Leaflet Geometry and Anisotropy of Bioprosthetic Heart Valves: Do They Matter?
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\textbf{Introduction:} The most popular replacement heart valves continue to be bioprosthetic heart valves (BHV), which are fabricated from biologically derived biomaterials. While these devices benefit from low thrombogenicity and excellent hemodynamics similar to the native valve, device failure continues to be the result of leaflet structural deterioration mediated by fatigue and tissue mineralization. Moreover, valve performance is highly dependent on leaflet geometry. There is thus a profound need to enhance the physical realism of the BHV dynamics simulation in the design context. In this study, we developed a framework for parametric study of BHV to investigate the influence of the geometry of the leaflets on heart valve performance and to simulate the effect of leaflet material model of the leaflets on valve dynamics.

\textbf{Materials and Methods:} We modeled the leaflets as a thin shell structure using different constitutive models. In particular, both nonlinear isotropic and anisotropic material models have been considered and compared. A Rhino-Grasshopper based interactive geometry design platform is used to construct the valve according to the aortic root geometry. We simulate the valve deformations with various perturbations of the tissue properties including the collagenous fiber orientation, as well as the fiber and matrix stiffness to investigate the effect of alteration of the tissue mechanical properties. We also examine the effect of changing leaflet’s shape on valve dynamics by adjusting some geometrical parameters such as leaflet’s thickness and surface curvature. To approximate this problem, we use a thin shell isogeometric structure dynamic finite element solver for parametric studies of the material properties by applying a physiological transvalvular pressure load to the leaflets to enforce the pressure difference between left ventricle and aorta. Parametric studies of the leaflet’s geometry have been considered in the framework of an immersogeometric fluid-structure interaction (FSI) methodology. Validation of the FSI model is performed using pulsatile duplicator heart valve system to compare the FSI simulation results to the experimental data. The results of this validation make a convincing case for the fidelity of the numerical method for our analysis.

\textbf{Results and Discussion:} The functionality of BHV was evaluated by its effective orifice area and leaflet coaptation without regurgitation. The influence of the geometry on valve dynamics has been performed by comparing the valve effective orifice area and coaptation area for different designs of the leaflets. We observed a noticeable influence of the surface curvature on the effective orifice area of the valve and the overall tissue deformation. Sensitivity results for different values of fiber stiffness show that perturbing fiber stiffness coefficient in our anisotropic material model has a significant influence on the valve deformation only at the closing stage. The reason is that in dynamic simulation of heart valve in a full cardiac cycle, the opening phase is in the small strain regime, when fibers has not been recruited and the tissue matrix dominates the valve deformation. Therefore, the role of the anisotropic term is only pronounced during the closing stage, that representing the fiber action.

\textbf{Figure 1.} Deformation of the valve colored by Maximum in-plane principal Green-Lagrange strain (MIPE) for different values of fiber stiffness parameter. The chosen time point is at the end of cardiac cycle when the valve is fully closed.

\textbf{Translational Impact:} The goal is to present a framework which enables us to use more physically realistic soft tissue material model in heart valve simulations and to identify the role of leaflet’s shape on valve functionality, indicated by the effective orifice area during the opening and the coaptation area during the closing. These results can provide guidelines for designing leaflet tissues to improve valve durability. We are currently formulating a phenomenological material model that covers the interaction between the tissue’s collagen fibers and its ground matrix as well as the interaction between different fibers and permanent set. This computationally tractable material model facilitates the integration of an anisotropic model into our FSI solver.