Unified continuum fluid-structure interaction modeling of the left ventricle with aortic valves

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ABSTRACT

We present a finite element model of the blood flow in the left ventricle (LV) including fluid-structure interaction (FSI) simulation of aortic valves. The interacting fluid and structure are jointly discretized using a Unified Continuum (UC) approach based on the finite element method.

This work aims at developing a finite element simulation model of the blood flow in the LV to be used as a tool in a patient-specific simulation pathway [1]. In particular, our focus is on the extension of the finite element model to accommodate an effective discretization of fluid-structure interaction (FSI) of the aortic valves with the flowing blood. Computational modeling of aortic valves poses several challenges, among which we find the formulation of suitable geometric and constitutive models and the solution of the resulting coupled FSI problem. To actually perform the computations we let the mesh track the structure deformation; this causes severe deformation and degradation of the mesh in the fluid part of the domain, thus we employ mesh smoothing techniques to improve the mesh quality [2].

The LV model is based on a local ALE finite element method. As a part of the larger goal of a patient-specific pathway, the deformation of the endocardium is provided as input data from echocardiography. The coupled equations describing FSI of the blood and the valves are solved using a monolithic approach based on the UC model of the ALE-FEM-FSI problem including also contact between the leaflets, which is handled within the UC model by changing constitutive law for fluid elements that are identified as being inside a contact zone. The models are implemented in Unicorn [3] as part of the FEniCS-HPC open source software [4]. Unicorn runs on regular workstations or laptops, but is also optimized for massively parallel hardware architectures, opening for large scale simulations using supercomputers.

Preliminary results for the LV model include aortic valves simulation for a mechanical bileaflet valve as well as for a native biological valve. Currently, the mechanical bileaflet valve is attached to the patient-specific LV model, whereas the biological valve is separated from the LV model, connected by boundary conditions only. The full LV model including valves currently runs on the Cray XC40 system Beskow at the PDC Center for High Performance Computing at KTH. We note from our preliminary results that the computational model, including contact between the leaflets, is robust. In this work we extend these results by also connecting the biological valve model to the LV. Validation, robustness and uncertainty quantification of the complete patient-specific pathway is investigated elsewhere [1].

REFERENCES

[1] D.Larsson et al. *Patient-specific flow simulation of the left ventricle from 4D echocardiography feasibility and robustness evaluation*. Ultrasonics Symposium (IUS), 2015 IEEE International, pp.1-4, 2015.

[2] Hoffman, J., Jansson, J. and Stckli, M. *Unified Continuum Modeling of Fluid-Structure Interaction*. Mathematical Models and Methods in Applied Sciences, 21(3), 491-513.

[3] J.Hoffman et al. *Unicorn: Parallel adaptive finite element simulation of turbulent flow and fluidstructure interaction for deforming domains and complex geometry*, Computers and Fluids, Vol.80, pp.310-319, 2013.

[4] J.Hoffman et al. *FEniCS-HPC: Automated predictive high-performance finite element computing with applications in aerodynamics*. International Conference on Parallel Processing and Applied Mathematics, pp.356-365, 2015.