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INTERNATIONAL CAE CONFERENCE

33rd INTERNATIONAL CAE CONFERENCE AND EXHIBITION

(rbf-morph)™

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Fondazione Toscana Gabriele Monasterio

bcl BioCardioLab Fondazione Toscana/CNR G.Monasterio

HEMO-ELASTIC STUDY OF ASCENDING THORACIC AORTA ANEURYSMS THROUGH RBF MESH MORPHING

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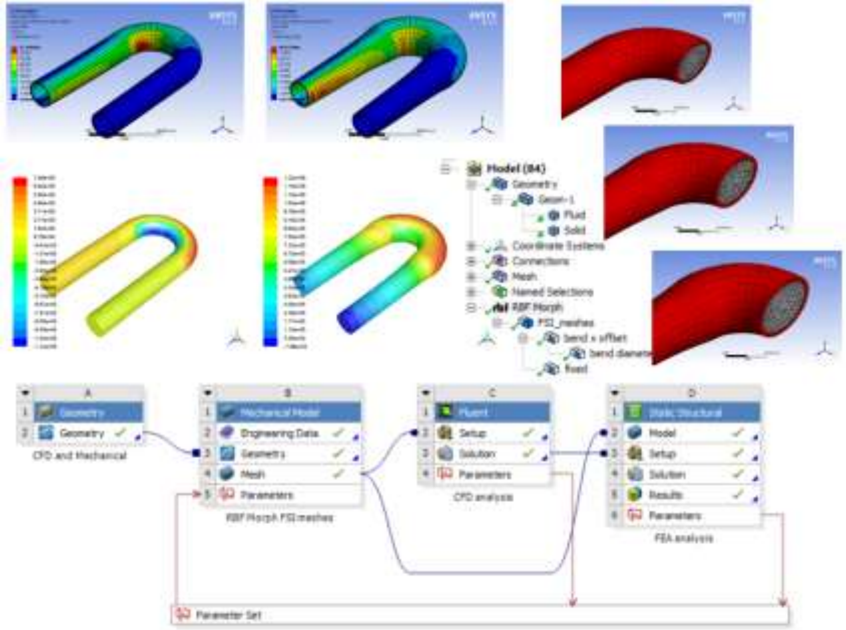
Outline

- Introduction
- RBF Background
- Application Description
- Mesh Morphing Set-up
- Mesh Morphing Effects
- CFD Results
- FEM Results
- Conclusions
- Further Improvements

Introduction

- The aim of the present work is to consolidate a **mesh morphing based multi-physics workflow**.
- In a multi-physics environment a **specific grid** has to be generated for each kind of analysis and in for each shape to be tested.
- Creating **new grids** for each of the physics to be analyzed can consume the **70%** of the **total analysis time**.
- The proposed methodology will be applied to a hemo-elastic study of the Ascending Aorta Aneurysm.



Introduction

- The Ascending Aorta Aneurysm is a severe threatening condition because it is a **silent disease** and its rupture can lead to **mortal consequences**.
- The only treatment option is **surgery repair** and the parameter for surgical intervention is diameter of the aneurism.
- Research efforts aimed at correlating the **risk of rupture** to **histo-mechanical tissue properties** and morphological characteristics.
- Hemodynamic features of the blood flux were investigated during the growth process of ascending aneurism.

E. Vignali, K. Capellini et al, European Society of Cardiology, ESC congress, Barcelona, 2017
E. Vignali, K. Capellini et al, European Society of Biomechanics, ESB congress, Sevilla, 2017
K. Capellini, E. Costa, et al, ESB-ITA17 VII Annual Meeting, Rome, 2017

Introduction

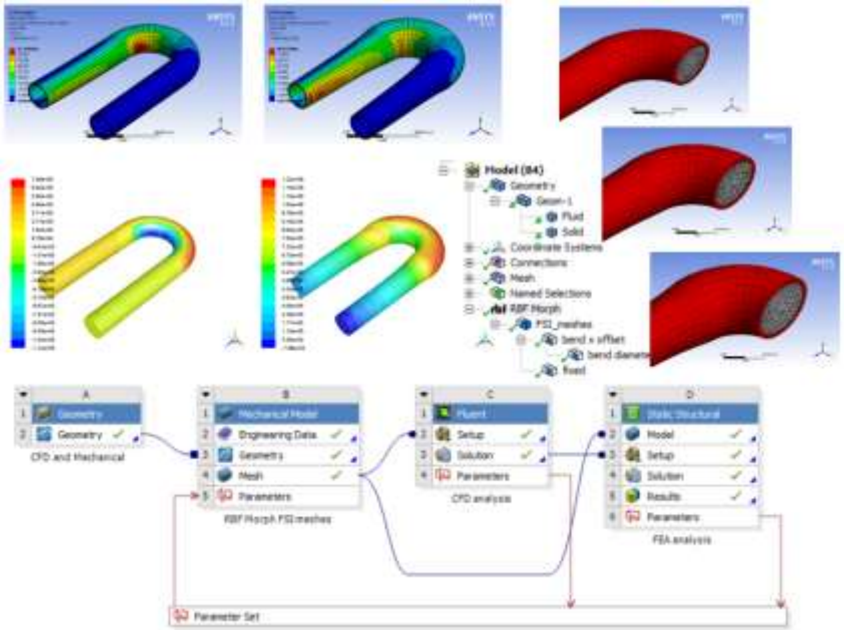
- To properly investigate through numerical models the growth of aneurism, the **shape** of the aorta model has to be **modified** according to the actual configuration of the real aorta.
- Following the classical approach the update of the model corresponds to a re-generation of the computational grid (**remeshing**), whose **automation (if possible)** can be **complex**, **painful** and **time-consuming**.

Introduction

- In the present work, the tool adopted for morphing the **FEM** mesh is **RBF Morph™**, which is based on Radial Basis Functions (**RBF**).
- The mesh morphing tool is used inside **ANSYS® Workbench™**, thanks to the **ANSYS® ACT™** customization framework.
- The shape modification can be used in **multi-physics** application, such as **one-way** fluid-structure interaction (**FSI**) analysis, performed with **ANSYS® Fluent™** and **ANSYS® Mechanical™** solvers.

Introduction

- The **baseline geometry** are imported/generated in the CAD tool ad meshed simultaneously.
- The **shape modification** are applied to the baseline meshes through the mesh morphing tool to obtain the meshes of the modified configurations.
- The morphed meshes are **translated to the solvers** to compute the multi-physics parameters of interest.



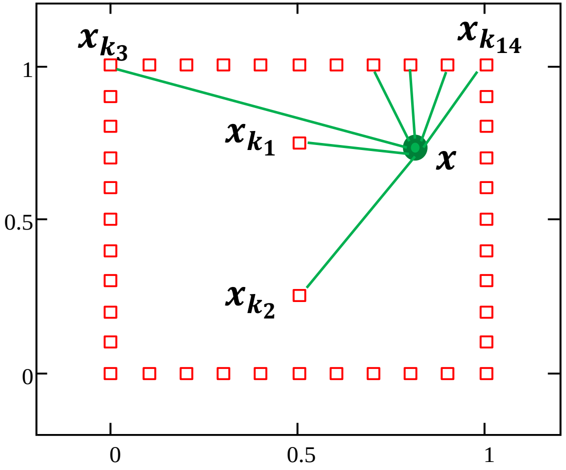
RBF Background

- RBFs are a **mathematical tool** capable to **interpolate** at a generic point in the space a function known in a discrete set of points (source points).
- The interpolating function is composed by a radial basis and by a polynomial:

radial basis — polynomial

$$s(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i \varphi\left(\left\| \mathbf{x} - \mathbf{x}_{k_i} \right\|\right) + h(\mathbf{x})$$

distance from the i-th source point



RBF Background

- If evaluated on the source points, the interpolating function gives exactly the input values:

$$s(\boldsymbol{x}_{k_i}) = g_i \qquad 1 \le i \le N$$
$$h(\boldsymbol{x}_{k_i}) = 0$$

- The RBF problem (evaluation of coefficients γ and β) is associated to the solution of the linear system, in which **M** is the interpolation matrix, **P** is a constraint matrix and **g** is the vector of known values at source points:

$$\begin{bmatrix} \mathbf{M} & \mathbf{P} \\ \mathbf{P}^{\mathrm{T}} & 0 \end{bmatrix} \begin{pmatrix} \boldsymbol{\gamma} \\ \boldsymbol{\beta} \end{pmatrix} = \begin{pmatrix} \boldsymbol{g} \\ 0 \end{pmatrix} \qquad M_{ij} = \varphi\left(\boldsymbol{x}_{k_i} - \boldsymbol{x}_{k_j}\right) \qquad 1 \le i, j \le N \qquad \mathbf{P} = \begin{bmatrix} 1 & x_{k_1} & y_{k_1} & z_{k_1} \\ 1 & x_{k_2} & y_{k_2} & z_{k_2} \\ \vdots & \vdots & \vdots & \vdots \\ 1 & x_{k_N} & y_{k_N} & z_{k_N} \end{bmatrix}$$

RBF Background

- Once the RBF problem is solved, each displacement component is interpolated:

$$\begin{cases} s_x(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^x \varphi\left(\mathbf{x} - \mathbf{x}_{k_i}\right) + \beta_1^x + \beta_2^x x + \beta_3^x y + \beta_4^x z \\ s_y(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^y \varphi\left(\mathbf{x} - \mathbf{x}_{k_i}\right) + \beta_1^y + \beta_2^y x + \beta_3^y y + \beta_4^y z \\ s_z(\mathbf{x}) = \sum_{i=1}^{N} \gamma_i^z \varphi\left(\mathbf{x} - \mathbf{x}_{k_i}\right) + \beta_1^z + \beta_2^z x + \beta_3^z y + \beta_4^z z \end{cases}$$

- Several different radial functions (kernel) can be employed:

RBF	φ(r)	RBF	φ(r)
Spline type (Rn)	r^n, *n odd*	Inverse multiquadratic (IMQ)	$\frac{1}{\sqrt{1+r^2}}$
Thin plate spline	$r^n \log(r)$ *n even*	Inverse quadratic (IQ)	$\frac{1}{1+r^2}$
Multiquadratic (MQ)	$\sqrt{1+r^2}$	Gaussian (GS)	e^{-r^2}

Application Description

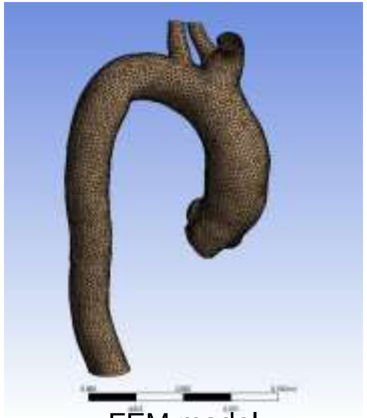
- The CAD description of the ascending aorta was obtained from a database of healthy patients.
- The CAD geometries of the aneurysm were extracted from a database of patients selected for surgical treatment
- The geometry extraction procedure is described in: *“K. Capellini, E. Costa, et al, ESB-ITA17 VII Annual Meeting, Rome, 2017”*

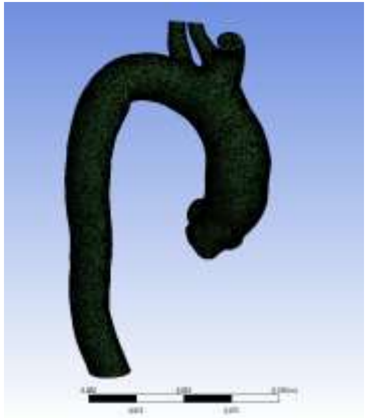
CAD of healthy ascending aorta

CAD of developed aneurysm on the ascending aorta

Application Description

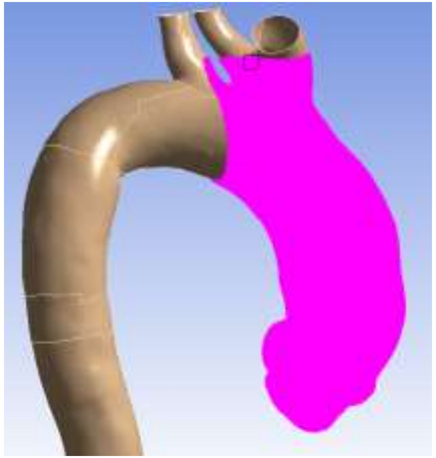
- From the provided geometries two different models were realized:
  - a FEM one, realized using 7,8 k nodes and 15,6 k quadratic triangular shells
  - a CFD one, realized using 3,7 M nodes and 2,4 M elements. A hybrid mesh was realized for the CFD model, inflating 4 layers of pentahedral elements on the aorta walls and adopting tetrahedral elements to discretize the internal volume.
- Both models were in the same ANSYS® Mechanical™ cell, the FEM one was set up as 'Solid' whilst the CFD one was set up as 'Fluid'


FEM model

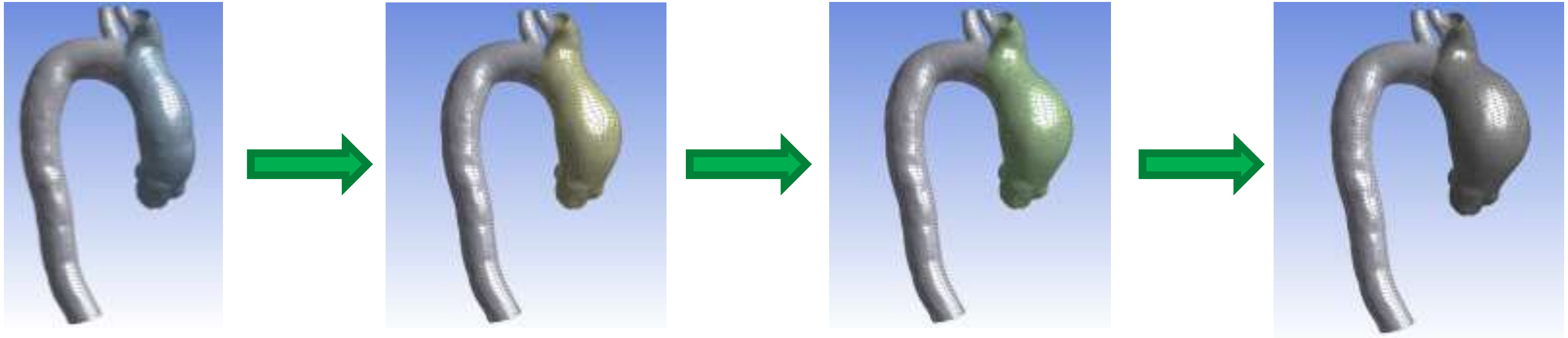

CFD model

Mesh Morphing Set-up

- Due to the large amount of nodes, only the region interested by the shape variation was selected as morphing domain (source points 3’222, target points 1,8 M).
- The ‘Surface Targeting’ shape modification was used in order to project mesh nodes from the baseline position onto the surfaces representing the identified phases of aneurysm growth.

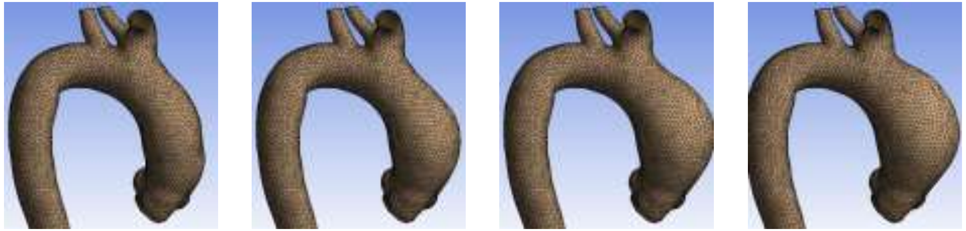


Region interested by the morphing action

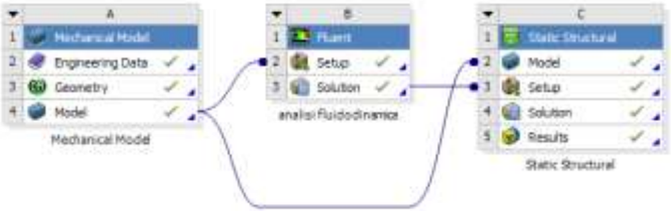


Mesh Morphing Set-up

- Both FEM and CFD meshes were successfully morphed through the sequential growth phases of the aneurysm.
- The morphed meshes were successfully imported into the numerical solvers to be analyzed.
- The final workflow is: the meshes are firstly morphed, then the CFD solution is computed, the pressure results are then mapped onto the structural mesh and finally the FEM solution is evaluated.



Sequential steps to obtain the morphed configuration



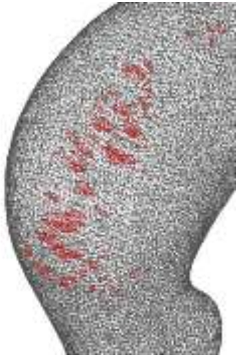
Workbench Workflow

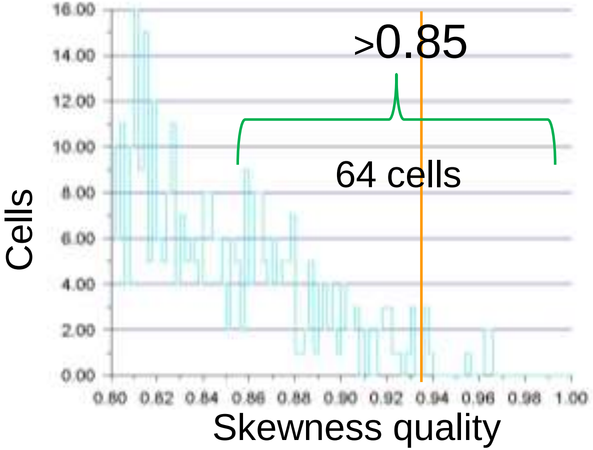
Mesh Morphing Effects

- Mesh morphing moves mesh nodes, element quality decreases. In the present application, the final mesh skewness is above 0.85 only for 64 cells of the CFD mesh.

baseline

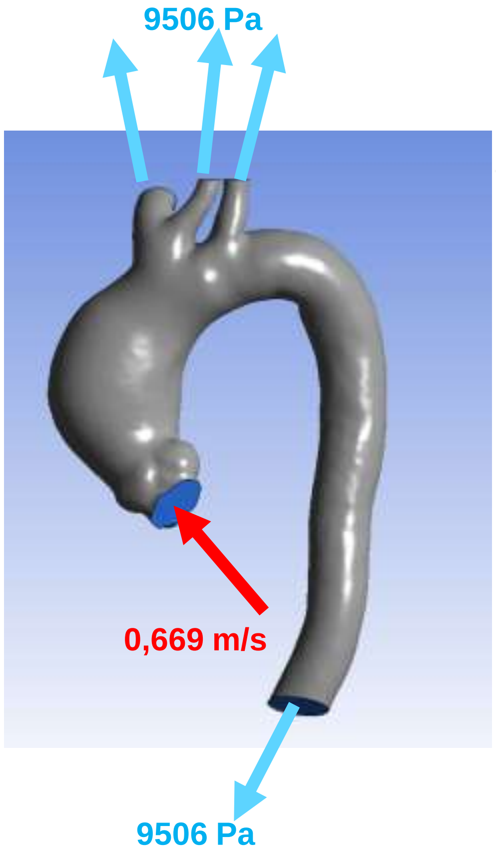
final



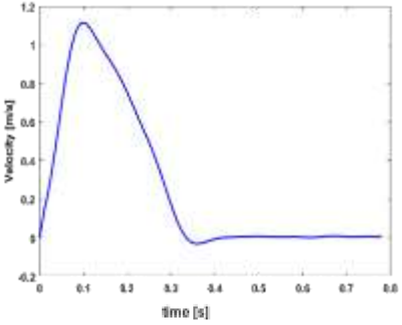


CFD Results

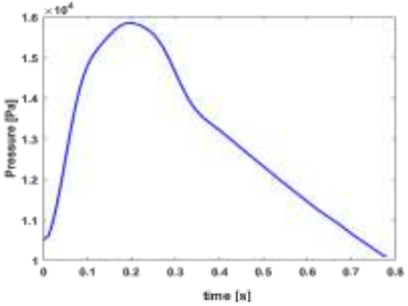
- CFD models were analyzed in steady condition using ANSYS® Fluent™
- Boundary condition were set at the selected surfaces as ‘velocity inlet’ and ‘pressure outlet’
- the pressure and velocity values were assumed equal to 60% of the systolic peak of the selected cycle.
- CFD set-up:
  - Blood flow incompressible and Newtonian,
  - density 1.06 x 10^3 kg/m^3
  - dynamic viscosity 3.5 x 10^{-3} Pa*s
  - laminar flow



inlet velocity profile



outlet pressure profile

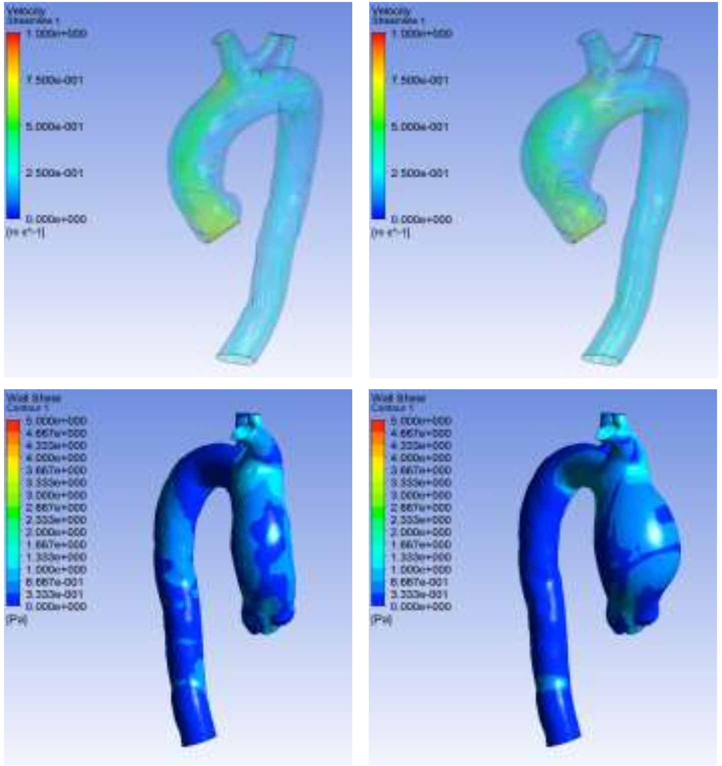


CFD Results

- Results are presented in terms of blood velocity inside the simulation volume and shear stress on the aorta walls

Blood Velocity

Wall Shear distribution

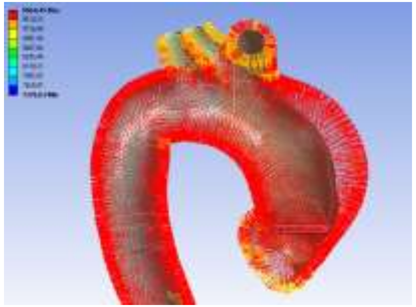


Healthy patient geometry

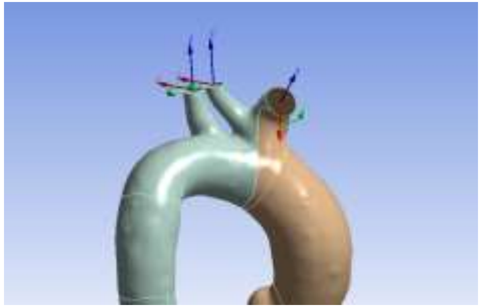
Fully developed aneurysm geometry

FEM Results

- The FEM models were loaded with the pressure obtained from CFD analyses. The pressure values were interpolated by ANSYS® Workbench™ routines.
- Constraints were applied taking into account the ability of the blood vessels to dilate themselves adopting local cylindrical coordinate systems.
- The material model used in FEM analyses is a Mooney-Rivlin 2 parameter hyperelastic material.



Mapped Pressure



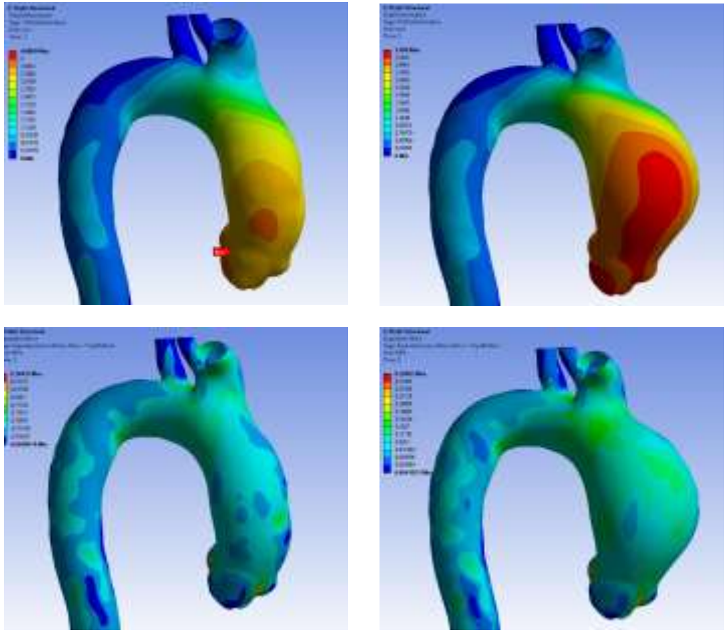
Local Cylindrical Coordinate Systems

FEM Results

- Results are presented in terms of displacements and equivalent stress in the hyperelastic material

Total displacements

Equivalent stresses



Healthy patient geometry

Fully developed aneurysm geometry

Conclusions

- The presented study **focuses on a methodology** to perform **multi-physics** analyses varying the model shape only one time.
- The procedure has been put in place exploiting the **mesh morphing** RBF Morph™ ACT™ extension for ANSYS® Workbench™ and tested on a one-way FSI application.
- The starting geometries were obtained from two different databases: the first representing a population of healthy patients and the second composed by patients selected for surgical intervention.
- In the Workbench environment, numerical models were generated for each physics to be analyzed (i.e. fluid-dynamics and structural mechanics).

Conclusions

- Exploiting the RBF Morph ACT extension, a **single set-up** for the **shape modification** was build and then the shape modification was **applied to all the generated numerical models**.
- The **mesh quality** of the morphed configuration resulted to be **acceptable** to successfully complete the numerical calculations.
- The procedure allowed to perform a multi-physics analysis at different geometrical configurations without remeshing the modified geometry, allowing a considerable time saving with respect to the whole analysis required time.

Further Improvements

- Constraint system can be improved to take into account the effects of blood vessels, tissues and muscles around the modeled part of the ascending aorta.
- Material used to modeling the aorta tissue can be improved taking into account patient specific mechanical characteristics and increasing material stiffness due to the aneurysm growth.
- Numerical simulations (CFD and FEM) will be performed taking into account the whole blood pressure and velocity cycle (transient analyses).

Other RBF Morph applications

- CAE Conference 2017 – Transportation session (Tue 7/11 9:30 – 16:00):

  - U. Cella, M.E. Biancolini, A. Clarich, F. Franchini, «Constrained Geometric Parametrization by Mesh Morphing for a Catamaran Foils Optimization Procedure»

  - M.Bonvecchio, M.E. Biancolini, U. Cella, M. Ponzi, «Shape Optimization of a 3d Printed High Performances Automotive Parts»

Thank you for your attention!

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