Implementation of an ALE - Coupled Momentum Method for the simulation of patient-specific nonlinear FSI phenomena in CRIMSON

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CRIMSON (CardiovasculaR Integrated Modelling and SimulatiON) is a three-dimensional modelling and simulation software environment for patient specific computational hemodynamics. The computational core of CRIMSON relies on PHASTA [1], a massively parallel flow solver for both compressible and incompressible flow. To account for the compliance of the vessel wall and, consequently, capture the wave propagation phenomena within the human vasculature, CRIMSON uses the Coupled Momentum Method algorithm, presented by Figueroa and coauthors [2]. The CMM represents the vessel wall as a linear membrane working under the small displacement assumption (infinitesimal strain theory), which allows solving a FSI problem without having additional degrees of freedom nor considering the deformation of the fluid mesh. Overall, this results into a computationally efficient algorithm that has proven to be very robust and has provided numerous clinically relevant results [3].

Despite the small displacement assumption is valid for a good part of the arterial tree (medium and small size vessels) under normal physiological conditions, there are other clinically relevant instances in which this assumption does not hold. For example, under non-physiological conditions such as trauma, impact or for example during surgery, the vessels may experience large deformations. Also, in normal physiological conditions, the Ascending Thoracic Aorta experiences large displacements and rotations between systole and diastole due to its attachment to the heart [4]. This is also the case for some of the important branches of the vein system, which often suffer from compression and even collapse, due to their low (and sometimes negative) transmural pressures [5].

With the objective of capturing capture blood and vessel mechanics in these clinically relevant cases, the current work presents an extension of the CMM to large displacements. This is achieved by means of a fully coupled Arbitrary-Lagrangian-Eulerian (ALE) formulation. The vessel wall is modeled by means of a Total Lagrangian nonlinear membrane model using convective coordinates. For the fluid part, the Navier-Stokes equations under their ALE form are solved using a stabilized finite element scheme. As in the CMM, the membrane degrees of freedom are shared with those of the fluid boundary, so no additional degrees of freedom are introduced. The mesh motion is handled using a 3D linear elastic solid and the time integration is performed using the generalized alpha method. Special care is taken to obtain a consistent linearization of the weak form. More importantly, the implementation has been carried out in small steps to ensure the accuracy and robustness of the implementations, without affecting the previous work carried out in CRIMSON. The paper presents a series of tests carried out during the implementation, which ensured a consistent development towards the final goal of a nonlinear FSI solver for patient specific hemodynamics.

References

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