In-silico evaluation of a patient-specific ATAA case through experimental mechano-microstructural characterization

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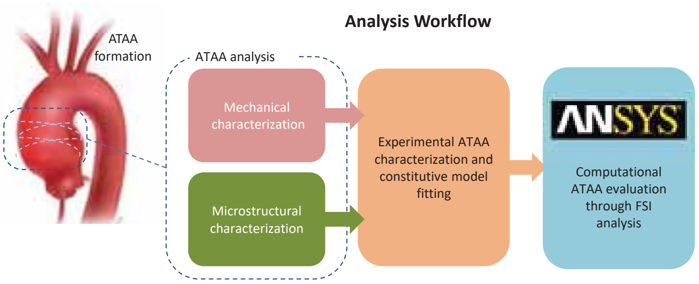
Introduction

Introduction: The microstructure of the aortic tissue influences the mechanical properties of the aorta and it is the main responsible for the onset of pathology of the aneurysm (ATAA) [1]. The presence of collagen fibers within the tissue provides mechanical hyperelasticity and anisotropy. Previous state of art *in-silico* studies considered the Finite Element simulation of ATAA cases through simplified linear elastic or non structurally motivated models [2]. However, a complete analysis of the ATAA tissue has to include both mechanical and microstructural characterization for the definition of a proper constitutive model, which is anisotropic and hyperelastic.

Aim: The simultaneous evaluation of the biaxial mechanical properties together with the fiber content of the aortic tissue specimens.

- An experimental setup for the optical and mechanical characterization of ATAA through Small Angle Light Scattering (SALS) [3] and biaxial traction was developed.
- The fitted experimental data were used to reproduce an ATAA case in the *in-silico* FE environment, through a patient case specific Fluid Structure Interaction (FSI) simulation.



Analysis Workflow

ATAA formation

ATAA analysis

Mechanical characterization

Microstructural characterization

Experimental ATAA characterization and constitutive model fitting

ANSYS

Computational ATAA evaluation through FSI analysis

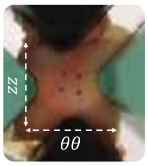
Materials and Methods

Experimental setup: The setup is composed by an optical part responsible for the SALS characterization of the specimen and a mechanical part responsible for the biaxial traction

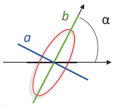
Optical components
- Unpolarized HeNe laser (λ = 632.8 nm, P = 5 mW)
- Broadband dielectric mirror
- Achromatic doublet focal lens (f. length = 150 mm)

Mechanical components
- 4 servo motors
- 2 load cells (0.1 N accuracy)
- optical extensometry (0.03 mm/px)
- 4 pneumatic grippers

Experimental testing protocol: Tests performed on 3 healthy and 5 ATAA specimens. Biaxial stresses/stretches and SALS pattern parameters were evaluated at different tension ratios ($T_{\theta\theta}$:T_{zz} = 1:1, 1:0.5, 1:0.75, 0.5:1, 0.75:1). Fiber distributions were evaluated as well, by fitting the SALS patterns through two gaussian functions.



$$E = \sqrt{1-(b/a)^2}$$



SALS Pattern parameters

Eccentricity Variation (ΔE) → Fiber dispersion

Inclination angle (α) → Fiber preferred direction

Data fitting: The SALS and mechanical data were used to fit a fiber-based constitutive model for the ATAA tissue [4]. The microstructural parameters were evaluated on the basis of fiber distribution from SALS analysis.

$$W = \frac{c}{2}(I_1-3) + \frac{k_1}{2k_2}\sum_{i=4,6} \exp([k_2(I_i^*(\phi,k_{ip},k_{op})-1)^2]-1)$$

SALS data analysis

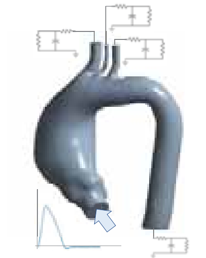
Microstructural parameters
- ϕ, k_{ip}, k_{op}

Constrained mechanical data fit

Mechanical parameters
- c, k_1, k_2

Computational Finite Element setup: The experimental data were used for the *in-silico* simulation. A one-way FSI simulation was imposed on a patient specific ATAA geometry obtained from CT data segmentation. The fiber based constitutive model was implemented for ANSYS through a custom user defined function developed in FORTRAN.

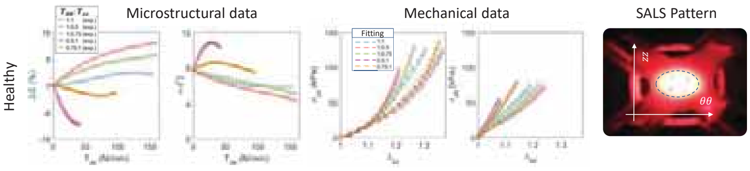
Fluid domain
- Three elem. Windkessel models
- Physiological valvular inlet

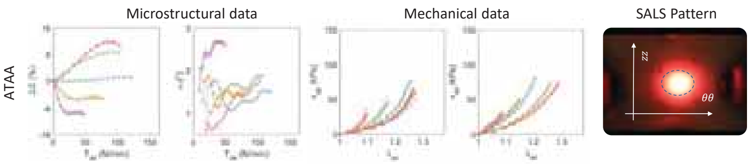


Structural domain
- Fixed constraints
- Elastic foundation at ext. surface

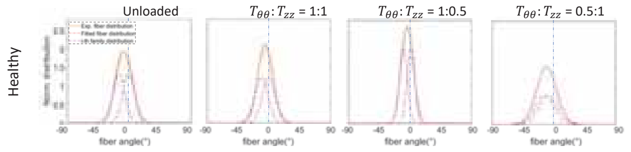
Results and Discussion

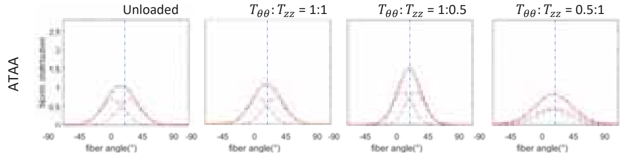
Constitutive model fitting results: The constitutive model correctly coped the experimental data according to the constrained fitting (R^2= 0.96 and R^2= 0.97 for healthy and ATAA cases)



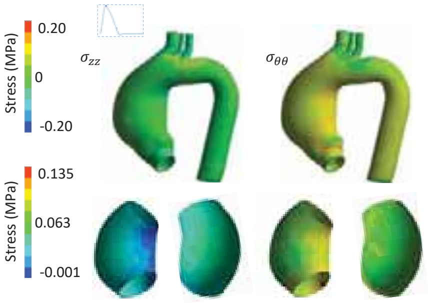


Dynamic fiber distribution results: The ATAA case revealed an higher fiber dispersion in comparison with the healthy case. Sensible differences emerged from the evaluation of distributions according to the different tension states. A strong fiber redistribution occurred at the 1:0.5 and 0.5:1 tension ratios.





***In-silico* FE model results:** The fiber-based model was correctly implemented in the FE environment. The hydraulic pressure and flow range were correctly reproduced within the physiological range (110-76 mmHg and 2.35 m/s). The presence of the ATAA bulge produced a sensible pressure drop at systolic peak. The results on the structural domain are reported at systolic pressure maximum. The stress distributions on the structural domain revealed a strong anisotropy. In particular, the circumferential stress exhibited peaks in the inner curvature of the ATAA structure, while the longitudinal stress peaks occurred at the outer curvature area.



Conclusion

The complete characterization of both healthy and ATAA tissue was assessed through a new experimental setup providing both microstructural and mechanical characterization. The experimental data were interpreted through a fiber-based hyperelastic and anisotropic constitutive model and the dynamical redistribution of the fibers within the biaxially tensioned specimen was assessed. Finally, the fiber-based constitutive model was correctly implemented in the FE environment through the simulation of a given patient specific ATAA case.

[1] Bianchi et al., J of Biomech, 2016
[2] Martin et al., Am J Physiol Heart Circ Physiol. 2015
[3] Gaul et al., J Mech Behav Biomed Mater, 2017
[4] Holzapfel et al., J. Royal Soc. Interface, 2015.

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