From Preloading to Fully Coupled Electro-Mechanics of the Left Ventricle: a Finite Element Comparison

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Computational models of the human heart can support clinical decision-making and improve understanding of cardiac function by capturing coupling between electrical activation and mechanical contraction. However, numerical accuracy and robustness remain challenging due to near-incompressible tissue behavior and electro-mechanical coupling.

To address this, we considered a nonlinear, near-incompressible mechanical model of an anatomically realistic left ventricle coupled with electrophysiology in a staggered scheme. Myocardial contraction was described using an active strain formulation, while electrical activation followed the ten Tusscher cell model. Non-physiological oscillations were suppressed by Rayleigh damping.

We compared the established conforming Galerkin (cG) discretization with an enriched Galerkin (eG) discretization using linear and quadratic elements across mesh refinements. The comparison involved both static mechanical preloading, establishing the end-diastolic state, and subsequent fully coupled electro-mechanical simulations, focusing on qualitative and numerical robustness indicators such as cavity volume, apex displacement and computational costs. We further investigated the influence of volumetric penalty parameters in the hyper-elastic strain energy formulation enforcing near-incompressibility.

In the preloading problem, cG exhibited locking on coarse meshes with linear elements, restricting deformation and degrading local volume conservation. In contrast, eG produced stable, physiologically plausible deformations, including wall thickening and apex motion. Left-ventricular myocardial volume varied by less than $2\,\%$ across penalty parameters with eG, compared to nearly $10\,\%$ with cG, while local volume preservation improved by up to one third. EG remained robust across mesh refinements, at slightly higher computational cost due to an additional degree of freedom per element.

These differences were amplified in the coupled simulations, during which inaccurate cG-based preloading led to inconsistent mechanical responses during activation, resulting in non-physiological contraction, reduced robustness, and increased sensitivity to penalty parameters. The eG approach improved coupling stability and consistent mechanical response, enhanced local volume preservation during active contraction, and yielded more robust coupled electro-mechanical dynamics.