<td>Andrew Drach</td>
<td>b8cd2bb</td>
<td>refactoring, minor fixes, add new features + Add [Leaflets] histogram fro...</td>
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<td>5e438c3</td>
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<td>+ [Abaqus]: added Abaqus pre- and post-processing module + [BCS]: a...</td>
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<td>Andrew Drach</td>
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<td>+ [Chordae]: added a module to perform projection, flaring, and export ...</td>
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<td>+ Added a new module [BCS] for processing of boundary conditions data</td>
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<td>+ [Leaflets]: added thickness processing functionality + [CFA]: added affi...</td>
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<td>- added the pipeline for processing of CFA data - minor update to the O...</td>
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<td>updated the code for Chordae processing, added the meshing module</td>
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<td>- Added a script to design new marker locations - Minor update to the ...</td>
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<td>- Finished the morphing scripts [OpenClosed-02 and Open-Closed-03] ...</td>
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<td>9e7cc51</td>
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<td>91509ab</td>
<td>Initial commit</td>
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Unfortunately, no version control for the documentation (user guides)
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# Import modules

```python
# $ python

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

import triangle
import matplotlib.pyplot as plt
from mpl_toolkits.axes_grid1 import make_axes_locatable
from matplotlib.colors import *
from matplotlib.ticker import *

# Define the function which performs 2D ball pivoting to build the curve connectivity from scatter data
# INPUT ARGUMENTS:
#  - angle: angle constraint
#  - radius: radius constraint
#  - scaling: y scaling
# OUTPUT: sorted indices of a connected curve

def BallPivoting2D(data, lim_a=120, lim_B=0.025, scl_y=0.5, duptol=1e-9):
    data = np.copy(data)
    scl_y = np.sort(scl_y)

    for i in range(len(data[1])):
        if np.array_equal(data[1], scl_y):
            return data[1]
```

**Initialize variables and setup logging**

INFO: START OF LEAFLETS-02-map_markers

**Read CSV and MAT files**

INFO: Opening [c:\Academia\__MW\UT09\leaflets\input\UT09_attributes.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:\Academia\__MW\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 (10.738) 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 (15.040) is larger than the limit (2.0)
INFO: [BallPivoting2D]: Total number of points in the curve: 523

**Reconstructed and fitted curves with 0.2% relative error**
High-fidelity reference model:
healthy open (0 mmHg)

- dilated @ 0 mmHg
- surgically modified @ 0 mmHg
- healthy @ 0 mmHg

in-vitro

in-vivo

- dilated @ 0 mmHg
- Physio AP @ 0 mmHg

CALIBRATION

- healthy @ 30 mmHg
- dilated @ 30 mmHg
- SM @ 30 mmHg
- healthy @ 100 mmHg
- dilated @ 100 mmHg
- SM @ 100 mmHg

VALIDATION

- healthy @ 30 mmHg
- dilated @ 30 mmHg
- healthy @ 100 mmHg
- dilated @ 100 mmHg
- dilated @ 100 mmHg

PREDICTION
Illustration of Simulation Results

Leaflets MVCT

Normal

Dilated

Flat-ring repair

A

Leaflets MVCT

350

2000

B

Leaflets MVCT

0.30

0.40

C

TER

1.00

0.75

0.50

0.25

0.00

normal

dilated

flat-ring repair
R9: Test competing implementations
R10: Conform to standards

Unfortunately, no comparison to the external / independent models, approaches or standards
Sensitivity Studies: Resolution of Features

Thickness

10x10 (80%)  20x20 (93%)  30x30 (97%)  50x50 (99.6%)  100x100 (100%)
Sensitivity Studies: FE Discretization

- N100: 2,610 tri, elm.size ~0.94 mm
- N150: 5,770 tri, elm.size ~0.63 mm
- N200: 10,338 tri, elm.size ~0.47 mm
Sensitivity Studies: Material Model

Isotropic

PD = CC, $\sigma = 30^\circ$

PD = mapped, $\sigma = 30^\circ$

Fully mapped PD, $\sigma$

---

Simplified Structural Model (SSM) by Fan&Sacks 2014

$\mu_m = 10.11$ kPa

$c_0 = 0.0485$ kPa

$c_1 = 24.26$

$\sigma = 22.94^\circ$

$E_{ub} = 0.55$
Sensitivity Studies: Chordae Prestrain

avg S
S = 436 kPa

avg F
F = 0.37 N

F = Reaction

Fully mapped pre-strain
Simulation Results

Normal
LOW
HIGH

Diseased
LOW
HIGH

Repaired
LOW
HIGH

Normal
Diseased
Repaired
R3: Evaluate within context (in-vitro)

\[
\text{CAS} = \sum_k \left( 1 - \frac{\sqrt{\sum_i^N (q_{i,k} - q_{i,k}^*)^2}}{\sigma_{i,k}} \right) / \text{dim}(k) \quad k = \{S_{CC}, S_{RR}, E_{CC}, E_{RR}, X_{CC}, X_{RR}\}
\]

- Normal
- Dilated
- Repaired

Accuracy Composite Score

- LOW: 13 min
- LOW2: 13 min
- MED: 32 min
- MED2: 32 min
- HIGH: 88 min
R3: Evaluate within context (in-vivo)

Accuracy of the Method

- Circumferential
  - Stretch range:
    - Minimum: 0.6
    - Maximum: 1.4

- Radial
  - Stretch range:
    - Minimum: 0.6
    - Maximum: 1.3

Statistical analysis:
- **Circumferential**
  - Mean: 1.05
  - Standard Deviation: 0.05
  - Sample Size: 9
  - *p*-value: 0.240

- **Radial**
  - Mean: 1.3
  - Standard Deviation: 0.15
  - Sample Size: 3
  - *p*-value: 0.808
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


PRESENTATIONS AT INTERNATIONAL CONFERENCES


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

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