

Neural Operators Approximations for Fluid-Structure Interaction in Aortic Aneurysm Modeling

Wednesday, 11 March 2026 12:25 (20 minutes)

Aortic aneurysms pose a significant clinical risk due to the potential for rupture, a life-threatening event whose likelihood depends on the hemodynamic forces acting on the arterial wall. Quantities such as wall shear stress, intraluminal pressure, and wall displacement are critical indicators of rupture risk, yet their accurate computation requires solving coupled partial differential equation systems that model both blood flow and vessel wall mechanics.

The hemodynamics are governed by the incompressible Navier-Stokes equations, while the arterial wall is modeled as a nonlinear hyperelastic material using constitutive laws such as the Holzapfel-Gasser-Ogden model. The two-way coupling between these domains – fluid-structure interaction (FSI) – introduces additional complexity through kinematic, dynamic, and geometric interface conditions. High-fidelity numerical simulations of this coupled system require meshes with millions of elements and thousands of time steps per cardiac cycle, resulting in computational times on the order of hours to days on high-performance computing systems.

This work investigates neural operator methods as a means to approximate the FSI solution operator directly, learning mappings between function spaces from simulation data. We present two complementary architectures: the Fourier Neural Operator, which leverages spectral convolutions for global information propagation, and graph-based neural operators, which naturally accommodate the irregular mesh topology of patient-specific vascular geometries. The presentation covers the mathematical foundations, the data generation pipeline, training and evaluation methodology, and ethical considerations for clinical deployment. Central research questions address approximation capacity, generalization to unseen geometries, preservation of physical constraints such as incompressibility, and operator stability. Preliminary analysis suggests that trained neural operators can achieve speedups of three to five orders of magnitude over classical solvers, opening pathways toward real-time cardiovascular risk assessment.

Keywords: Neural operators, Fluid-structure interaction, Aortic aneurysm, Fourier Neural Operator, Graph neural networks, Cardiovascular modeling

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Session Classification: AI Driven Biosciences & Ethical Autonomy

Track Classification: General sessions: AI Driven Biosciences & Ethical Autonomy