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The importance of mechano-electrical feedback and inertia in cardiac electromechanics

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Abstract

In the past years, a number cardiac electromechanics models have been developed to better understand the excitation-contraction behavior of the heart. However, there is no agreement on whether inertial forces play a role in this system. In this study, we assess the influence of mass in electromechanical simulations, using a fully coupled finite element model. We include the effect of mechano-electrical feedback via stretch activated currents. We compare five different models: electrophysiology, electromechanics, electromechanics with mechano-electrical feedback, electromechanics with mass, and electromechanics with mass and mechano-electrical feedback. We simulate normal conduction to study conduction velocity and spiral waves to study fibrillation. During normal conduction, mass in conjunction with mechano-electrical feedback increased the conduction velocity by 8.12% in comparison to the plain electrophysiology case. During the generation of a spiral wave, mass and mechano-electrical feedback generated secondary wavefronts, which were not present in any other model. These secondary wavefronts were initiated in tensile stretch regions that induced electrical currents. We expect that this study will help the research community to better understand the importance of mechanoelectrical feedback and inertia in cardiac electromechanics.

Keywords: Electro-mechanics; Excitation-contraction; Cardiac mechanics; Finite element analysis; Abaqus

1. Motivation

The heart is composed of four chambers and its primary function is to circulate blood in the cardivascular system. To achieve this goal, electrical waves travel through the cardiac tissue to trigger muscle contraction and generate a coordinated movement of the ventricles that pump blood through the arteries. Despite tremendous scientific advances, heart disease is responsible for half a million deaths each year in the United States alone [39]. Many of these deaths are caused by lethal arrhythmias, which provoke an abnormal electrical activity of the heart that ultimately leads to mechanical dysfunction and death. In the case of cardiac fibrillation, arrhythmias are driven by electrical spiral waves that self-excite, preventing the coordinated contraction of cardiac tissue and diminishing the pumping capacity of the heart [45]. The electrical wave that modulates muscle contraction is influenced by the mechanical deformation. Indeed, mechanical contraction deforms the domain where the electrical wave is propagating, altering wave dynamics. Moreover, transmembrane currents are generated by the stretching of ionic channels. This mechano-electrical feedback is thought to be responsible for "commotio cordis", a condition in which the precordial impact of an object may start ventricular fibrillation [33]. Mechano-electrical feedback is also responsible for "precordial thump", a procedure in which the currents generated by this mechanism are used to stop fibrillation [7].

Computational modeling can help to better understand the interplay between the electrical and the mechanical behavior in the heart, that would otherwise be difficult to characterize in laboratory experiments