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Complete Left Ventricular Wall Motion Estimation from Cascaded MRI-SPAMM Data

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Abstract

We present a new paradigm which incorporates multiple sets of tagged MRI data (MRI-SPAMM) acquired in a cascaded fashion in order to estimate the full 3-D motion of the left ventricle (LV) during its entire cardiac cycle. Our technique is based on the extension of the volumetric physics-based deformable models, whose parameters are functions, which can capture the local shape variation of an object with a small number of intuitive parameters. By integrating a cascaded sequence of SPAMM data sets into our modeling technique, we have extended the capability of MRI-SPAMM and have provided an accurate representation of the LV motion from end-diastole to end-diastole to better understand cardiac mechanics.

Keywords

Medical Image Processing; Visualization; 3-D Motion Estimation; Left Ventricle; Heart; MRI-SPAMM; Cardiac Mechanics

Introduction

In order to accurately measure left ventricular (LV) wall motion; a number of material points must be located and tracked. A widely used method in the past for providing intramyocardial markers has been the surgical implantation of radiopaque markers or beads [1,2,3] into the myocardium. Although the implantation method provides the most accurate localization, the invasive nature of the procedures does not allow a sufficient number of markers to be implanted for an adequate reconstruction of the LV geometry. Moreover, it poses potential problems of altering local myocardium properties due to the introduction of foreign objects. As an alternative method, some researchers have utilized naturally occurring landmarks like bifurcations of coronary arteries [4][5] to avoid surgery. However, intra-coronary injection of contrast medium is usually required to highlight the blood vessels in acquired images. Moreover, when the blood supply is severely obstructed due to arterial occlusion, the tracing of the feature points around the region can be very difficult to achieve [4].

Magnetic resonance (MR) tagging [6,7] has advantages over the aforementioned approaches because a large number of material points can be marked and tracked in a non-invasive manner. In particular, the Spatial Modulation of Magnetization technique (MRI-SPAMM) uses a fairly simple procedure to locally perturb the magnetization in tissue in a way, which creates spatial grid patterns. Those patterns or magnetization tags are seen as dark regions in subsequent images (within a certain relaxation time T1). As magnetization moves with tissue, the magnetization tags will move in the corresponding images, directly reflecting the motion of the underlying tissue, allowing us to follow the motion patterns within otherwise featureless structures, such as heart wall. The MRI-SPAMM technique has been used to demonstrate regional motion patterns during systole [8][9][10]. Figure 1 shows MRI-SPAMM images of an LV from a short-axis view acquired during systole. We can easily observe that these images reveal the underlying motion of the myocardium.

However, there are two drawbacks in current MR tagging techniques: First, we can only obtain in-plane (i.e., 2-D) motion from SPAMM images acquired over time. Given that every image plane is spatially fixed, while a heart being imaged moves, the through-plane motion cannot be captured by the SPAMM datapoints (SPAMM datapoints are referred to the intersection points of the tagging grids within the inner and

end-diastole early systole systole end-systole

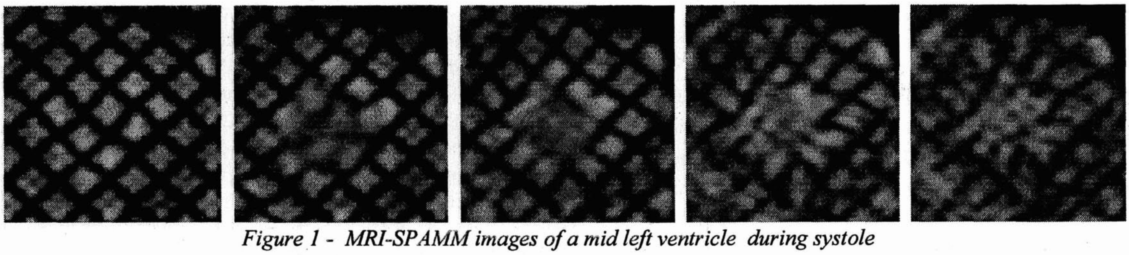

Figure 1 - MRI-SPAMM images of a mid left ventricle during systole

outer boundaries of the LV) on the image plane. Second, it is possible to track only a part of the cardiac cycle (e.g., systole), due to decay of the magnetization signal over time (see Figure 1). In this paper, we show how to overcome these limitations and propose a method for estimating the 3-D LV motion over its complete cardiac cycle from multiple sequential sets of MRI-SPAMM data in conjunction with the use of our physics-based deformable models.

Methods

Deformable Model

In order to assess the volumetric 3-D LV motion from a set of 2-D time-varying SPAMM data, we have recently developed a physics-based volumetric deformable model [10][11] which uses as input SPAMM data sets from mutually orthogonal image planes. The geometry of the volumetric model is defined based on its parameters, which are functions. These parameters comprise an intelligent grouping of the many local parameters that are necessary to accurately analyze the volumetric shape and motion of the LV. Using Lagrangian dynamics and finite element theory, we convert these volumetric primitives into dynamic models that deform due to "forces" exerted from datapoints.

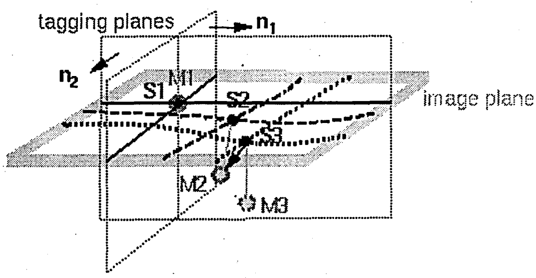

Figure 2 - Force Computation

The algorithm for fitting the model to the data is based on the calculation of forces exerted from MRI-SPAMM data to the deformable model. The force calculation algorithm is based on the constrained physical motion of SPAMM datapoints in three dimensions. Since only the in-plane motion of a SPAMM datapoint can be estimated from a given set of planes, we combine forces from SPAMM datapoints originating at two sets of orthogonal planes: short-axis view and long-axis view. We first register the SPAMM datapoints from all image planes at initial time t_1 and mark them as material points on the model. Suppose **S1** is a SPAMM datapoint at time t_1, and let **S2** and **S3** be the SPAMM data points corresponding to the point **S1** at the next two time frames (see Figure 2). Then the force on the material point **M1** from **S2** is computed as

$$\mathbf{f}_{S2} = \gamma[\,((\mathbf{S2}-\mathbf{M1})\cdot\mathbf{n}_1)\,\mathbf{n}_1 + ((\mathbf{S2}-\mathbf{M1})\cdot\mathbf{n}_2)\,\mathbf{n}_2\,] \qquad (1)$$

where γ is the strength of the force and $\mathbf{n}_1$, $\mathbf{n}_2$ are the unit normals of the corresponding initial (i.e., at time t_1) tagging stripes. The force $\mathbf{f}_{S2}$ from **S2** to **M1** will be distributed to the nodes of the volume element which encloses the material point **M1**. The combination of the forces from all SPAMM datapoints will cause the material point at **M1** to move to a new position, **M2**, as shown in Figure 2. Subsequently, the force $\mathbf{f}_{S3}$ (depicted by an arrow in Figure 2) on **M2** from **S3** will be computed in a similar fashion.

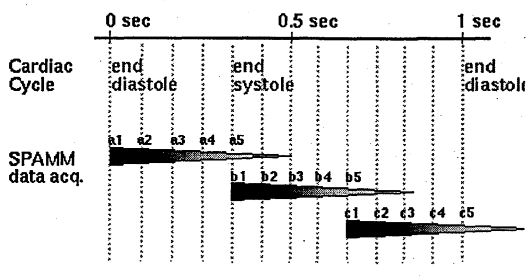

Figure 3 - Data acquisition time table

Sequential MRI-SPAMM Data

While the cycle duration of a heart beat is approximately 1 second, the magnetization tagging lasts approximately 0.3 - 0.5 second. In order to study the cardiac motion in its complete cycle, we obtain sequential sets of MRI-SPAMM data as illustrated in Figure 3. We simply create another reference set of SPAMM grids just before the previous reference tags fade away. For example, the first set of SPAMM grids are created at time a_1 and the first image is acquired at a_1. The subsequent images are acquired at $a_2, a_3, \ldots, a_N$. At time a_N, a new set of SPAMM grids is created. Its subsequent images are then acquired at $b_2, \ldots, b_N$. Since our method of LV motion recovery is a forward estimation in time, the only requirement of these sequential data sets for recovering the LV motion is to have the time overlap between them - i.e., the time point of a_N is the same as the time point of b_1. We repeat the cascaded application of magnetization tags until we cover the entire cardiac cycle. These data sets are then used to recover the LV motion from end-diastole to end-diastole.

Results and Discussion

As we can see from Equation (1), to recover the motion at time t_i, we only need the datapoints from the immediately following time phase t_{i+1} and the normal vectors of the reference (initial) tag stripes. Therefore, after we recover the motion at time a_N, for example, we register the SPAMM datapoints at time b_1 into the model at a_N and continue with the recovery process with the new reference tags. We have successfully implemented the sequential MRI-SPAMM technique, and we are currently conducting experiments to evaluate the accuracy of our technique.

Figure 4 shows a fitted model to a normal LV data set from MRI-SPAMM at end-diastole and at end-systole. On the model at end-diastole, we show SPAMM datapoints at one short-axis level. Note that the material points are marked at the same location as the SPAMM datapoints. On the model at end-systole, we show the traces of the SPAMM datapoints as well as the corresponding material points, which has moved in 3-D during systole. It clearly shows that the missing through-plane motion in the SPAMM data sets has been recovered. Figure 5 shows only the epicardium of the model at end-systole. It depicts the traces of node positions (white dots) from end-diastole to end-systole. We can easily observe the contraction and twisting motion of the LV during systole.

Due to the limitations of current imaging technology, we were only able to estimate and analyze the LV motion during systole. However, we are now able to estimate 3-D LV motion during its entire cardiac cycle by extending our previous technique and incorporating multiple sets of MRI-SPAMM data acquired in a cascaded fashion.

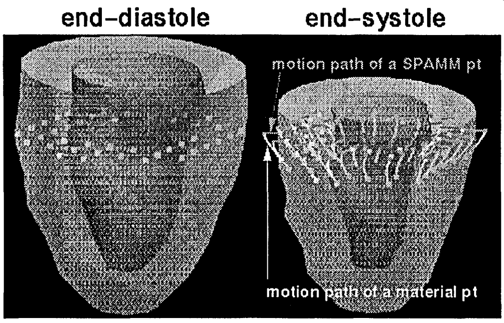

Figure 4 - Fitted model at end-diastole and end-systole

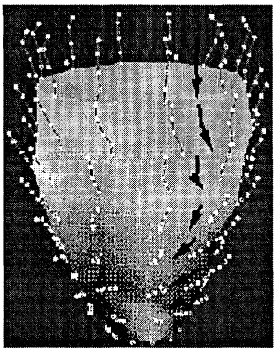

Figure 5 - Fitted model at end-systole (epicardium)

Conclusion

We have extended the capability of MRI-SPAMM by integrating a cascaded sequence of SPAMM data sets into the physics-based volumetric deformable models, and we have presented a comprehensive method for estimating the shape and non-rigid motion of the left ventricle (LV) over its entire cardiac cycle (systole and diastole). Based on the new extension of our method, we are currently conducting experiments to quantitatively analyze the volumetric 3-D LV motion not only when it is pumping out the blood to the body but also when it relaxes to fill its cavity.

Acknowledgments

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