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Elastic Foundations as Heterogeneous Adventitial Boundary Condition for the Assessment of Aortic Wall and Peri-Aortic Stiffness from Dense-MRI Data Using Inverse FEM Approach

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ETM3 Engineered Tissue Multiscale Mechanics & Modeling
CMIL Cardiovascular Mechanics & Imaging Lab

Introduction

- Arterial stiffness has been associated with numerous cardiovascular pathologies and remains an important predictor of cardiovascular morbidity and mortality in clinical practice.
- DENSE-MRI is a technique that allows *in vivo* measuring of the displacement of the aortic wall.
- Aortic wall deforms heterogeneously during the cardiac cycle.
- Perivascular tethering is likely a relevant factor on vascular mechanics, though there has not been much research on quantifying its effects.

We propose using inverse FEM and heterogeneous Elastic Foundation Boundary Conditions to assess aortic wall mechanical properties and perivascular stiffness distribution.

We hypothesize that:

1. The heterogeneous EFBC is consistent for specific aortic locations among individuals with similar ages and health conditions.
2. Patient-specific aortic wall stiffness can be quantified non-invasively with inverse FEM and DENSE MRI.

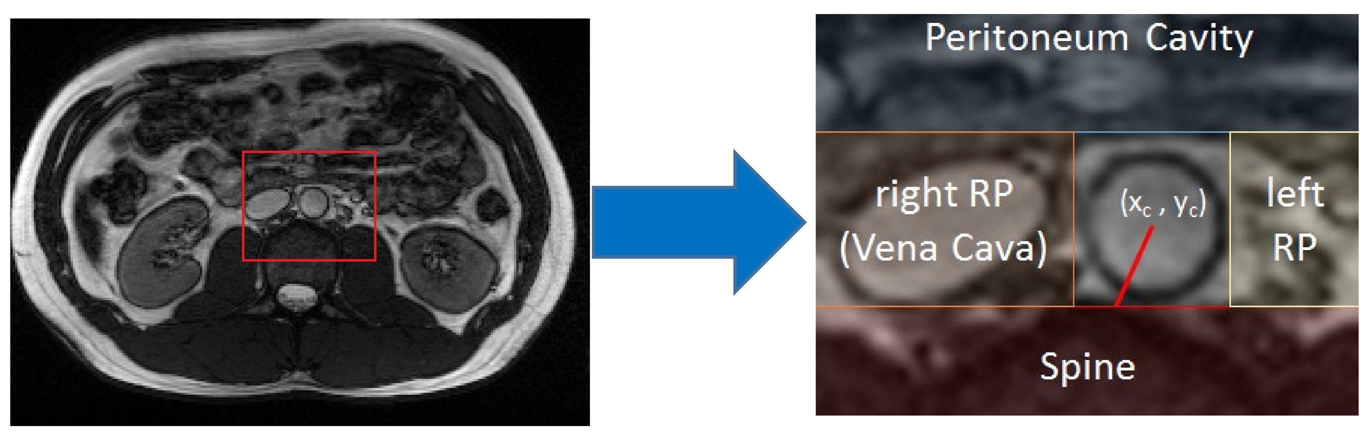


Figure 1. Axial cut at the infrarenal human abdomen, and the aorta and surrounding tissues as region of interest for the analysis. (Anatomic view).

Displacements

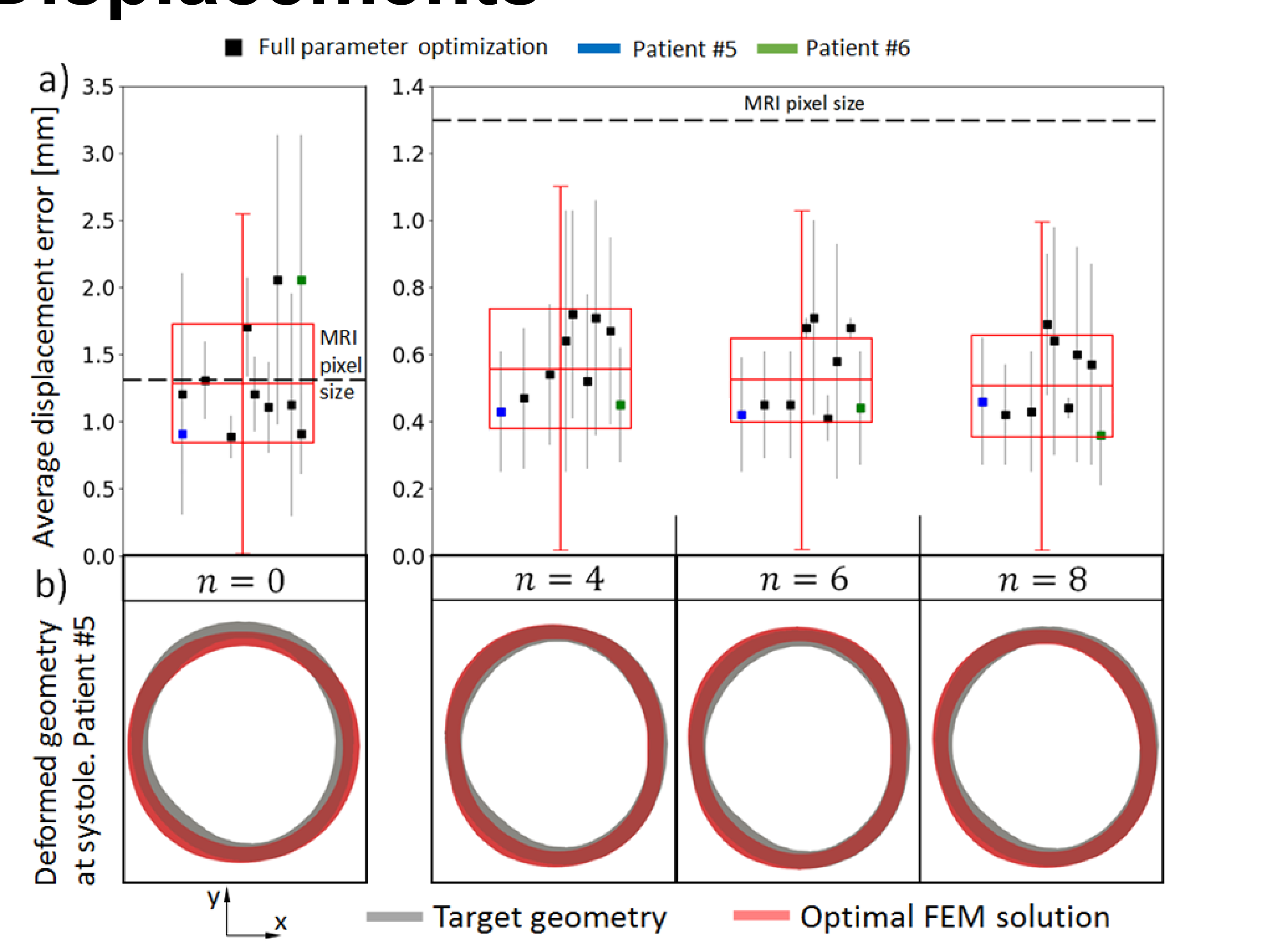
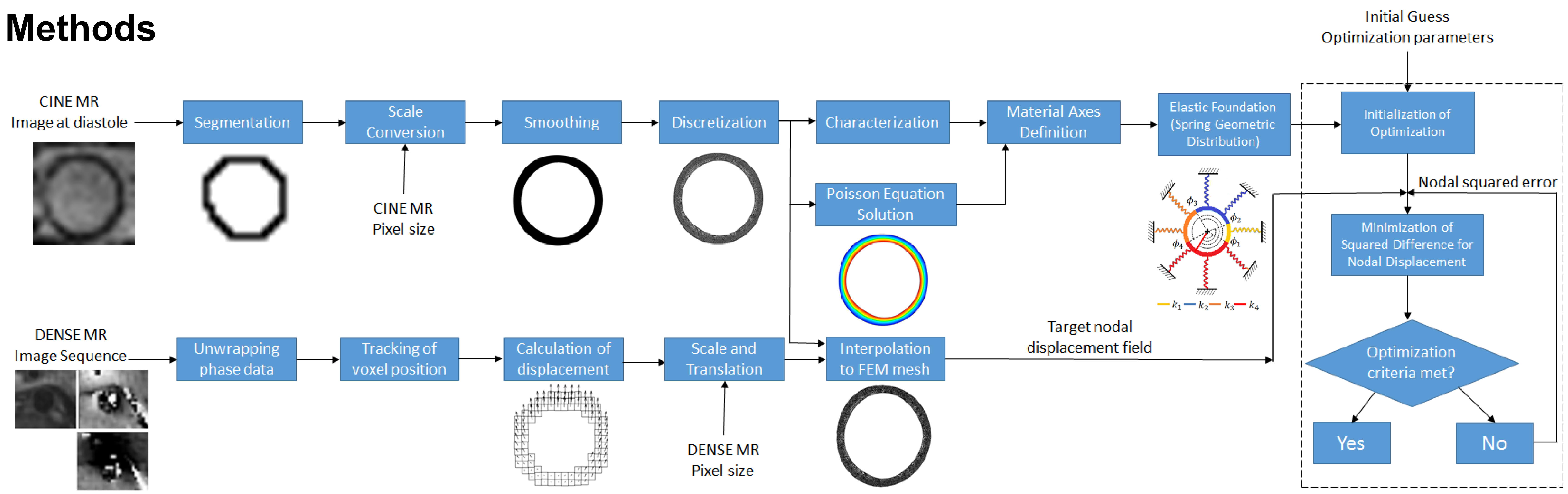


Figure 2. Simulated to measured mean displacement field error for different discretization of the EFBC (n=0 means traction free boundary condition at the adventitia).

Methods



Mechanical Properties

Ifrarenal Aortic Wall

Fung's orthotropic pseudo-elastic constitutive equation was used as the material model assuming plane strain state.

$$\Psi = \frac{c}{2}\left(e^{Q} - 1\right) + \frac{k}{2}(\ln J)^2$$

$$Q = a_{rrrr}\boldsymbol{E}_{rr}^2 + a_{\theta\theta\theta\theta}\boldsymbol{E}_{\theta\theta}^2 + 2a_{rr\theta\theta}\boldsymbol{E}_{rr}\boldsymbol{E}_{\theta\theta}$$

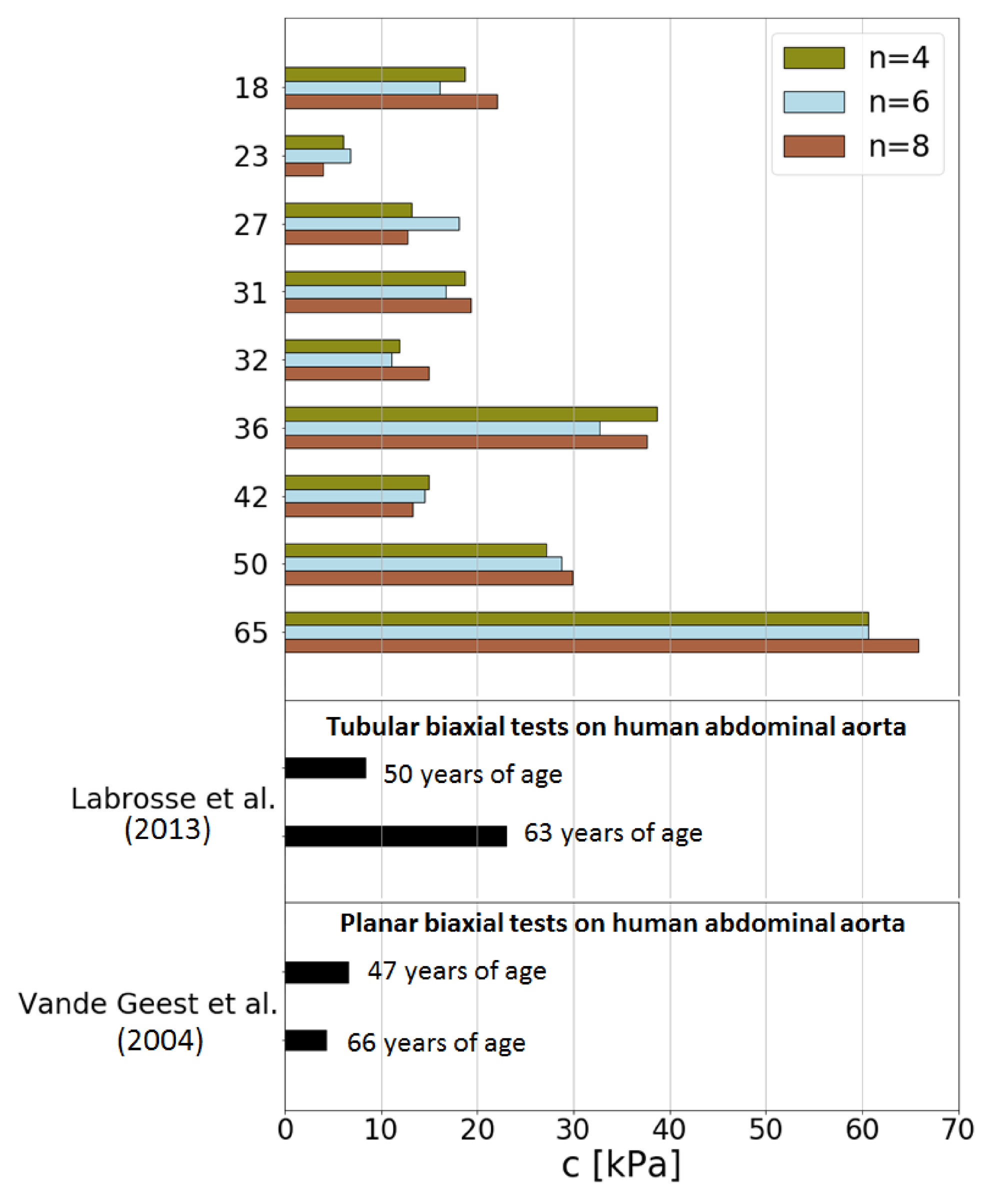


Figure 3. Material constant c for patients of different ages and comparison to results from biaxial tests reported previously reported in literature.

Perivascular Tissues

Perivascular tissues were modeled as a discrete collection of compression-only radial lineal springs.

EFBC regional stiffness is normalized to aortic-wall's material constant c.

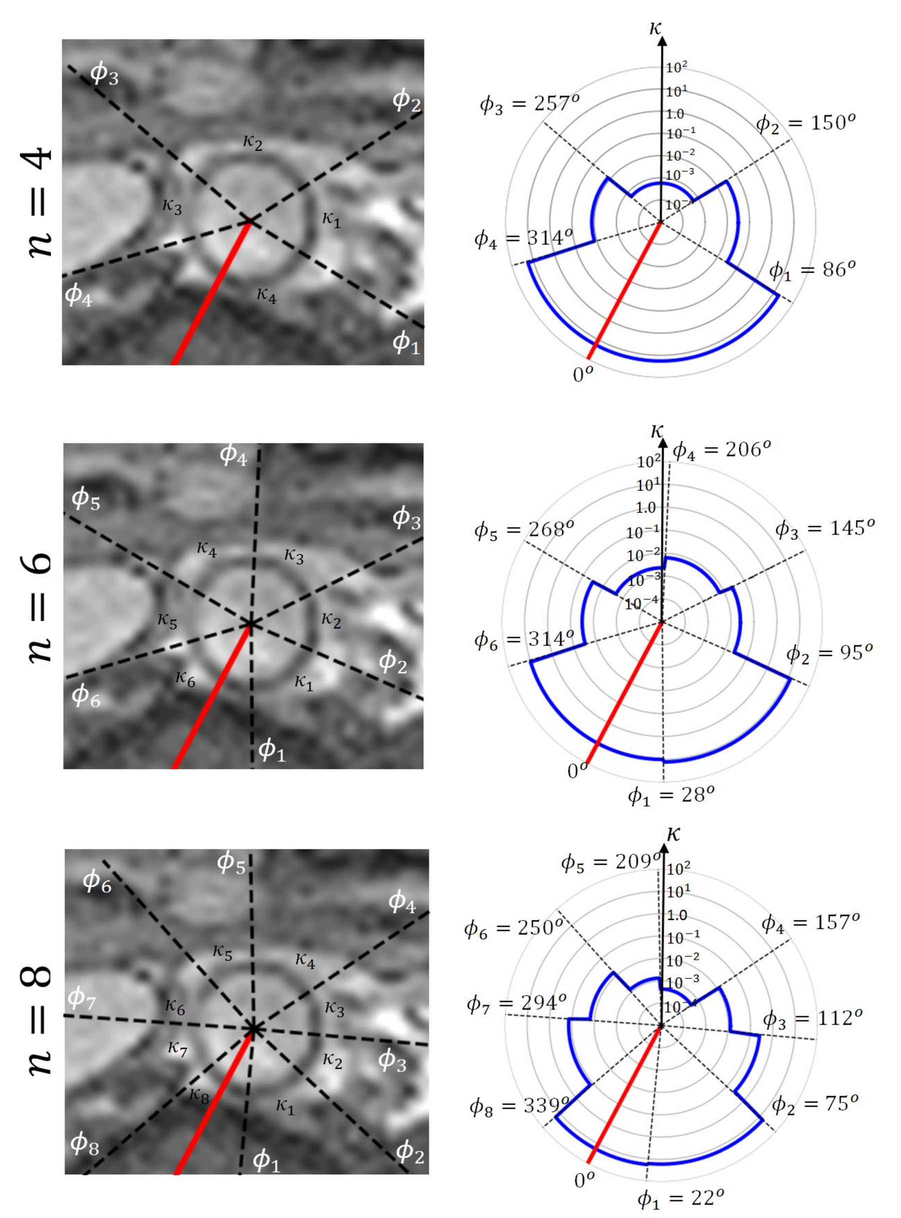


Figure 4. Normalized stiffness distribution of EFBC for different discretization and its correspondence to anatomical features.

Conclusions

- Normalized elastic EFBC stiffness distribution is consistent among healthy patients of different genders and ages.
- The EFBC stiffness distribution is consistent with the location of anatomical features (Figure 4).
- Normalized EFBC stiffness could be considered patient independent in healthy volunteers.
- There is no significant benefit from increasing the number of EFBC regions above 4 at the infrarenal abdominal aorta (Figure 2).
- Our methodology offers material properties of the same order of magnitude as values obtained by *ex vivo* biaxial tests reported in literature.
- Our methodology reproduces the widely known arterial wall stiffening with ageing (Figure 3).

Future work

- Include the effects of pre-strain and residual stresses.
- Consider patient specific pulse pressures.
- Include more individuals older than 50 y.o.
- Apply the methodology to patients of specific pathologies (i.e. hypertension).

Acknowledgements

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