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Automatic mitral valve leaflet tracking in Echocardiography via constrained outlier pursuit and region-scalable active contours

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ABSTRACT

Tracking the mitral valve leaflet in Echocardiography is of crucial importance to the better understanding of various cardiac diseases and is very helpful to assist the surgical intervention for mitral valve repair. In this paper, we present an automatic mitral leaflet motion tracking approach, which consists of two phases: constrained outlier pursuit for mitral leaflet detection and its shape refinement. In the former phase, we first learn a low-rank subspace which can gradually change over time to model the background sequence, and simultaneously detect sparse outliers through such low-rank representation. Then, we extract the supported states of the myocardial tissues to constrain the outlier pursuit for mitral leaflet detection, featuring on reliably removing the irrelevant outliers. In the latter phase, we further present a region-scalable active contour to refine the shapes of the detected mitral leaflet for final tracking. The proposed approach does not require any user-specified interactive information or pre-collected training data for learning. The robustness of its performance has been demonstrated against the fast mitral leaflet motions, shape deformation and unstable myocardial tissue appearance. Experimental results have shown that the proposed approach performs favorably on four challenging sequences in comparison with the state-of-the-art methods.

1. Introduction

The mitral valve leaflet (simply called mitral leaflet hereinafter), whose function is to govern the fluid interaction in-between the left atrium (LA) and the left ventricle (LV), holds a key role in the cardiovascular system [1]. In clinical diagnosis, the analysis of mitral leaflet motions is of crucial importance to the better understanding of various cardiac diseases such as mitral regurgitation and mitral valve prolapse. To date, precise morphological and functional knowledge about the mitral leaflet status are always based on two-dimensional images [2]. Among all the medical imaging modalities, Echocardiography (i.e., ultrasound imaging of the heart) is currently the most popular imaging technique utilized to assess cardiac function visually [3]. Such a modality featuring portability, easy implementation, non-invasiveness and relatively low cost, has been widely utilized for the clinical diagnosis of various cardiac diseases, especially in the emergency room and intensive care units. Within Echocardiography, effective acquiring patient-specific information about the motion of mitral leaflet will be very helpful to the surgical intervention assistance, e.g., mitral valve repair. In addition, such an image-guided intervention will also hold a key role in the success of Computer Aided Surgery (CAS) [4], Robot Assisted Surgery (RAS) [3], therapy-planning [5] and other medical services. Therefore, it is imperative to derive such information reliably in a very timely fashion for cardiac disease diagnosis clinically.

In the past years, different kinds of visual tracking approaches have been developed in the literature, e.g., see [6] and references therein. However, these methods are usually designed to track the natural objects, which are unsuitable for automatically tracking the mitral leaflet motions in Echocardiography. The main reasons are four-fold: (1) The complex image patterns: there almost always exist the non-significant edges, poor contrast and intensity inhomogeneity in echocardiographic images, which make difficult to well detect the positions and the boundaries of the mitral leaflets. (2) Lack of representative features: reliable features aiming at discriminating the object from its surrounding parts always play an important role in the tracking applications. However, the mitral leaflet always shares the similar intensity and texture with its surrounding tissues such as myocardium, which may cause motion ambiguities. (3) Fast and non-rigid motion: mitral leaflet movements, incorporating the elastic shape, non-rigid motion, feature motion decorrelation and inter-patient variability problem [2], will make it hard to determine the shape and

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the position of the mitral leaflet simultaneously. (4) Noisy effects: the echocardiographic images are often corrupted by the speckle noise, which will degrade the image qualities and result in missing boundaries. Under these circumstances, the existence of speckle noise would generate a negative impact for mitral leaflet detection and tracking.

To resist these attacks existing in the Echocardiography-based systems, some specific approaches integrating the edge, intensity with the anatomical information have been proposed to segment the mitral leaflet in static frame individually [7,8]. Nevertheless, these methods incorporating the low-level image-precessing techniques often fail to provide efficient solutions and the obtained results may not well match the shapes of the moving leaflets. In addition, these approaches have a limitation in application domains due to the requirement of manual delineation for initialization or large annotated datasets for training priors [9,10]. Therefore, it is desirable to develop an algorithm that can automatically detect and track the mitral leaflet motions from a practical viewpoint.

In this paper, we will present an automatic mitral leaflet motion tracking approach throughout an echocardiographic sequence. Without user-specified interactive information or pre-collected training data for learning, the proposed approach improves the state-of-the-art methods by providing the following two contributions: (1) We utilize the difference in motion patterns between the mitral leaflet and the myocardium, and formulate the mitral leaflet detection problem as the constrained outlier pursuit in the low-rank framework. Comparing with the single frame level, the mitral leaflet sharing the similar appearance with myocardium nearby can be well identified via the motion patterns in echocardiographic sequence. Meanwhile, such a formulation is able to automatically detect the interested regions of mitral leaflet without any manual assistance and will also be robust against the speckle noise and fast mitral leaflet motions; (2) We present a region-scalable active contour to further refine the shapes of the detected mitral leaflet, through which the actual boundaries of the valve leaflet can be well fitted. This kind of operation can well handle the leaflet shape deformations during the tracking process. The experiments have shown the promising results.

The remaining part of this paper is organized as follows: Section 2 will overview the related works, and Section 3 presents the proposed approach including its framework and implementation details. Section 4 provides the experimental results to compare the proposed approach with the existing competing methods. Finally, we draw a conclusion in Section 5.

2. Related works

In the past years, only a few techniques related to mitral leaflet detection and tracking are introduced. The active contour, one of the most successful models based on level set theory or parametric curve representation, has been extensively studied and successfully utilized for medical image segmentation. It aims at driving an initial contour towards the object boundary with an arbitrary topology. Along this way, Mikic et al. [2] proposed an optical flow guided active contour to extract the boundaries of mitral leaflet from one frame to another. Nevertheless, the accuracy of optical flow computation was always degraded by the speckle noise such that this method may fail to match the boundaries of the tracked mitral leaflets. Meanwhile, this approach is required to manually segment the mitral leaflet in the first frame and compute the optical flow field throughout the whole sequence, which were computational expensive. Latter, Martin et al. [1] first utilized a transformation fitting method to provide a rough segmentation, and then employed two connected active contours associated with dynamic programming minimization scheme to track the mitral leaflet. For fast implementation, they further considered the intensities of mitral leaflet to be the local maximum and employed two constrained active contours associated with curve fitting techniques to segment the mitral leaflet [8]. Both these methods are needed to segment the first frame manually for initial curve template placement and compute the principal curvatures of the interested mitral leaflet to constrain the active contours, which were known to be noise sensitive. To well separate the mitral leaflet with its surrounding tissues, Shang et al. [11] integrated a region competition based active contour with an additional speed-controlling term to extract mitral leaflet boundaries. This active contour aiming at minimizing a region-based probabilistic energy function was able to evolve onto the weak edges of mitral leaflet boundaries. Nevertheless, such a method is needed to manually assign the initial template for contour evolving and required to learn the probabilistic distribution of the interested mitral leaflet in advance. Meanwhile, this type of active contour may converge to the wrong result if there exists obvious speckle noise.

In general, the active contour only based approaches may often fail to isolate the mitral leaflet from its surrounding tissues when the image qualities are poor. Recently, a machine-learning based image processing method was proposed to build a comprehensive physiologically driven model, through which the major anatomic landmarks and structures of the patient-specific mitral leaflets can be fitted [4]. Such an approach has a strong ability to determine the correct positions of the mitral leaflet in complex echocardiographic images. Nevertheless, this method is required to collect a large amount of expert-annotated datasets and perform a training process to learn the mitral leaflet model, which was therefore unsuitable for clinical diagnosis practically. Schneider et al. [9] first exploited the mitral annulus information to construct a geometric prior for the mitral valve and then propagated it to all other frames. Accordingly, the location of the mitral leaflets can be estimated throughout valve closure. However, such a method still required two pre-selected frames to indicate the start and the end of valve closure and simultaneously is needed to label a single point near the closed valve to get prior information. In addition, this method may not be able to provide a good match to those mitral leaflet shapes during valve opening process.

Note that, the above-mentioned approaches always required the intensive human interactions. Recently, researchers have found that the moving objects may be absorbed into the background model. Specifically, the background sequence can be modeled by a low rank subspace that can gradually change over time, while the moving foreground objects constitute the correlated sparse outliers [12,13]. Inspire by these findings, Zhou et al. [14] have demonstrated that the image sequence of a cardiac cycle excluding the mitral leaflet region with fast motion can be well approximated by a low-rank matrix. Accordingly, they proposed an automatic mitral leaflet tracking approach by contiguous outlier detection in the low-rank representation. This method has achieved an impressive tracking result with higher accuracy, but which, unfortunately, may lead to a tracking drift due to the unstable surrounding tissues. That is, the tracked position has been significantly deviated from the ground truth. Meanwhile, the obtained shapes of the detected leaflets may not match their actual boundaries quite well.

3. The proposed tracking framework

In general, the scale size of the moving mitral leaflet is usually small and will not appear in the same location during a short period. Comparatively speaking, the surrounding tissues corresponding to myocardium almost hold a stable appearance. Therefore, the motion