3D Stress Analysis of Blood Vessels During Thrombectomy Using Multi-View Imaging

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American Heart Association. International Stroke Conference

UCLA Health

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Background and Motivation

Clinical Motivation

- Thrombectomy can cause vessel injury (e.g. perforation or rupturing).
- Determining vessel deformations and stresses during simulated thrombectomies on in-vitro silicone models may inform safer procedures.

Measurement gap

- Global metrics (e.g. force from a sensor) fail to localize vessel deformation.
- Conventional 3D imaging is often too slow, too costly, or cannot handle the complex 3D geometry needed to measure stresses in an ICA-MCA model.

Our approach

- We reconstruct 3D vessel deformations over time using a multi-camera system.
- We quantify regional displacements and stresses to compare the safety of different thrombectomy conditions.

Methodology

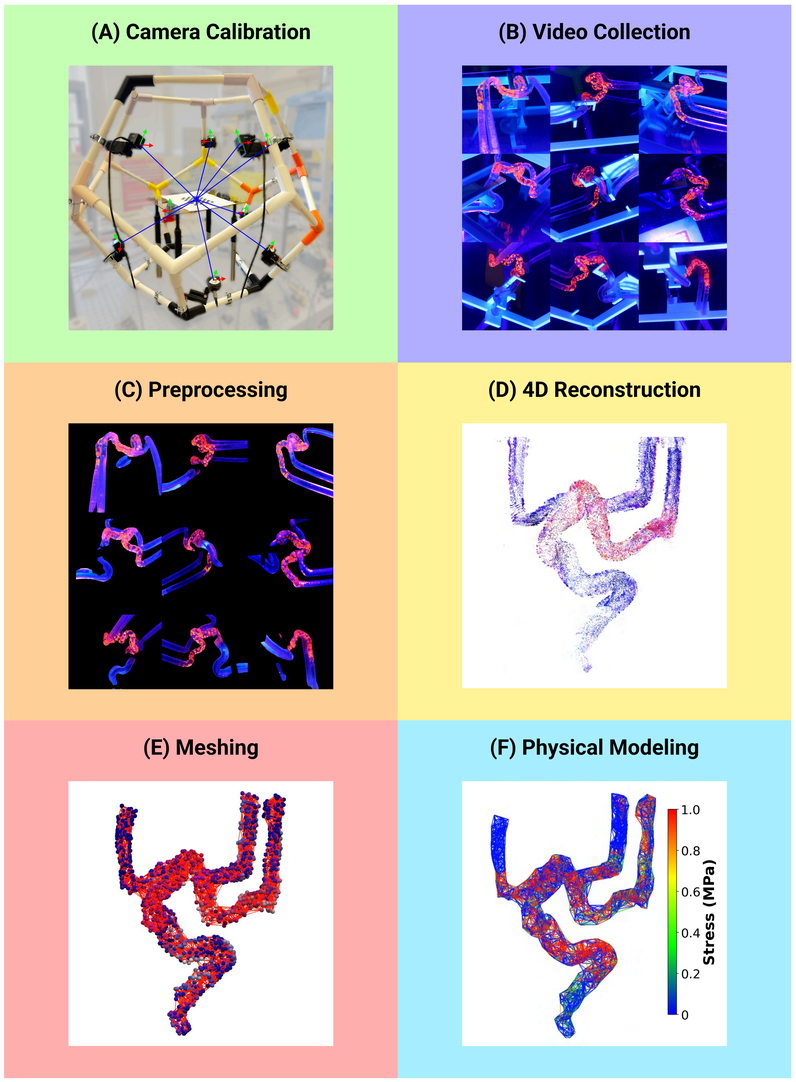

Figure 1. *Pipeline for multi-camera reconstruction of 3D vessel surface motion and estimation of stresses during thrombectomy in ICA-MCA phantoms.*

(A) Camera Calibration

- Nine 4K cameras recording at 20 fps were mounted equispaced on a dodecahedron setup to maximize view coverage of the vessel model.
- Camera positions and orientations were extracted using OpenCV's chessboard calibration.

(B) Video Collection

- ~4000 300 µm fluorescent microspheres were attached on the vessel model using clear silicone, and 400 nm UV light was shone to increase contrast for surface-tracking.

(C) Preprocessing

- Segment Anything Model 2 (SAM2) was used to filter for only the vessel model.
- Videos were synchronized and cropped for more accurate downstream reconstruction.

(D) 4D Reconstruction

- 4D Gaussian Splatting (4DGS) was used to produce temporally-stable time-deforming point clouds, and small-radii/low-opacity Gaussians were filtered out as noise.

(E) Meshing

- 5-Means was applied on points' colors, and DBSCAN was applied on points' positions.
- Delaunay triangulation was applied on the first-frame clusters, and cluster identities were propagated over time to create a time-evolving mesh of the vessel surface.

(F) Physical Modeling

- Point displacements at clinically-relevant regions were measured.
- A neo-Hookean spring-network model on the mesh was used to quantify stresses.

Validation

To validate our method, the 3D modeling software, Blender, was used to apply known bending and twisting deformations on the vessel while rendering views to feed into our pipeline for comparison. At peak deformation, the spatial distribution and magnitudes of point displacements (distance from initial position) show high fidelity between the ground-truth (GT) obtained from Blender and our method's reconstruction (Ours) (**Fig. 2A**). We also calculated time-resolved means of displacements within nine predefined vessel regions (**Fig. 2B**), and the max regional means demonstrate strong agreement between GT and Ours (**Fig. 2C**).

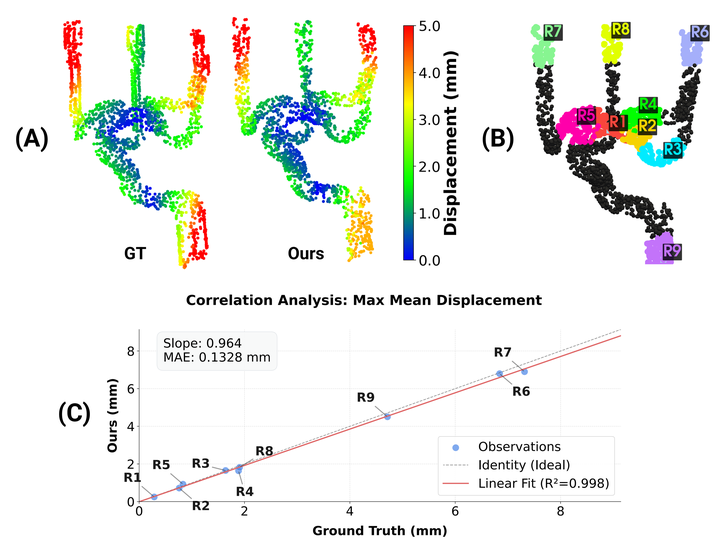

Figure 2. *Synthetic validation of displacement reconstruction*

(A) *Displacements for a representative synthetic bending and twisting deformation rendered in Blender. Ground truth (GT) and reconstructed (Ours) points displacements exhibit similar spatial patterns and magnitudes across the vessel surface.*

(B) *Regions of analysis for averaging of point displacements:* **R1** *(M1 Convex),* **R2** *(M1/M2 Bifurcation),* **R3** *(M2 proximal inferior),* **R4** *(M2 proximal superior),* **R5** *(ICA terminus / M1 origin),* **R6** *(MCA M2 end),* **R7** *(ACA end),* **R8** *(PCA end), and* **R9** *(ICA end).*

(C) *Correlation analysis of max mean displacements of regions from synthetic validation. Reconstructed displacements closely match ground truth across regions, with near-unity slope and low mean absolute error.*

Results

We analyzed a silicone ICA-MCA vessel model under two aspiration catheter (AC) placement conditions while undergoing a standardized linear-actuator-driven thrombectomy. Max mean displacements were larger with cervical ICA placement than with ICA terminus placement (2.53 vs. 0.56 mm at the M1/M2 bifurcation and 1.84 vs. 0.30 mm at the proximal M2; **Fig. 3A**). Point displacements at the time of peak deformation show greater values for the cervical condition compared with the terminal condition (**Fig. 3B, top**). Using the mesh-based spring-network model, we observed regions of high stress at the M1 segment, M1/M2 bifurcation, and M2 proximal regions, particularly in the cervical condition (**Fig. 3B, bottom**).

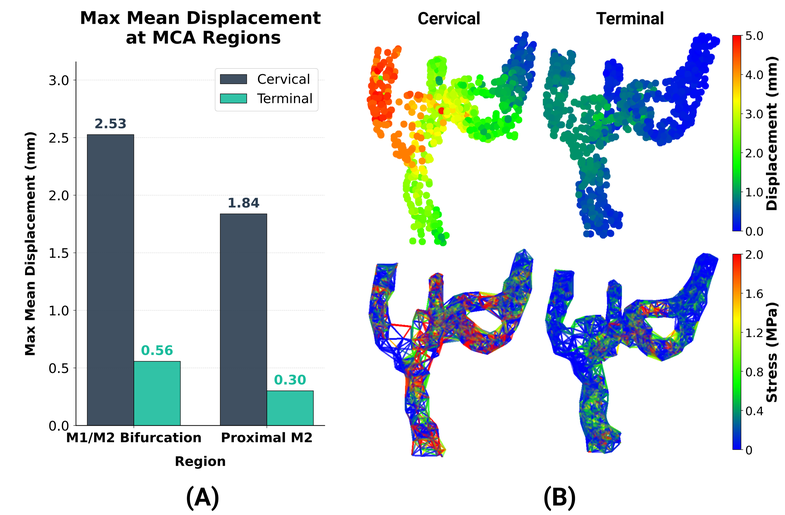

Figure 3. *Comparative vessel displacements and stresses for thrombectomy on the ICA-MCA model.*

(A) *Max mean displacement at the M1/M2 bifurcation and proximal M2 for the two AC positions. Cervical ICA placement resulted in greater displacement than ICA terminus placement at both regions.*

(B) *Point displacements (top) and spatial distribution of stresses (bottom) at the time of peak deformation for cervical ICA (left) and ICA terminus (right) AC placement.*

Discussion and Conclusion

Synthetic validation confirms our method accurately measures displacements of regions within complex vessel geometry with sub-millimeter precision (MAE = 0.13 mm, slope = 0.964, R^2 = 0.998; **Fig. 2C**) under controlled deformations. Benchtop experiments showed that moving the AC from the terminus to the cervical ICA caused a 4.5-fold spike in M1/M2 bifurcation displacement (2.53 vs. 0.56 mm; **Fig. 3A**). The spring-network model showed high stresses in regions with high curvature and bending, especially under cervical AC placement (**Fig. 3B**).

These findings suggest that AC placement in the ICA terminus may reduce the risk of iatrogenic vessel injury by minimizing vessel deformation during thrombectomy. This method enables a quantitative comparison of thrombectomy techniques by quantification of vessel displacements and stresses. While this silicone model makes simplifications (e.g. lacks extravascular support), this model still provides a consistent baseline for condition comparison. Future work will increase the number of trials and evaluate while varying more parameters such as pulling speed, pulling manner, vessel tortuosity, and clot location.

COI: None
Funding: UCLA Health and UCLA Physics and Astronomy Department

Further information
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