Shape-Driven Surrogate Modeling of Thoracic Aortic Hemodynamics

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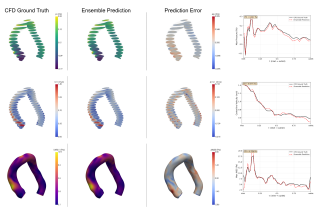
Computational fluid dynamics (CFD) provides detailed characterization of thoracic aortic hemodynamics, but its computational cost limits routine use. We present a deep learning surrogate for fast prediction of velocity, pressure, and wall shear stress (WSS) from aortic shape and inlet velocity.

Aortic geometries were parameterized with the Vascular Encoding Framework using B-spline coefficients. Synthetic cases were generated from a statistical shape model and simulated with steady-state RANS using the SST k-ω turbulence model. Of 6,000 simulations, 5,477 converged and were retained. Velocity, pressure, and WSS fields were reduced with principal component analysis, and an ensemble of five multilayer perceptrons was trained to predict 300 PCA coefficients from 831 inputs.

On 821 held-out synthetic samples, the ensemble achieved $R^2 = 0.917$ for velocity, 0.917 for pressure, and 0.912 for WSS, with mean normalized absolute error (MNAE) of 1.04%, 1.62%, and 1.39%, respectively. Leave-one-velocity-out validation showed strong generalization to unseen inlet conditions ($R^2 \geq 0.891$, MNAE $\leq 0.96\%$). Validation on 33 real patient-specific geometries yielded MNAE values of 1.5%, 1.7%, and 2.1% for 26 geometries involved in shape-model construction, and 4.6%, 4.6%, and 5.1% for 7 anatomies fully external to the shape model.



Synthetic test case showing CFD, prediction, error, and centerline profiles for pressure, velocity, and WSS.

Inference required 0.1 s per case, corresponding to a speedup greater than $3000\times$ over CFD. These results support shape-driven surrogate modeling as a fast and accurate approach for thoracic aortic hemodynamics, while highlighting the need for broader validation on fully external anatomies.