Biomechanical Modeling of Brain Shift During Neurosurgery

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Introduction

- Craniotomies for glioma tumor resection are often challenging as brain shifting (due to fluid loss, gravity, pressure changes, edema, etc.) causes a mismatch when intra-operative anatomical positions are compared to pre-operative imaging
- Low accuracy in pre-op planning due to uncertainty in brain shifts increases the difficulty of the procedure and the risk of harm to healthy tissue and further complications
- Biomechanics and Finite Element Modeling (FEM) can be utilized to accurately simulate brain shifts (i.e., sagging or swelling) for improved surgical planning

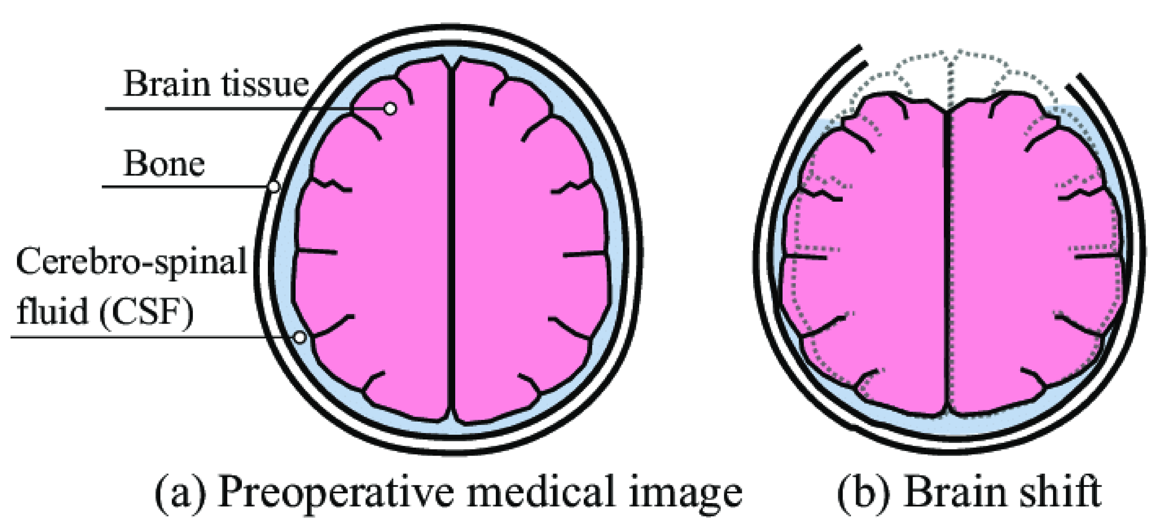

Fig. 1. Illustration of brain shift from (5) Chen et al, 2017, *IEEE Xplore*

Materials & Methods

- Brain shift simulated is due to the craniotomy prior to tumor resection through the following steps (Fig. 2):
- FEMs were created from a 3D mesh generated using several modeling software systems (RayStation, SimLab, HyperMesh, and various C scripts)
- Two material models were used in the FEM computation:
  - Viscoelastic – material with combination of viscous and elastic properties (i.e., gelatin). Models sagging
  - Poroelastic – material is porous and elastic (i.e., sponge). Takes into account more complex physics (brain drainage), and predicted to produce more accurate simulations. Models sagging, shrinking and swelling
- In addition, varying levels of cranio-spinal fluid (CSF) and head orientation were investigated (Fig. 3)
- Finite element analysis (FEA) simulations were computed using open-source software GetFEM on the MD Anderson SeaDragon super-computer
- FEA results were visualized on ParaView
- Accuracy of the model is determined using target registration error (TRE) based on pre-op MR images with ~15 set landmarks and compared to a grand truth based on intra-op ultrasound (iUS) of the same patient (see Fig 3)

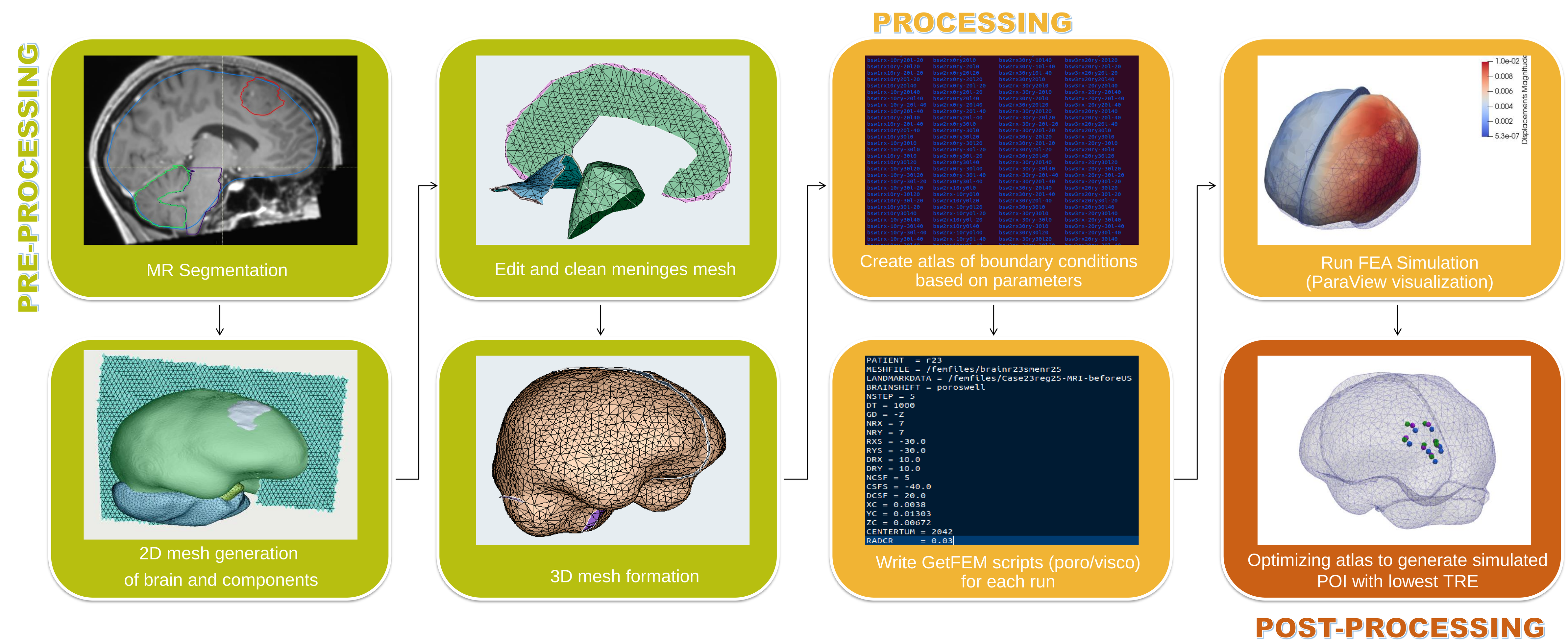

Fig. 2. Flowchart depicting general methodology of simulating brain shift in three phases: pre-processing (mesh generation), processing (FEM), and post-processing (optimization).

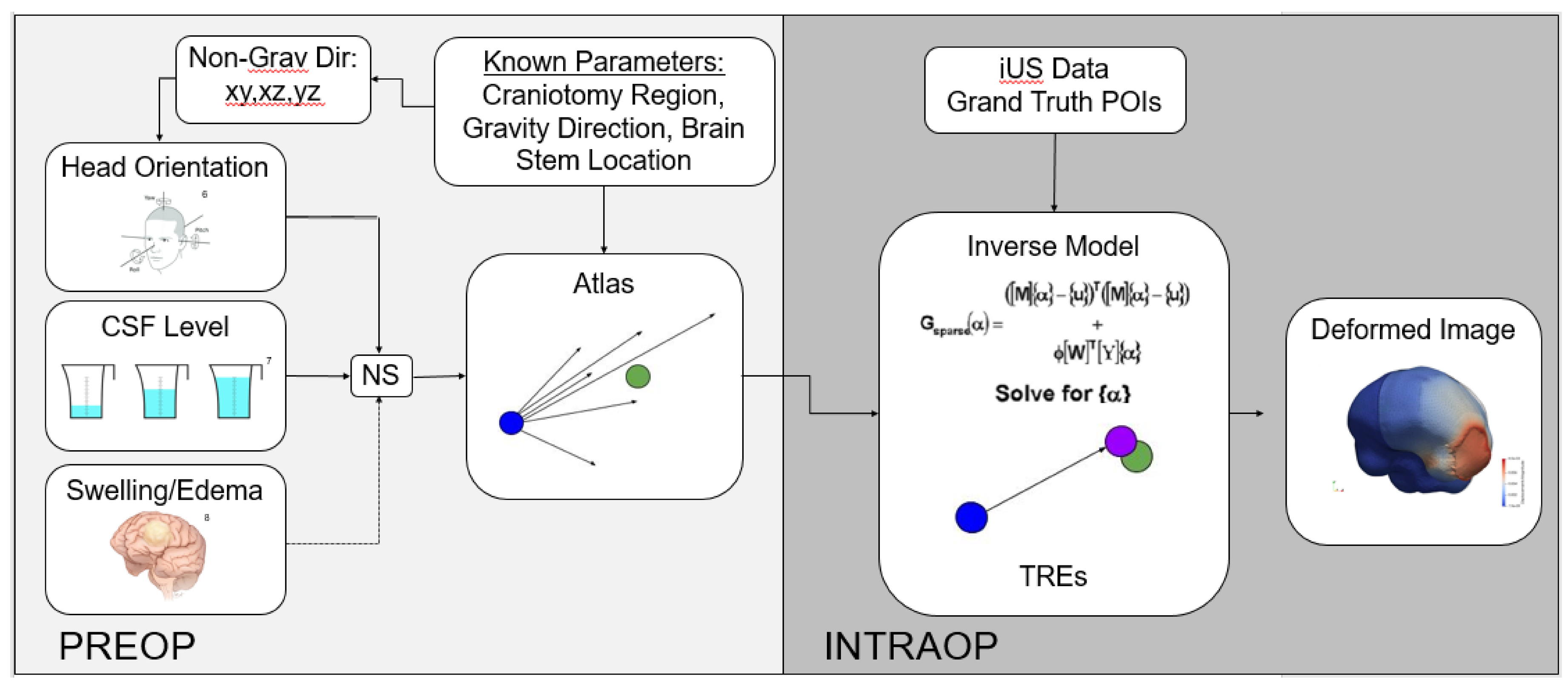

Fig. 3. Flowchart displaying atlas simulation process based on known and unknown parameters. Based on grand truth data, atlas is optimized with a linear combination formula, producing a deformed image. POI types color coded as: pre-op (blue), intra-op (green), simulated (purple). Illustrations from references (6), (7), and (8).

Results

A. Sagging: Poroelastic vs. Viscoelastic

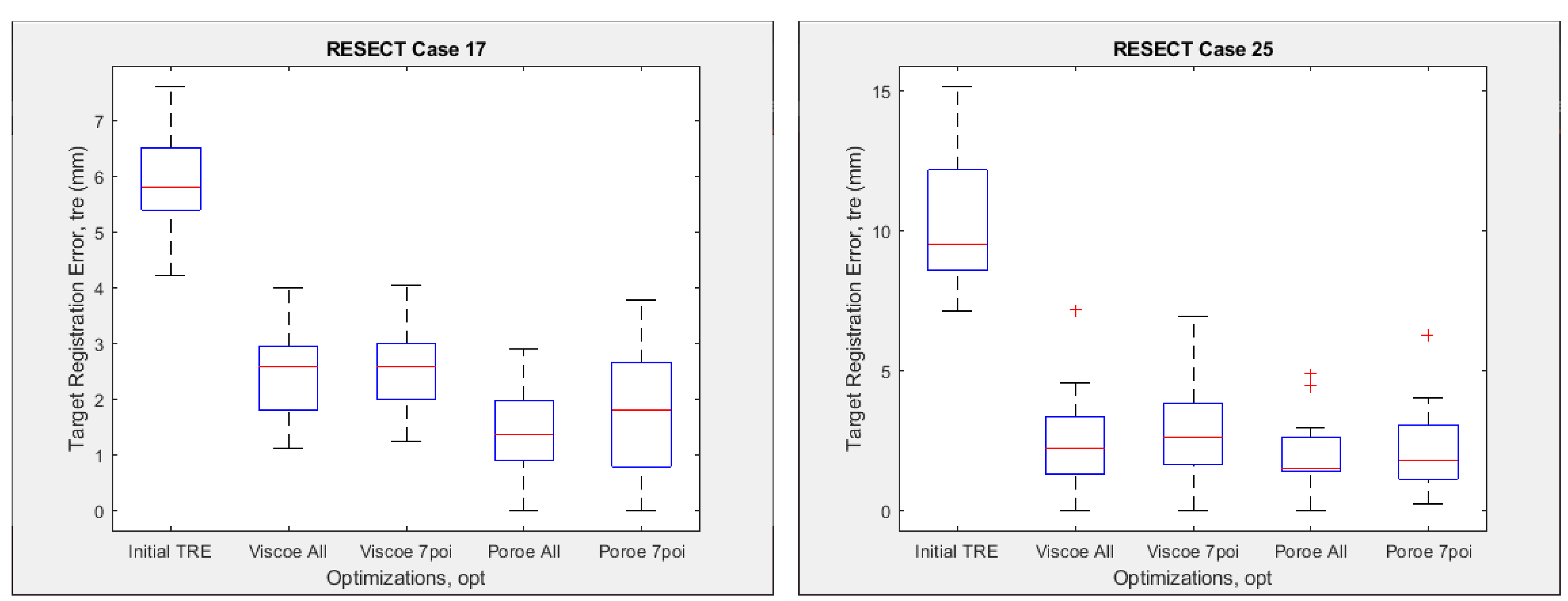

Fig. 4,5. Box and whisker plots of RESECT cases 17 and 25 (sagging). Target registration error (TRE) is the distance between the grand truth intra-op POI and the simulated point. Viscoelastic and poroelastic optimized target registration errors of all and 7 POIs are compared to initial TRE (original pre-op landmark without simulation). Optimized TRE with 7 POIs (about half of all) are reported to demonstrate continued accuracy of model with fewer data. Poroelastic model was found to produce lower TREs than viscoelastic. Using less POIs produced slightly less accurate and precise TREs.

B. Swelling

Fig. 6. Box and whisker plot of RESECT case 23 (swelling). Poroelastic optimized target registration errors are compared to initial TRE (original pre-op landmark without simulation). Optimized TRE with 7 POIs (about half of all) are also reported to demonstrate accuracy of model with fewer data. Having fewer POI TREs impacted accuracy assessment more than with sagging.

Conclusion

- Poroelastic model is more accurate than viscoelastic
  - Supports prediction that including more physical parameters increases simulation accuracy
- Poroelastic also took less time due to nature of its formula – elastic modulus does not vary with time whereas visco does
- Currently working on improving run time and accuracy
  - Pre-process mesh making takes >4 hours, FEA processing takes 4-12 hours
  - FEM code runs into some bugs due to minor errors in mesh modeling
- Future works: developing deep learning to automate simulation process and translate work to clinic

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