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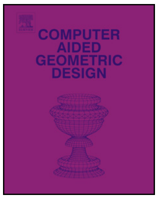

Biomechanics simulations using cubic Hermite meshes with extraordinary nodes for isogeometric cardiac modeling

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ABSTRACT

Cubic Hermite hexahedral finite element meshes have some well-known advantages over linear tetrahedral finite element meshes in biomechanical and anatomic modeling using isogeometric analysis. These include faster convergence rates as well as the ability to easily model rule-based anatomic features such as cardiac fiber directions. However, it is not possible to create closed complex objects with only regular nodes; these objects require the presence of extraordinary nodes (nodes with 3 or >= 5 adjacent elements in 2D) in the mesh. The presence of extraordinary nodes requires new constraints on the derivatives of adjacent elements to maintain continuity. We have developed a new method that uses an ensemble coordinate frame at the nodes and a local-to-global mapping to maintain continuity. In this paper, we make use of this mapping to create cubic Hermite models of the human ventricles and a four-chamber heart. We also extend the methods to the finite element equations to perform biomechanics simulations using these meshes. The new methods are validated using simple test models and applied to anatomically accurate ventricular meshes with valve annuli to simulate complete cardiac cycle simulations.

1. Introduction

Computational models of cardiac biomechanics have been used to study normal cardiac physiology (Kerckhoffs et al., 2007) and pathological conditions such as heart failure (Kerckhoffs et al., 2010; Niederer et al., 2011). Advances in non-invasive imaging technology have made it feasible to generate patient-specific ventricular models (Aguado-Sierra et al., 2011; Krishnamurthy et al., 2013), but it remains difficult to create high-quality meshes that include anatomic features such as valve annuli automatically, owing to the irregular shape of the resulting cardiac geometry.

Cubic-Hermite finite element interpolation schemes have been popular in cardiac modeling because of their convergence properties in finite element simulations of ventricular biomechanics (Costa et al., 1996) and their ability to capture smooth geometries compactly. However, construction of cubic-Hermite geometric meshes has been limited to ventricular geometries below the valve plane due to difficulties in handling complex topologies of the atria and great veins (Fig. 2). Most previous cardiac models using high-order meshes have been restricted to geometries described by a single set of parametric coor-

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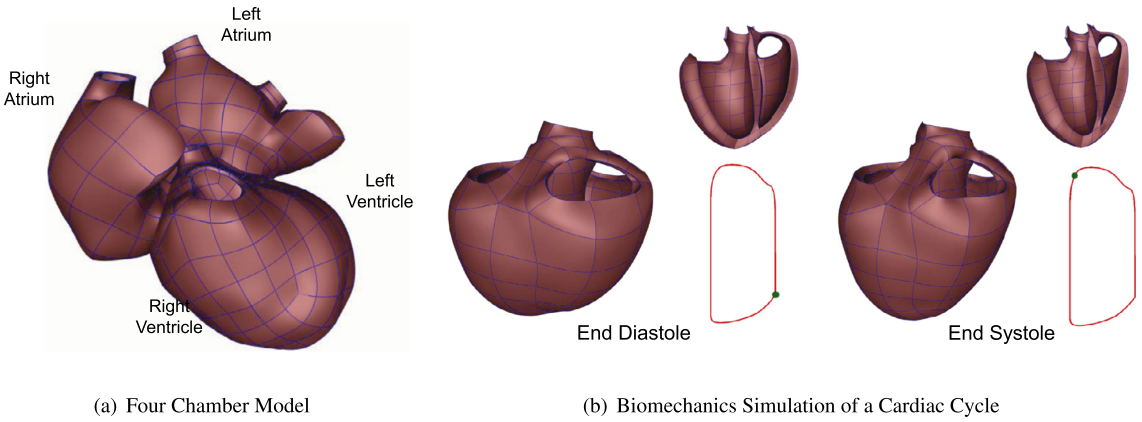

(a) Four Chamber Model (b) Biomechanics Simulation of a Cardiac Cycle

Fig. 1. Topologically complex four-chamber model and a ventricular model with valve annuli at the end-diastolic and end-systolic states of the cardiac cycle. A cut-section (top) and a PV-loop (bottom) are shown inset.

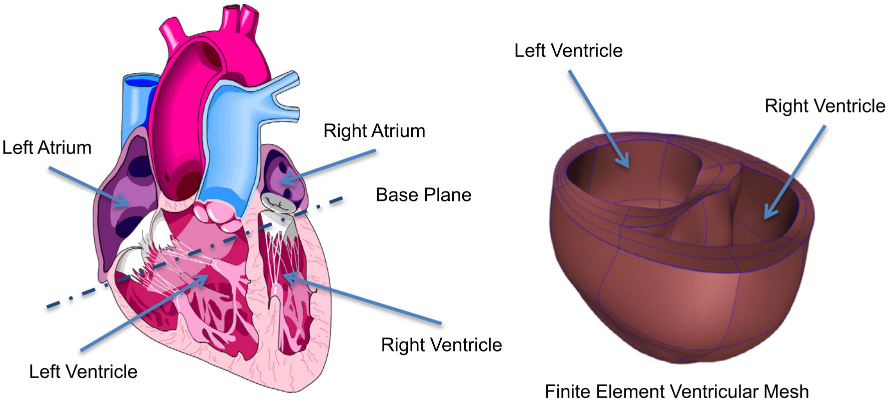

Fig. 2. Cubic-Hermite cardiac finite element meshes have previously been used for modeling ventricular geometry that do not include the valve annuli or the atria.

dinates that are topologically equivalent to a cylinder (Vetter and McCulloch, 1998). However, such meshes require special boundary conditions at the cardiac apex to enable multiple overlapping nodes or "sector" elements (Bradley et al., 1997) to close the mesh. The restriction of using a single set of parametric coordinates enables enforcing continuity across element edges easier, but introduces element distortions.

Gonzales et al. (2013) removed the restriction of having a single set of parametric coordinates in the mesh. The mesh is discretized into a number of sub-regions, each with its own set of parametric coordinates. However, this introduces nodes with an irregular number of neighboring elements, known as extraordinary nodes, at the interface between the sub-regions. Extraordinary nodes are routinely used in linear hexahedral meshes. However, in high-order meshes, enforcing smoothness (i.e., C^0, G^1, or C^1 continuity) conditions along edges incident on extraordinary nodes becomes complicated. Gonzales et al. (2013) described new methods for constructing high-quality bicubic and tricubic Hermite finite element meshes of the human atria. Their meshes preserved smoothness between cubic Hermite elements by introducing an ensemble coordinate frame centered on the nodes and using a generalized local-to-global mapping to transform the derivatives. They used this mapping to construct static finite element meshes of the human atria that can be used to perform non-deforming electrophysiology simulations. We make use of the same mapping in this paper to create finite-element meshes of a four-chamber heart and cardiac ventricles with valve annuli. In addition, we extend the mapping to displacements and coordinate frames, to perform deforming biomechanics simulations using these finite-element meshes.

Cardiac biomechanics simulations make use of the finite strain theory to model deformation of the myocardial tissue. This is because the tissue undergoes large deformations during the cardiac cycle. In addition, the tissue properties are non-linear and anisotropic; the cardiac muscle tissue is stiffer along the axial direction of the cells called the fiber direction. Hence, the constitutive models used for cardiac mechanics make use of hyperelastic, exponential stress-strain relationships with the parameters being different for the fiber and the two cross-fiber directions. In order to capture these large deformations accurately, the displacements of the nodes in the deformable mesh need to be consistently mapped across extraordinary nodes. We make use of the local-to-global mapping used for the geometry to map the global displacements to the local coordinate frame.