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Medially constrained deformable modeling for segmentation of branching medial structures: Application to aortic valve segmentation and morphometry

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ABSTRACT

Deformable modeling with medial axis representation is a useful means of segmenting and parametrically describing the shape of anatomical structures in medical images. Continuous medial representation (cm-rep) is a “skeleton-first” approach to deformable medial modeling that explicitly parameterizes an object’s medial axis and derives the object’s boundary algorithmically. Although cm-rep has effectively been used to segment and model a number of anatomical structures with non-branching medial topologies, the framework is challenging to apply to objects with branching medial geometries since branch curves in the medial axis are difficult to parameterize. In this work, we demonstrate the first clinical application of a new “boundary-first” deformable medial modeling paradigm, wherein an object’s boundary is explicitly described and constraints are imposed on boundary geometry to preserve the branching configuration of the medial axis during model deformation. This “boundary-first” framework is leveraged to segment and morphologically analyze the aortic valve apparatus in 3D echocardiographic images. Relative to manual tracing, segmentation with deformable medial modeling achieves a mean boundary error of 0.41 ± 0.10 mm (approximately one voxel) in 22 3DE images of normal aortic valves at systole. Deformable medial modeling is additionally demonstrated on pathological cases, including aortic stenosis, Marfan syndrome, and bicuspid aortic valve disease. This study demonstrates a promising approach for quantitative 3DE analysis of aortic valve morphology.

1. Introduction

1.1. Deformable modeling of heart valves in 3D echocardiographic images

Echocardiography is the most commonly used imaging modality for the evaluation of heart valve disease. Image segmentation of heart valves in 3D echocardiographic (3DE) data is a means of extracting visual and quantitative information about patient-specific in vivo valve morphology that can support valve diagnostics and surgical treatment planning (Jassar et al., 2014; Noack et al., 2013; Veronesi et al., 2009; Vergnat et al., 2011). Image segmentation in this context, however, is difficult due to the signal dropouts and noise that are characteristic of echocardiographic imaging, as well as the fact that many clinically relevant valve landmarks are defined geometrically rather than by distinctive image intensity characteristics. For example, several components of the aortic valve complex, such as the sinotubular junction (STJ), the commissures, and the attachments of the aortic cusps, are identified anatomically rather than by distinctive image intensity patterns. Given these challenges, shape-guided deformable modeling methods are well suited for 3DE heart valve segmentation. Deformable modeling methods capture the geometry of an image region by deforming parametric surfaces under the influence of external data-driven forces and internal regularization forces. Shape constraints imposed on the deformable model can fill in areas of intensity inhomogeneity or establish boundaries between

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anatomical components that are not demarcated by image gradients. Once a parametric model of the valve is obtained, it can be interactively visualized, quantitatively analyzed, and statistically compared to other valve geometries.

Several deformable modeling methods for heart valve segmentation in 3DE images have been proposed, each of which uses a different means of representing valve shape. Ionasec et al. (2010) developed a fully automatic technique for segmenting the aortic and mitral valves in 3DE images. Given a database of manually landmarked images, machine learning algorithms globally locate and track several valve landmarks throughout the cardiac cycle. Spline surfaces are fitted through these points with the aid of learned boundary detectors to represent the geometry of the valves. In other work, Schneider et al. (2011) present a deformable model-based 4D segmentation of the mitral leaflets in real-time 3DE data in which the leaflets are represented with a triangulated mesh. Once the leaflets are segmented at diastole, the mesh deforms to subsequent time points in the cardiac cycle under the influence of multiple image-driven and regularizing forces. The regularizing forces encourage leaflet stretching during valve closure, prevent excessive leaflet bending and collision, and encourage the leaflet free edges to point into the left ventricle. This segmentation and deformable modeling method has only been applied to the mitral valve and has not yet been extended to the aortic valve.

Our earlier work (Pouch et al., 2013, 2014) differs from the above deformable modeling methods in that it represents mitral and aortic leaflet geometry volumetrically, i.e. as structures with locally varying thickness. The shape descriptor we use for the deformable model is 3D continuous medial representation, or cm-rep (Yushkevich et al., 2006a). This representation describes the relationship between the surfaces and the interior, or morphological skeleton,[1] of the leaflets. In 1967, Blum introduced the notion of the medial axis in 2D as a means of shape classification and discrimination for biological problems. The definition naturally extends to 3D, as described in Section 2.1, and has been leveraged for parametric deformable modeling of anatomical structures in medical images. Deformable models based on the medial representation were pioneered by Pizer et al. (1999, 2003, 2013) and have two particular advantages in medical image segmentation and shape analysis: they can be used to constrain the branching configuration of the segmented anatomical structure, and they can be used to statistically compare skeleton-derived shape features in a population of instances of those segmented anatomical structures. In the continuous medial representation (cm-rep) framework described in Yushkevich et al. (2006a), a deformable model represents an object's medial axis as a parametric surface, and the thickness of the object at each point on the medial axis is also parametrically defined. This is in contrast to the original medial representation of Pizer et al. (2003), in which the medial axis is described using a discrete set of primitives, or "atoms". The parametric description of the skeleton as a surface with thickness can be "inflated" using a simple analytical expression to form a volumetric representation of the object, a process referred to as *inverse skeletonization*. (Note that since the object's boundary is derived from the object's skeleton, the cm-rep method is considered a "skeleton-first" approach to medial representation.) By modifying the parameters of the skeleton, the cm-rep model can be deformed to take on new shapes. Gradient-based optimization schemes can be applied to the model parameters in order to deform the model to approximate the shape of anatomical structures in 3D image data. Typically, these structures are first segmented using some separate segmentation algorithm, and the cm-rep model is fitted to the binary or multi-label segmentation of the structure of interest (Yushkevich et al., 2006a, 2008; Pouch et al., 2014). However, the optimization can also be formulated to fit the model directly to image intensities, as in (Sun et al., 2010). The motivation for using cm-rep as a shape descriptor for heart valve leaflets is that it is useful for volumetric modeling of thin sheet-like structures. The parametric model explicitly defines leaflet thickness, which is an important tissue parameter in biomechanical valve simulation (Rausch et al., 2013) and may be indicative of valve pathology, such as calcification or degenerative processes. Moreover, the aortic and ventricular surfaces of the aortic cusps are both delineated, and constraints on medial geometry prevent these surfaces from intersecting during model deformation.

[1] Note that in this work, the terms medial axis and morphological skeleton are used interchangeably when referring to either 2D or 3D objects. The medial axis of a 2D object is a set of curves, and the medial axis of a 3D object is generically a set of surfaces. We also use the term medial scaffold to specifically refer to a 3D medial axis or skeleton.

1.2. Challenges of deformable modeling of the aortic valve apparatus with medial axis representation

A major limitation of the cm-rep method described above is that it is limited to modeling 3D structures that can be accurately represented using a single-surface medial axis. However, many sheet-like anatomical structures can only be described using a medial axis consisting of multiple adjoining surfaces, or "branches." So, while cm-rep has been effectively used to describe mitral and aortic leaflet morphology in 3DE images, applying it to the entire aortic valve complex (including the sinuses of Valsalva) is not possible. The heart valve leaflets themselves can be described in terms of a single non-branching medial manifold; however, the entire aortic valve complex has a branching medial representation, as illustrated in Fig. 1. The aortic root, extending from the left ventricular outlet (LVO) to the STJ, can be modeled with a single medial manifold in the absence of the aortic cusps, as in Fig. 1a. The aortic cusps can likewise be modeled as individual medial manifolds (Fig. 1b, blue surfaces), but the entire valve apparatus is a branching medial model where the cusps attach to the aortic root at seams, or branch curves, in the medial scaffold. The cm-rep methodology has the limitation that medial axes are difficult to explicitly parameterize along curves at which medial surfaces meet. For example, the inverse skeletonization equations that are used to obtain a volumetric representation from an object's medial axis (Yushkevich et al., 2006a) are asymptotic at the edges of the medial axis and along branch curves in the medial axis. Work that extends the cm-rep paradigm to medial axes with multiple branches has been very limited. Terriberry and Gerig (2006) describe a special spline-based representation that allows parametric representation of seam curves and demonstrates it in a toy example, but this method has never been shown to work in actual anatomical structures or in the context of deformable modeling. Sun et al. (2010) propose a cm-rep model with seams that is used to model the myocardium, but their model cannot handle seam-edge curve junctions and is thus limited to a very special class of anatomical modeling problems. In the original m-rep framework (Pizer et al., 2003), complex structures whose medial axis has multiple branches are approximated using a union of single-branch m-rep "figures" enveloped by a shrink-wrapped surface. While such a representation is versatile, it deviates from the actual 3D geometry of medial axes (i.e. the true medial axis of the shrink-wrapped surface can be completely different from the skeletons of the two component figures). In this work, as in the cm-rep method, our goal is to use 3D medial representations that are faithful to the medial geometry described by Blum and others.

1.3. Representation of the aortic valve apparatus with a medially constrained boundary-first deformable model

To overcome the challenge of modeling structures with branching medial topologies, a novel "boundary-first" deformable medial modeling paradigm was recently proposed (Yushkevich and Zhang, 2013). Rather than explicitly parameterizing a structure's medial axis and