Toward patient-specific computational study of aortic diseases: a population based shape modeling approach

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Outline

1. Research motivation
2. Statistical Shape Modeling approach
3. Training set data preparation
4. Statistical model result and mode analysis
5. Conclusion
Traditional treatment: surgery

Before surgery (*AHA)

After surgery

- Cardiac aneurysm treated by prosthetic graft
- High risks for elderly and with concomitant issues

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Alternative treatment

- Transcatheter Aortic Valve Replacement (TAVR)
- Much lower risks than surgical replacement
- Challenge: success s.t. aorta biomechanics
  device shape, size, position and orientation etc.
Biomedical simulations

- Numerical simulations: fast and inexpensive (FEM, CFD)
- Accuracy s.t. geometric modeling of aorta from CT/MRI
- Challenge: patient-specific geometric modeling of aorta
time-consuming process, noisy and incomplete data

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Statistical Shape Model

Patient data pool. e.g. femur

SSM: mean + modes

- Promising solution: **Statistical Shape Model** (SSM)
  - Shape variation pattern in a population of shapes
  - SSM (mean + modes): a compact representation

- Patient-specific model easily constructed from SSM

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Population based statistical shape modeling

- Formulated as an optimization problem
- Description length of statistical model defined by

\[ f = \sum_{m=1}^{n_S-1} L_m, \]

where each mode’s contribution is

\[ L_m = \begin{cases} 1 + \log(\frac{\lambda_m}{\lambda_{\text{cut}}}) & \lambda_m \geq \lambda_{\text{cut}} \\ \frac{\lambda_m}{\lambda_{\text{cut}}} & \text{otherwise} \end{cases} \]

- Optimization formulation

\[
\begin{align*}
\min_{\mathbf{b}} & \quad f(\mathbf{b}) = \sum_{\lambda_i \geq \lambda_{\text{cut}}} \left[ 1 + \log \frac{\lambda_k(\mathbf{b})}{\lambda_{\text{cut}}} \right] + \sum_{\lambda_k < \lambda_{\text{cut}}} \frac{\lambda_k(\mathbf{b})}{\lambda_{\text{cut}}} \\
\text{s.t.} & \quad \mathbf{E}(\mathbf{b}) \mathbf{v}_k(\mathbf{b}) = \lambda_i(\mathbf{b}) \mathbf{v}_k(\mathbf{b}) \\
& \quad \mathbf{v}_k^T(\mathbf{b}) \mathbf{v}_k(\mathbf{b}) = 1, \quad k = 1, \ldots, n_S \\
& \quad g(\mathbf{b}) < 0
\end{align*}
\]
Aorta statistical shape modeling flowchart

**Input**
Training set

**Mesh preprocessing**

**ICP alignment**

**Mesh parametrization**

**B-spline fitting**

**Landmark initialization**

**Landmarks redistribution**

**Correspondence Manipulation (Reparametrization)**

**PCA**

**Statistical Model (mean + modes)**

**Output SSM**

**DL converges?**

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Aorta SSM

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B-spline controlled landmarks manipulation

Reparametrization function $D(u)$

- Represented by B-spline

$$D(u) = \sum_{i=0}^{n_b-1} B_{i,p}(u)b_i$$

Before redistribution

After redistribution

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Aorta anatomy

1) Ascending aorta; 2) Aortic arch;
3) Left coronary artery; 5) Right coronary artery;
4) Left coronary sinus; 6) Right coronary sinus;
7) Non-coronary sinus
Input raw triangle meshes

<table>
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<th>Shape</th>
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<th>Sex</th>
<th>Age</th>
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<td>6</td>
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</tbody>
</table>

- From CT images
- 6 patients
- Patient C with severe aneurysm
Mesh processing

- Hole filling
- End trimming
- Smoothing
- Decimation

- Incomplete and/or noisy data
- Shape topology
One-time alignment

![Before alignment](image1)

![After alignment](image2)

- Iterative Closest Point algorithm

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Generatrix construction

- Consistent cylindrical topology

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Training set B-splines fitting

Shape 1

Shape 2

Shape 3

Shape 4

Shape 5

Shape 6
Optimization results

- Objective (DL) drops from 98.77 to 92.80 in 439 iterations
- Optimized mode variations
  \[ \lambda_1 = 2.06, \lambda_2 = 0.44, \lambda_3 = 0.38, \lambda_4 = 0.21, \lambda_5 = 0.11 \]
SSM result: mode 1

\[ b_1 = -3.00 \sigma_1 \]

- Mode variation:
  \[ \lambda_1 = 2.06 \ (64.5\%) \]

- Standard deviation:
  \[ \Sigma_m = \sqrt{\lambda_m} \quad (m = 1, ..., 5) \]

- Captured variation pattern:
  Ascending aorta dilation
SSM result: mode 2

\[ b_2 = -3.00 \sigma_2 \]

- Mode variation: 
  \[ \lambda_2 = 0.44 \ (13.8\%) \]
- Accumulative percentage 
  \[ \lambda_1 \ & \lambda_2 = 78.3\% \]
- Captured variation patterns:
  Ascending aorta dilation
  Coronary sinus dilation
SSM result: mode 3

\[ b_3 = -3.00 \sigma_3 \]

- **Mode variation:**
  \[ \lambda_3 = 0.38 \ (11.8\%) \]

- **Accumulative percentage**
  \[ \lambda_1 \ & \lambda_2 \ & \lambda_3 = 90.1\% \]

- **Captured variation patterns:**
  - Ascending aorta dilation
  - Coronary sinus dilation
  - **Annulus dilation**
Patient-specific modeling from SSM

Problem statement

- Input 1: SSM = mean $\bar{x}$ + modes $\{v_m\}$
- Input 2: any patient shape data $S_{Patient}$
- Output: Patient specific model $x_{Patient} = \bar{x} + \sum_{m=1}^{\tilde{m}} \beta_m v_m$
- Find $\{\beta_m\}$ s.t. $x_{Patient}$ sufficiently represents $S_{Patient}$

Viable methods

- Direct projection $x \approx, \beta_m = (x - \bar{x})^T v_m$
- Shape fitting. e.g. ICP etc.

Advantages

- More efficient, more convenient
- Less risky, less costly
- Less subject to incomplete data and/or feature noise
Conclusion

- Biomedical simulation: promising alternative to aorta surgeries
  - Advantage: much lower risks
  - Challenge: patient-specific geometric modeling of aorta

- Proposed solution: population based statistical shape modeling
  - Characterizes shape variation patterns in a set of shapes
  - Formulated as a optimization problem
  - Aorta variation across patients captured by statistical modes
  - Easy construction of patient-specific aortic model

- Future work
  - More complex topology
  - Larger population of aorta