3D myofiber reconstruction from in vivo cardiac DTI data through extraction of low rank modes

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Purpose

Recent advances in cardiac diffusion tensor imaging (DTI) have enabled robust imaging of the in-vivo human heart [1,2]. This allows to non-invasively assess myofiber and myosheet orientations, which has been a long standing bottleneck of patient-specific cardiac modeling [3]. However, in view of the relatively low scan efficiency and scan time constraints in-vivo, cardiac coverage and signal-to-noise ratio are limited. To this end, data extrapolation [4] and noise reduction [5] techniques have been proposed. The objectives of the present work are to propose an approach to (i) extract the most significant features from noisy myofiber and myosheet angle maps measured with in-vivo DTI, and (ii) extrapolate the data across the entire left-ventricle based on a limited number of acquired short-axis views.

Methods

The proposed method projects the helix (defined as the angle between fibers and short-axis plane, and denoted α), transverse (between fibers and tangential plane, β) and sheet angles (between sheet normal and short-axis plane, γ), which are general three-dimensional functions, onto a set (size M) of products of one-dimensional functions of transmural, circumferential and longitudinal positions (for instance for helix angle): $\alpha(r,\theta,z) \approx \sum_{m=1}^{M} f_m(r) g_m(\theta) h_m(z)$. The key difference relative to regular least-square projection is that no *a priori* knowledge is required and the algorithm yields the best shape functions to describe the data. This becomes critical when analyzing diseased hearts, for which remodeling processes can significantly alter the original orientations. Without loss of generality, each radial basis function is discretized using standard finite element procedures (for instance for the transmural function): $f_i(r) \approx \underline{\varphi}^T(r) \cdot \underline{F^i}$ where the φ_k are piecewise linear shape functions, and the F_k^i are the scalar degrees of freedom. The modes are computed using an iterative algorithm adapted from Proper Generalized Decomposition methods [4]: after initializing $\underline{G_0}$ and $\underline{H_0}$, the best $\underline{F_0}$ is computed by minimizing the distance to the data (for instance for helix angle): $\underline{F_0} = \text{argmin}_{\{\underline{F}\}} \left\{ \sum_{p=1}^{P} \left\| \left(\underline{\varphi^f}^T(r_p) \cdot \underline{F} \right) \left(\underline{\varphi^g}^T(\theta_p) \cdot \underline{G_0} \right) \left(\underline{\varphi^h}^T(z_p) \cdot \underline{H_0} \right) - \alpha_p \right\| \right\}$. This problem is piecewise-linear, as angles are defined modulo π, and solved by iteratively determining the solution associated to the Euclidian norm and wrapping the necessary angles. Once $\underline{F_0}$ has been determined, $\underline{G_0}$, $\underline{H_0}$, $\underline{F_0}$ are iteratively computed until convergence. Once the first mode has been determined, the second mode is computed, *etc*.

Example in-vivo cardiac DTI data were obtained in one healthy volunteer using a dual-phase dual-slice stimulated echo acquisition mode (STEAM) method [2]. Ten short-axis slices were acquired with diffusion weighting (b=450s/mm^2) along ten directions. Data were subsequently processed using the method proposed to derive interpolated helix, transverse and sheet angle maps of the entire left ventricle.

Results

Figure 1 illustrates the first modes of the helix, transverse and sheet angles as a function of transmural, circumferential and longitudinal positions. Figure 2 compares measured helix angle map to the first extracted mode of interpolated high-resolution helix map, in short-axis view and as a function of transmural position. In Figure 3, the high-resolution 3D reconstruction of the entire left ventricle is displayed.

Discussion

The method presented allows extracting key spatial features of the myofiber and myosheet angle maps from noisy cardiac DTI data. Thereby robust interpolation to higher resolution is facilitated. Likewise data extrapolation is possible. Helix angle, transverse and sheet angle variations were well captured by the algorithm. The data representation proposed here allows for straightforward integration of DTI data into finite-element models used in computational cardiac mechanics.

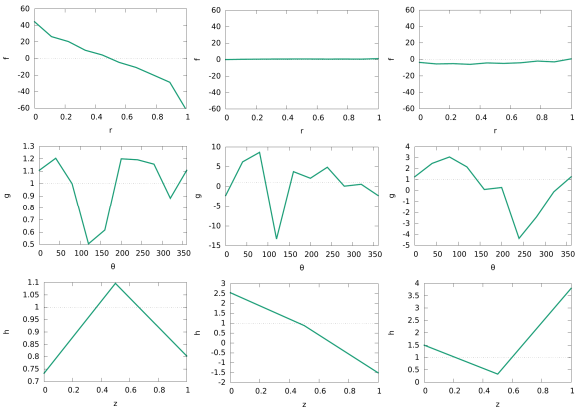

Figure 1. First modes for the helix (left), transverse (center), and sheet (right) angles, with transmural (top), circumferential (middle) and longitudinal (bottom) variations.

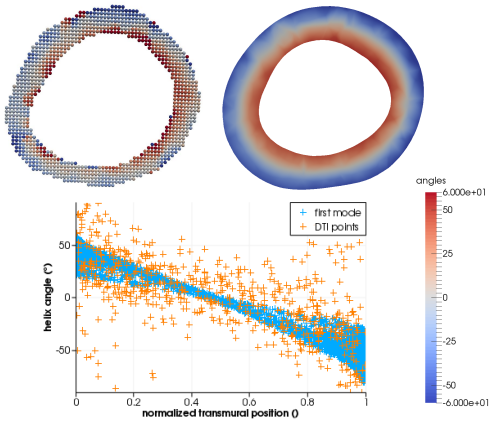

Figure 2. DTI data (left slice and +) vs. extracted first mode (right slice and +), showing helix angle.

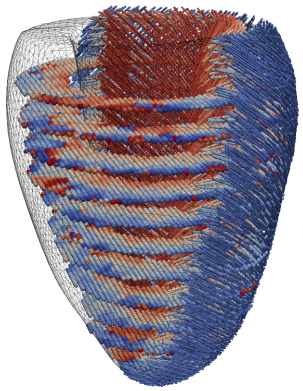

Figure 3. Sparse tensor points and extrapolated myofiber vector field.

References

[1] Nielles-Vallespin *et al.*, *MRM.*, 2013. [2] Stoeck *et al.*, *PLoS One*, 2014. [3] Lee *et al.*, *J. Card. Surg.*, 2014. [4] Toussaint *et al.*, *MedIA.*, 2013. [5] Lam *et al.*, 2013, *MRM.*