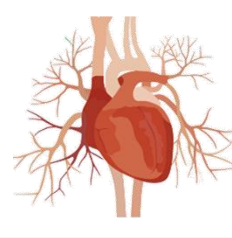

A MEDICAL DIGITAL TWIN DERIVED FROM A PATIENT-SPECIFIC THORACIC AORTA MODEL TO INVESTIGATE THE EFFECTS OF THE HEART MOTION ON THE VESSEL WALL

Geronzi L. [1,2], Martinez A. [1,2], Sensale M. [2], Rochette M. [2], Bel-Brunon A. [3], Valentini P.P. [1], Biancolini M.E. [1]

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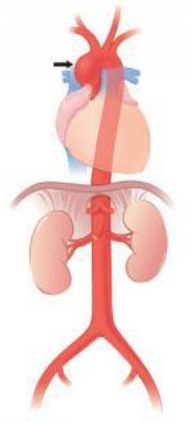
Introduction

CLINICAL CONTEXT AND PURPOSE OF THE WORK



When studying pathologies such as the ascending aortic aneurysm it is crucial to consider the effects of cardiac motion on the vessel [1],[2].

In deciding whether or not to operate, it would be interesting for the doctor to identify the consequences of possible conservative drug therapies.

AIM OF THIS WORK

➡ We want to present a high-fidelity model of the thoracic aorta that we calibrated with medical 2D+time images.

➡ We want to create a Medical Digital Twin (MDT) based on Dynamic Reduced Order Models (DROMs) with which the doctor can easily interact to investigate the aortic wall properties when certain input conditions change, for instance following the intake of a drug.

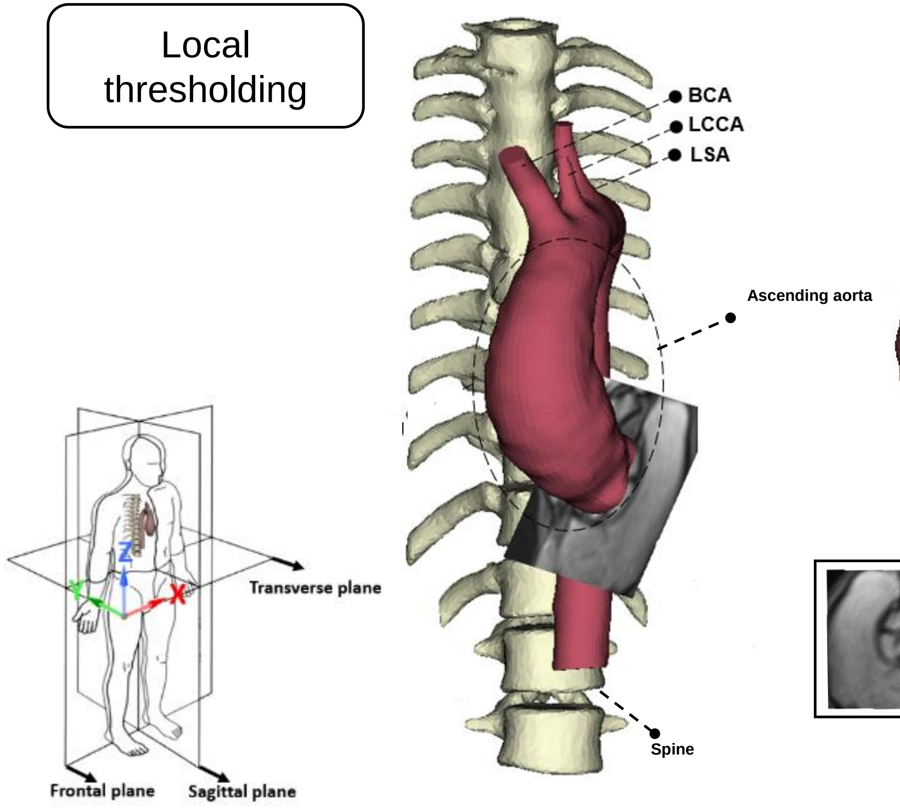
[1] Cutugno et al. (2021). Patient-specific analysis of ascending thoracic aortic aneurysm with the living heart human model. *Bioengineering*, *8*(11), 175.
[2] Beller et al. (2004). Role of aortic root motion in the pathogenesis of aortic dissection. *Circulation*, *109*(6), 763-769.

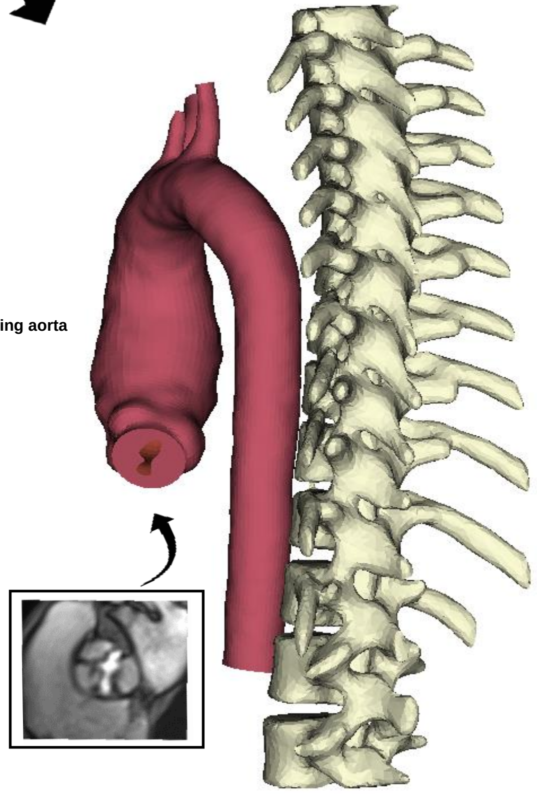
Materials and Methods

SEGMENTATIONS

From **MRI-Angiography**

Local thresholding



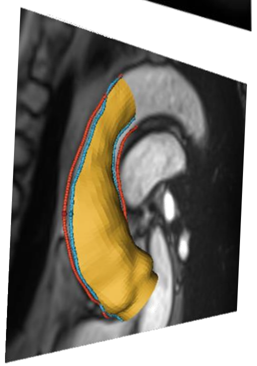


From **cine-MRI**

Region Growing

9 sagittal + 2 oblique sequences

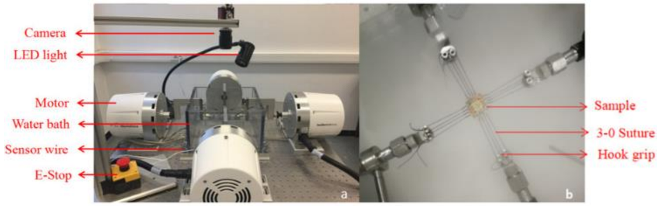
Splines used for the calibration of the parameters governing the mechanical boundary conditions.

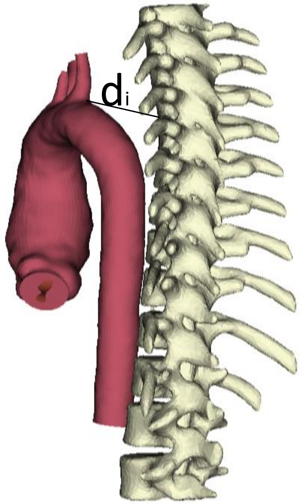


Materials and Methods

THE STRUCTURAL MODEL

- **Hyperelastic material**





d_i = minimum euclidean distance between the i-node and the spine

- **Robin boundary condition (BC) [3]:** to represent the interaction of the aorta with the spine and reproduce the effect of the soft tissue around the aorta.

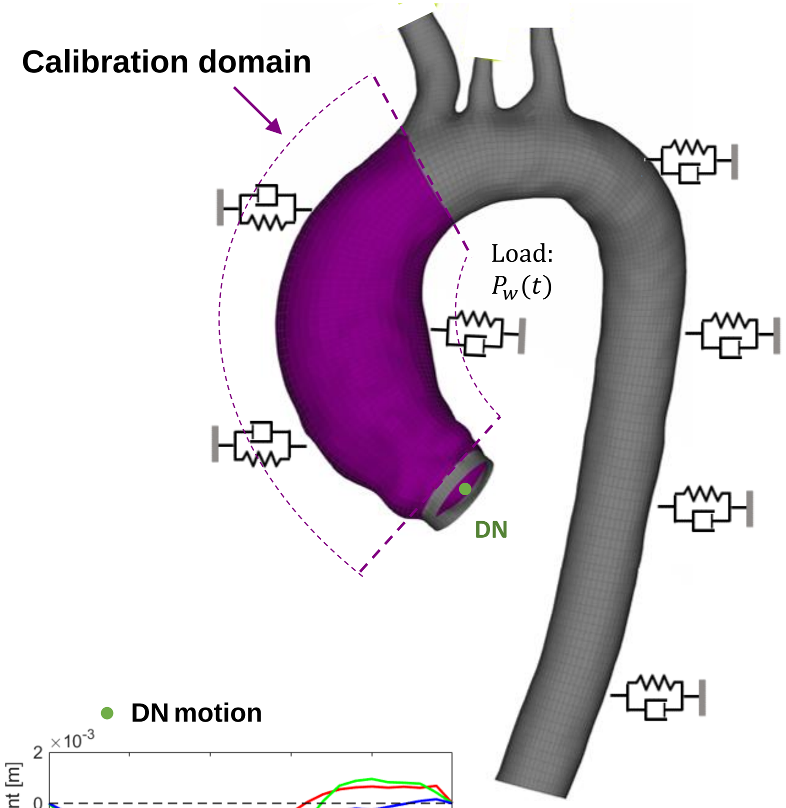
$$\sigma_{\text{ext}} = -\mathbf{K}\mathbf{x} - \eta\dot{\mathbf{x}} \qquad \eta = 10^5 \ (Pa \cdot s)/m$$

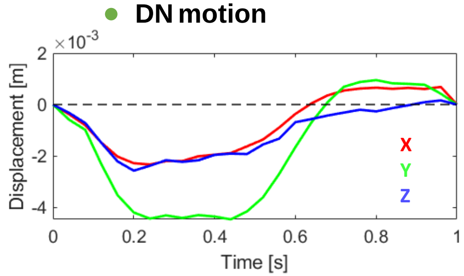
$$K_{X_i} = K_{ST} + \left(W_{d_i} W_X\right) K_{SPINE}$$
$$K_{Y_i} = K_{ST} + \left(W_{d_i} W_Y\right) K_{SPINE}$$
$$K_{Z_i} = K_{ST} + \left(W_{d_i} W_Z\right) K_{SPINE}$$

$\boldsymbol{d_{MAX}} = 142$ mm and $\alpha = \mathbf{0.95}$

$\boldsymbol{W_{d_i}} = \mathbf{1} - \alpha \dfrac{\boldsymbol{d_i}}{\boldsymbol{d_{MAX}}}$ and $K_{SPINE} = 10^6 \ Pa/m$

Input parameters: $\boldsymbol{p} = [W_X, W_Y, W_Z, K_{ST}]$ **to be calibrated**



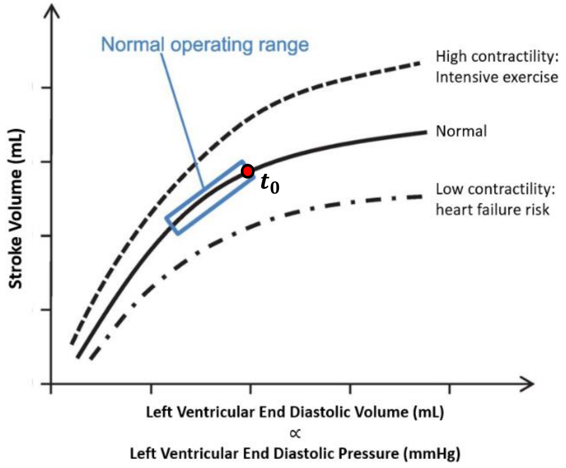


Derived from the annulus tracking

[3] Moireau et al. (2012). External tissue support and fluid–structure simulation in blood flows. *Biomechanics and modeling in mechanobiology*, *11*(1), 1-18.

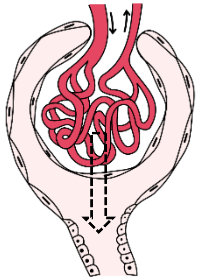
Materials and Methods

THE EFFECTS OF A DRUG THERAPY



Patient with hypertension

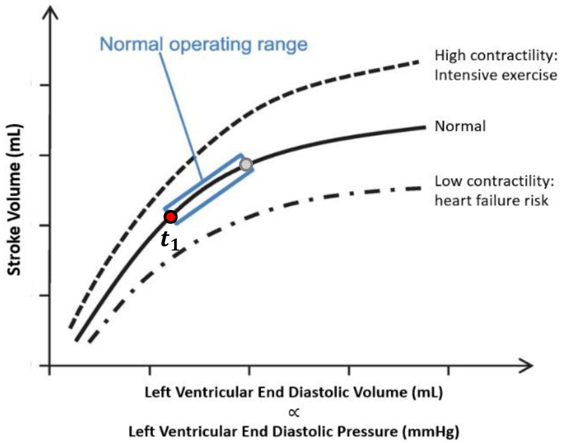
Diuretic Supply [4]



↓ **Left Ventricular End Diastolic Volume**

↓ Left Ventricular End Diastolic Pressure

↓ **Stroke Volume**



↓ **Ventricular expansion**

↓ **Cardiac ejection**

↓ **Aortic root motion**

↓ **Blood velocity**

= Variable input excitations

The **wall stress** is one of the most important biomarkers for understanding the aneurysm evolution [5].

Using the **MDT**, we can **predict** the time-varying simulation results as the wall stress (output) with respect to new excitations (input) in terms of heart motion and ejection velocity.

Model simplification: no variation of the 0D downstream parameters.

[4] Ernst et al. (2009) Use of diuretics in patients with hypertension. *New England Journal of Medicine* 361.22, 2153-2164.
[5] García-Herrera et al. (2012). Mechanical behaviour and rupture of normal and pathological human ascending aortic wall. *Medical & biological engineering & computing*, *50*(6), 559-566.

Materials and Methods

THE MEDICAL DIGITAL TWIN (MDT)

Generation of a MDT using ROMs based on Proper Orthogonal Decomposition (POD).

↳ "A posteriori" method: the ROM is built with the previously computed FSI simulations (high-fidelity scenarios).

The ROM is created using Dynamic Rom Builder in Ansys Twin Builder.

$$\frac{dX}{dt} = F\big(X(t), G(t)\big) \quad with \quad X(t=0) = X_0$$

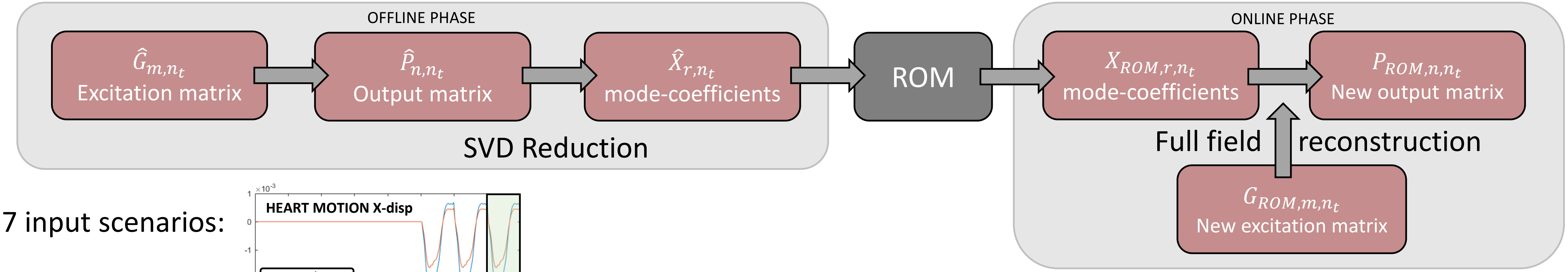
where :

- X is the solution vector (function of time) of size $n_{outputs}$
- G is the input vector (function of time) of size $n_{excitations}$
- F is a non-linear function of X and G
- X_0 is a vector of size $n_{outputs}$ which represents the initial conditions of the solution

The function F is identified thanks to learning data (i.e. one or several transient variations of X and the corresponding excitations G) and is determined by an optimization process aiming at minimizing $||X_{ROM}(t) - X(t)||$

Materials and Methods

The Dynamic ROM procedure

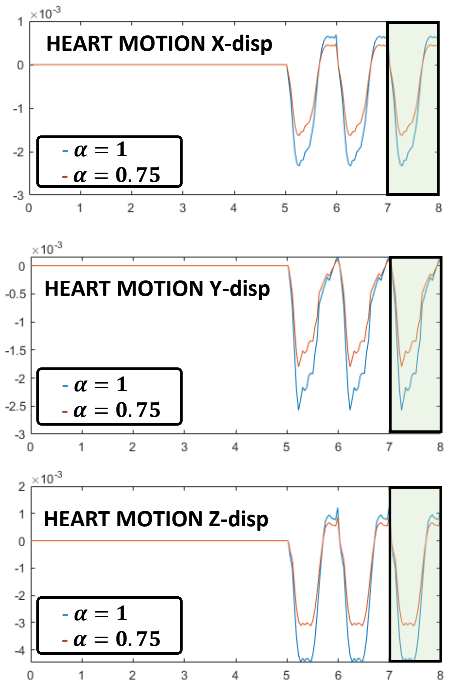


7 input scenarios:

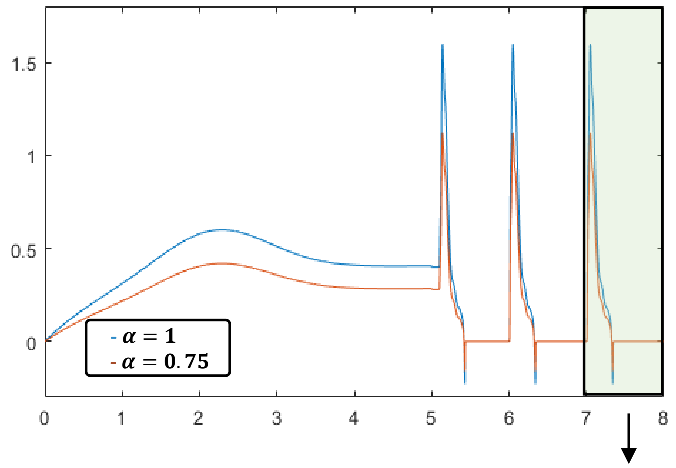
$$\alpha = \begin{bmatrix} 0.65 \\ \mathbf{0.75} \\ 0.85 \\ 0.95 \\ \mathbf{1.00} \\ 1.05 \\ 1.15 \end{bmatrix}$$

Investigation of even more pronounced excitations

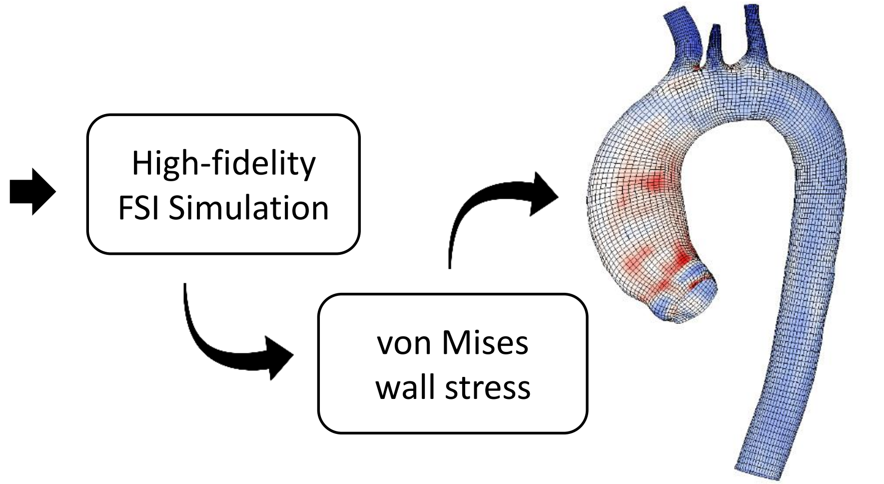
α = scaling factor



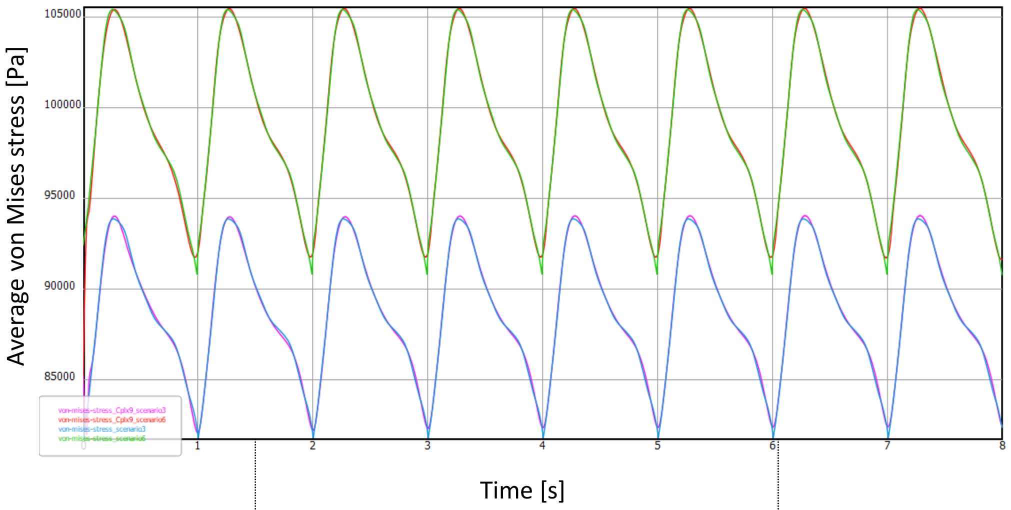
+



Part of the cardiac cycle used to build the ROM



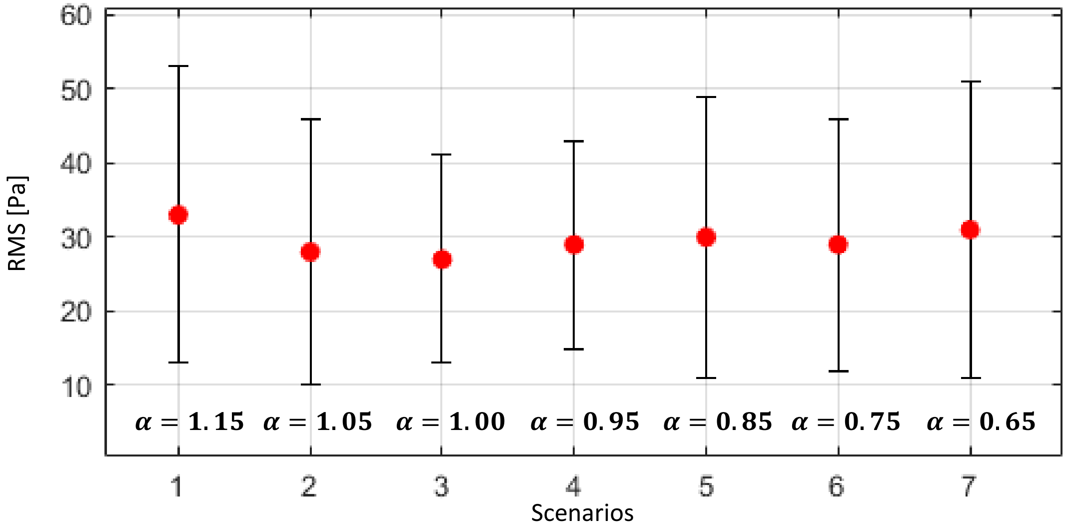
MDT RESULTS: MODEL ORDER REDUCTION



Average von Mises stress results in response to the modulation of the ejection velocity and the heart motion.

- $\alpha = 1$: High-fidelity
- $\alpha = 1$: ROM
- $\alpha = 0.75$: High-fidelity
- $\alpha = 0.75$: ROM

$mean \pm std\ of\ the\ RMS(von\ Mises\ stress) *$



$$RMSnode_i = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(\sigma_{vm_{i_{t,HF}}} - \sigma_{vm_{i_{t,ROM}}}\right)^2}$$

$\sigma_{vm_{i_{t,HF}}}$ = von Mises stress derived from the high-fidelity simulation

$\sigma_{vm_{i_{t,ROM}}}$ = von Mises stress derived from the ROM

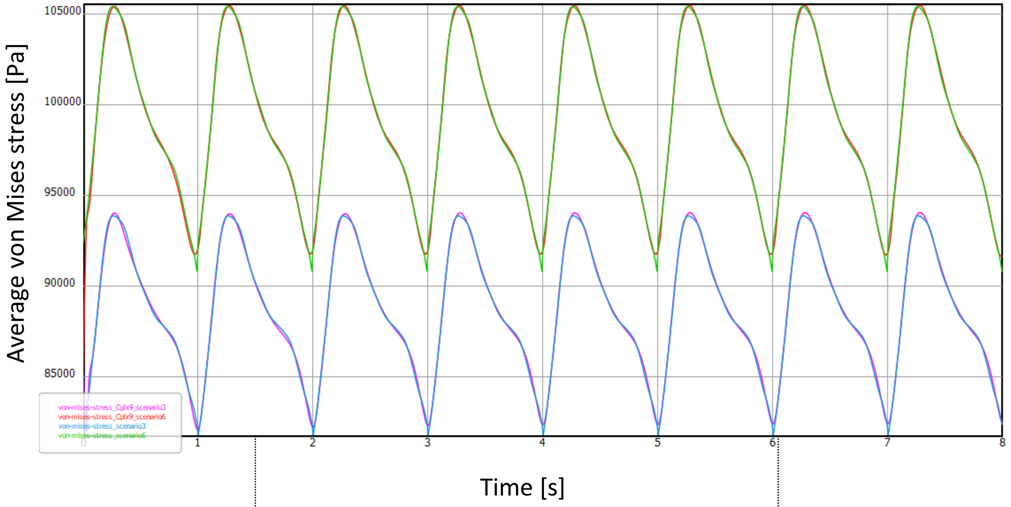
*This plot only evaluates the last cardiac cycle.

! **Higher annulus displacements** are associated with **increased stress** on the aortic wall of the ascending tract. This could affect the **aneurysm growth** [6].

[6] Beller et al. (2004), Role of aortic root motion in the pathogenesis of aortic dissection. *Circulation* 109.6: 763-769.

Results

MDT RESULTS: REAL-TIME STRESS COMPUTATION



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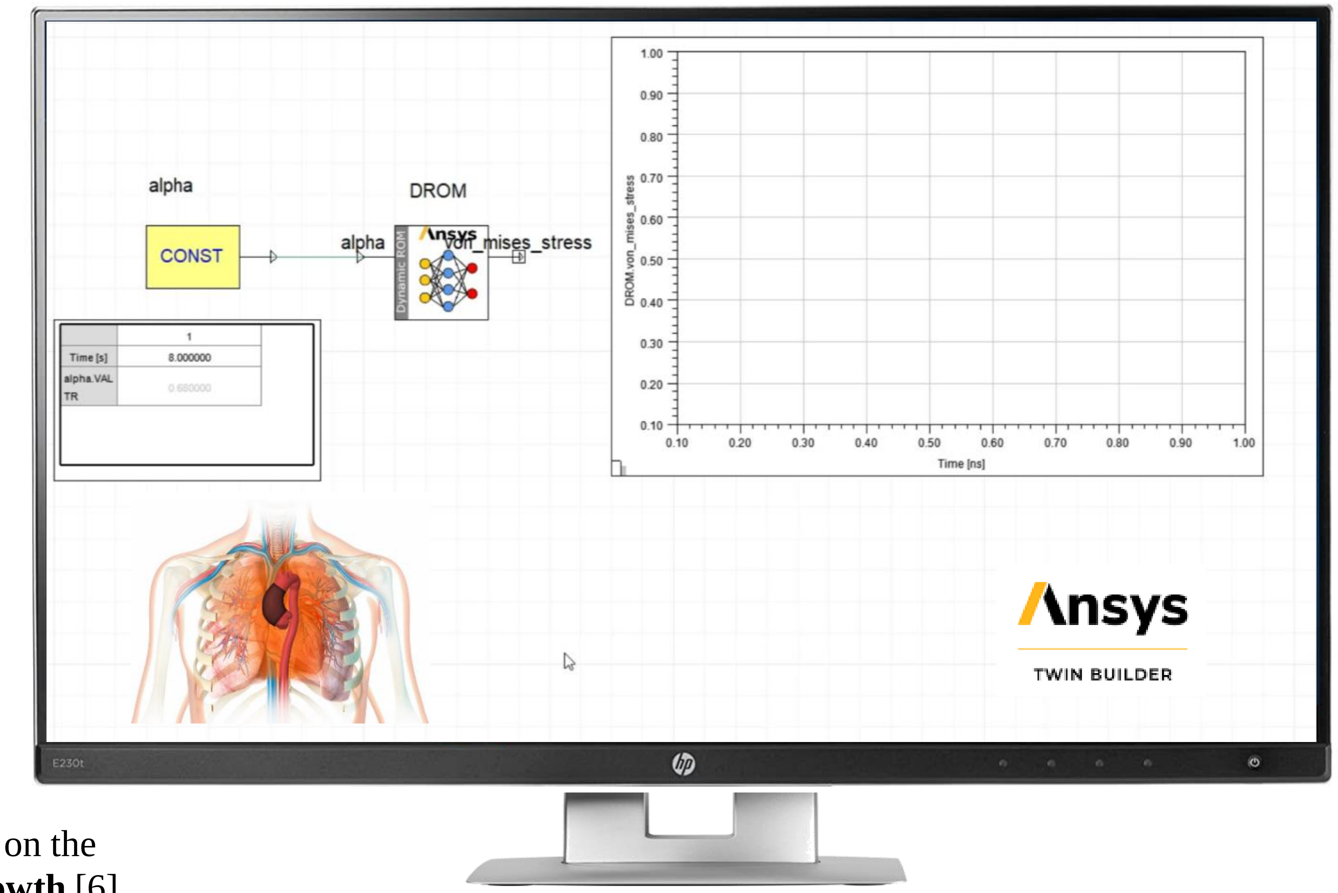
— $\alpha = 0.75$: High-fidelity
— $\alpha = 0.75$: ROM



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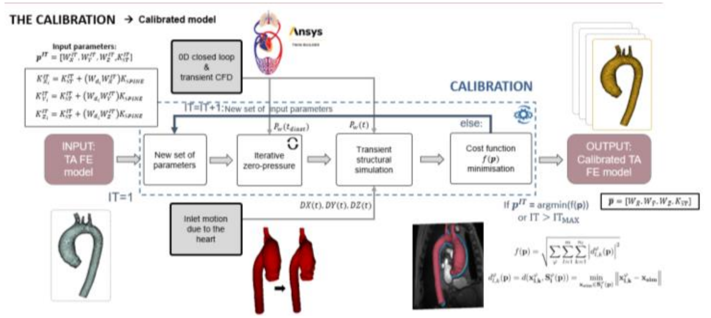
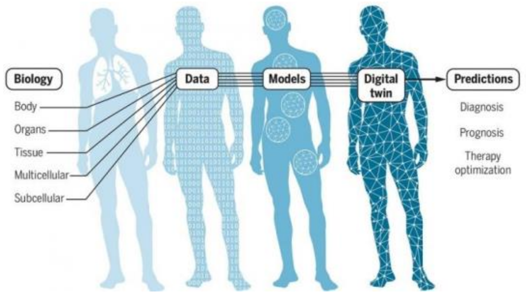
Conclusions



➡ We proposed a high-fidelity model of a thoracic aorta and presented a novel method of calibrating the mechanical boundary conditions using 4 parameters and taking into account the motion imposed by the heart on the aorta at the level of the annulus.

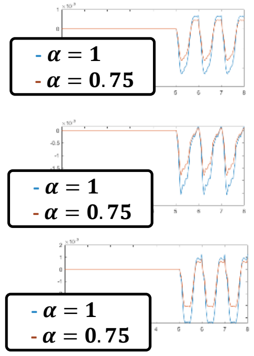


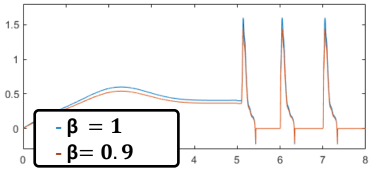
➡ We then presented a first example of Medical Digital Twin based on Reduced Order Models for the evaluation of stress at the wall of the aorta during the cardiac cycle.

FUTURE WORK

➡ ROM Cross Validation

➡ Enter more parameters in the Digital Twin such as the heart rate ($\boldsymbol{f}$) and use different parameters to scale the heart motion ($\boldsymbol{\alpha}$) and the velocity inlet curves ($\boldsymbol{\beta}$).





$\boldsymbol{\alpha} \neq \boldsymbol{\beta}$

➡ Extend the work to a wider population.

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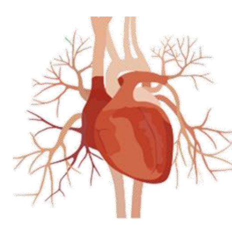

THANK YOU FOR THE ATTENTION!

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