On the Effect of Anatomy-based Multi-material Model Simulation of the Aortic Root

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Abstract—Anatomy related heterogeneous discontinuities in material properties strongly influence human soft tissue behavior under mechanical load. We present a parametric model of the aortic root, which defines multi-material surface regions for advanced tissue property control and supports patient-specific model refinement. Our results strongly indicate improvements for in-silico clinical application experiments using multi-material simulation.

Index Terms—aorta; valve; anatomy; material; simulation

I. INTRODUCTION

Human anatomy shows a high variety of heterogeneous materials, which are based on variable combinations of cell structures. Specific material models [1] are used to approximate their behavior in finite element (FE) simulations. In-silico experiments rely on FE meshes to simulate clinical interventions, such as transcatheter aortic valve implantation (TAVI). We analyze the anatomical structure of the aortic root and present a parametric model, which considers patient-specific input data for the generation of multi-material FE meshes. Previous methods have studied leaflet and annulus deformation separately [2],[3] or did not consider a separation of the aortic root into its anatomical subcomponents [4],[5]. Using parametric models, we can analyze biomechanical compatibility and optimal design of implants for patient-specific as well as population-specific experiments.

II. METHODS

Analysis of the aortic root: Soft tissue properties in the aortic root include non-linearities as well as hyperelastic and anisotropic characteristics. Heterogeneous cell-structure variation requires accurate geometry and material modeling for the simulation of tissue behavior under dynamic conditions. Extensive anatomical analysis has been performed by [6] and provides guidance on structuring a geometric model based on material considerations. The following components have been identified to require separate mechanical properties (Figure 1):

1) Ascending aorta and sinus of Valsalva (arterial tissue)
2) Valvar leaflets (collagen network embedded in elastin)
3) Aortic annulus crown (thick fibrous leaflet anchor)
4) Interleaflet triangles, membranous septum and mitral valve attachment (thin and fibrous)
5) Left ventricular myocardium (muscular tissue)

Each of these anatomical sections can be described using individual, homogeneous material models, which in combination, approximate the heterogeneous multi-material layout of the aortic root.

Parametric model design: For the purpose of this work, a shell-based surface model is constructed through parametric description of the aortic root. Distinct geometric relationships, as shown by [7] for leaflet attachment length (A), width (W) and height (H), allow parametric model generation, where comparable relations can be established for the sinus of Valsalva.

\[ A = 1 : 5W \]
\[ H = 0.9W \]

(1)

The parametric aorta model is constructed using a centerline, six points describing the annulus crown and eight scalar parameters describing the exact leaflet and sinus surface expansion through surface splines. The aortic root is defined by generating individual patches for each of the geometrically distinct areas from this input (Figure 2a). Meshing of the parametric structure is accomplished by subdividing each patch into regular quads (Figure 2b). By adapting spline progression and expansion through input parameters, this model can be optimized dynamically for patient specific geometry requirements by parameter fitting on medical images.

Each individual geometric section of the aortic root can now be associated with a different material model as the meshed geometry structure follows the internal material layout and individual tissue configurations.
III. EXPERIMENTS

For verification of the effect a multi-material aortic root model has on the outcomes of in-silico experiments, an exemplary phantom model of the aortic root was constructed with the presented approach and imported into Abaqus/Explicit. Initially, the phantom is simulated with two distinct material models for leaflet (Young’s modulus: 10 MPa) and aortic tissue (2 MPa) to generate a comparable baseline. In subsequent experiments, the material models are adapted for each component individually (Annulus: 70 MPa, Trigone Area: 40 MPa, Myocardium: 4 MPa).

1) Angioplasty Simulation: Angioplasty (balloon dilation) within the aortic root is a routine procedure before stent implantation. A deflated balloon is positioned at the center of the aortic root and inflated to tear adhesive, diseased valves and preload surrounding tissue.

2) TAVI Simulation: A self-expanding Medtronic CoreValve® is released dynamically within the aortic root. The stent is designed to apply constant pressure onto the surrounding tissue. Aorta and stent deformation should therefore be influenced substantially when considering multi-material models.

IV. RESULTS AND DISCUSSION

Each of the described simulation scenarios shows differences in stress and strain distribution when comparing single- and multi-material aortic root configurations. The increased local stiffness around the aortic annulus shows a sizable effect on aortic root deformation under clinical conditions. Through consideration of heterogeneous material properties in the aortic root, the average and maximal stresses are increased. Stress distribution for dual-material experiments can be compared to multi-material results in Figure 2, showing a clear decrease in circumferential expansion of the annulus area as expected in corresponding clinical applications.

To further improve model adaption to real soft tissue characteristics, continuous changes in material properties should be considered to allow smooth material blending at geometric seam-lines. However, element distribution and arrangement should follow the underlying material configuration to achieve optimal model alignment and a allow consistent material definition.

V. CONCLUSION

The use of anatomical knowledge in combination with patient-specific geometric input parameters allows for the design of multi-material tissue FE models. We have shown that integrating more realistic anatomical constrains during model generation improves model realism in different clinical applications. The presented method can directly improve in-silico modeling with locally optimized tissue characteristics for patient- or population-specific simulations and can help optimizing biomechanical compatibility of devices.

ACKNOWLEDGMENT

This work was supported by the Swiss National Science Foundation (SNSF grant no. CR32I3_135044) and the Swiss Heart Foundation.

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