On a reduced cylindrical model of the left ventricular dynamics

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1. Introduction

Cardiovascular diseases are among the main causes of death in Europe and the U.S.A. Because of the very nature of the heart–the pump that circulates blood in the body–, all cardiac diseases have mechanical ramifications, in their origin and/or their impact [8, 4]. As a consequence, many mechanical models of the heart have been developed until now, with the objective of better understanding the cardiac mechanics in health and diseases. A wide variety of approaches has been employed, with varying complexity at the geometrical, constitutive behavior (passive and active), boundary conditions and coupling (to, *e.g.*, electrophysiology or poromechanics) levels, depending on the objective of the model. If early models were naturally simpler [1, 6], in the past decades very complex finite element models have been proposed [8, 4]. They have the potentiality to address some of the critical issues of today's cardiology; however, they usually have a very high computational cost, which represents a bottleneck for further clinical use. Model order reduction techniques have been proposed to facilitate their use; however they are still emerging today. The M3DISIM team at Inria/École Polytechnique has proposed another class of reduced models, based on simplified geometries and kinematics but containing fully detailed passive and active constitutive behaviors, and associated energy-preserving integration schemes [2]. They have the advantage of relying on clear physical hypothesis. These reduced models can be used in a first step of model calibration [2], which can be very computationally demanding when performed directly on 3D models [3, 5, 4], or in applications where computation speed is critical [7].

2. Methods

In this presentation, we will introduce another reduced model of the left ventricle, which, in the team's hierarchy of models, is located in between the spherical (which is solved using a set of ordinary differential equations) and the full 3D model (which corresponds to a large system of partial differential equations). It is based on the cylindrical geometry and kinematics proposed by [6], where a point of coordinates (r_0, θ_0, z_0) in the reference configuration is transported to the coordinates

$$\begin{cases} r = r_0 + \rho(r_0) \\ \theta = \theta_0 + \beta z_0 + \phi(r_0) \\ z = (1+\epsilon) z_0 + \omega(r_0) \end{cases} \quad (1)$$

in the deformed configuration, where ρ characterizes the radial displacement, β the global twist, ϕ the in-plane, radial-circumferential, twist, ϵ the longitudinal shortening, and ω the out-of-plane, radial-longitudinal, twist. Thus, the kinematics is reduced to a manifold defined by two scalars (β & ϵ) and three functions of the radial position r_0 (ρ, ϕ & ω). We developed a fully dynamic formulation, where the spatial functions are resolved on a 1D finite element mesh through the thickness of the ventricle. The main advantage of the model, compared to the reduced spherical model introduced in [2], is *(i)* to contain a full description of the myofiber architecture through the ventricular thickness, and *(ii)* to describe ventricular twist, while keeping a very small computational cost. In the presentation, we will provide details on the model formulation and resolution, as well as extensive cross-validation with respect to the spherical and full-fledged 3D finite element models.

3. Results and discussion

Figures 1 & 2 show standard model output for a heartbeat simulation in the physiological regime.

4. Conclusion

The considered reduced cylindrical ventricular model lies, in the hierarchy of cardiac models developed within the M3DISIM team, in between the reduced spherical model [2] and full 3D models [3]. Thanks to the proposed efficient finite element-based computational strategy, it represents a good balance between model predictivity and computational cost, and could help pushing computational modeling-based tools in the clinic.

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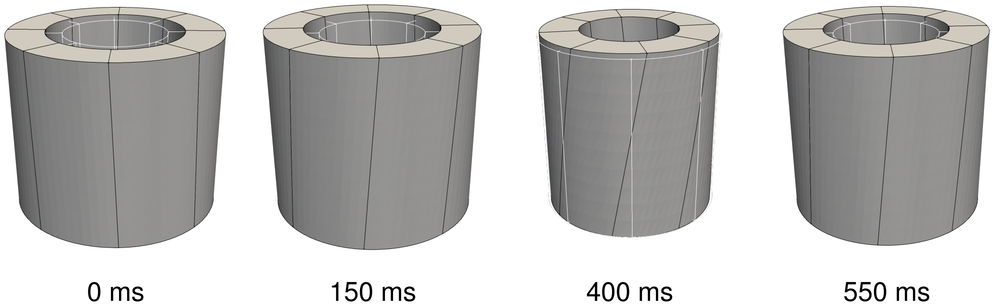

Figure 1: Visualization of the reduced cylindrical ventricular model deformation throughout the cardiac cycle. Full cycle is 800 ms. (The mesh shown here is only for visualization purpose, as only a 1D finite element mesh is used for the simulation. The reference mesh is shown in wireframe.)

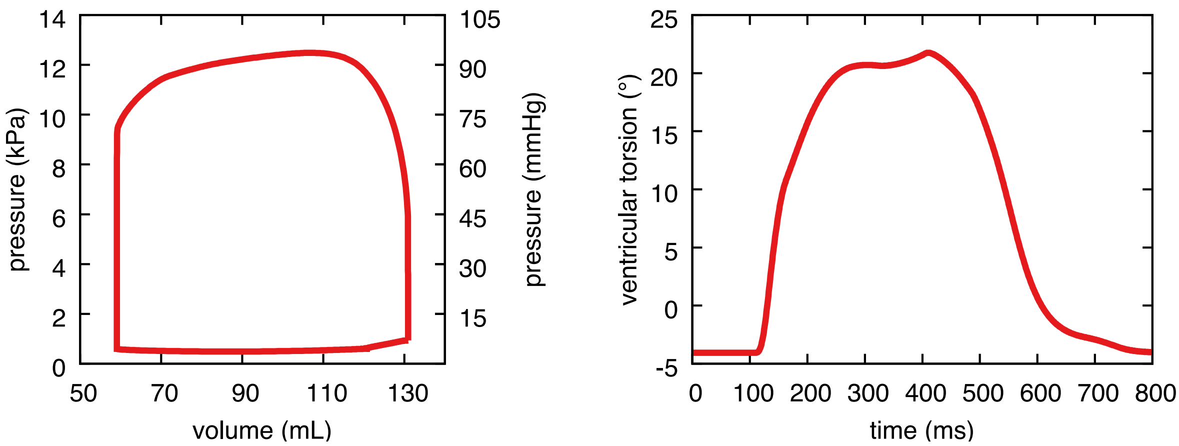

Figure 2: Pressure-Volume loop (left) and Ventricular twist temporal evolution (right) simulated using the proposed reduced cylindrical ventricular model.

6. References

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