On the Identification of the Multiaxial Mechanical Properties of the Human Myocardium Including its Microstructure

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ABSTRACT

In the multidisciplinary field of cardiac research it is of utmost importance to identify reliable material properties of the myocardium used for the description of phenomena such as mechanoelectric feedback or heart wall thickening. To (better) understand the highly nonlinear mechanics of complex structures such as the passive myocardium under different loading conditions a rationally-based material model is required. Unfortunately, for material parameter estimation there are not yet experimental data of human heart tissues available required to develop adequate constitutive models.

Therefore, this study aimed to determine biaxial extension and triaxial shear properties, and the underlying microstructure of the passive human ventricular myocardium [1]. Using state-of-the-art equipment, planar biaxial extension tests were performed to determine the biaxial properties of the passive human myocardium. Related shear properties were examined by triaxial simple shear tests on small cubic specimens excised from an adjacent region of the biaxial specimens. The three-dimensional microstructure was investigated through second-harmonic generation on optically-cleared tissues, which showed the 3D orientation and dispersion of the myofibers and adjacent collagen fabrics. The novel combination of biaxial extension data with different loading protocols and shear test data at different specimen orientations allows to adequately capture the direction-dependent material response [2].

The results suggest that the passive human myocardium under quasi-static and dynamic multiaxial loading is a nonlinear, anisotropic (orthotropic), viscoelastic and history-dependent soft biological tissues undergoing large deformations (Fig. 1). Material properties of the tissue components along local microstructural axes drive the nonlinear and orthotropic features of the myocardium. Second-harmonic generation revealed detailed information about the myocardial microstructure due to its high resolution (Fig. 2). It enabled the identification of structural parameters such as fiber and sheet orientations and corresponding dispersions.

With this complete set of material data a sophisticated material model and associated material parameters can be defined for a better description of the biomechanical behavior of the ventricular myocardium in humans. Such a model will lead to more accurate numerical simulations, leading to a better understanding of the fundamental underlying ventricular mechanics; a step needed in the improvement of medical treatment of heart diseases.

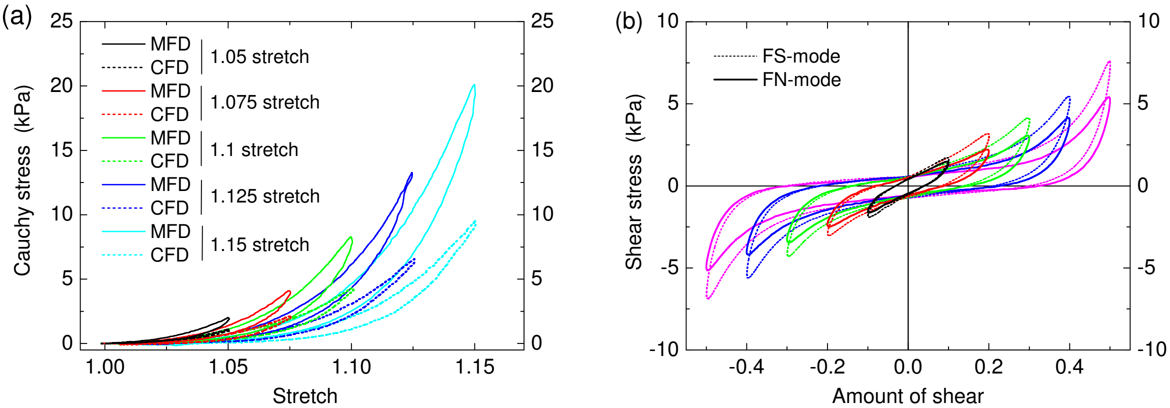

Figure 1: (a) Representative equibiaxial Cauchy stress vs stretch behavior in fiber (solid curves) and cross-fiber (dashed curves) directions and (b) shear stress vs amount of shear behavior corresponding to shear in the FS- and FN-plane with shear in the sheet direction (S) and sheet-normal direction (N), respectively. For a depiction of the different modes of simple shear applied to the human myocardial cubes, the reader is referred to Fig. 4 in [2].

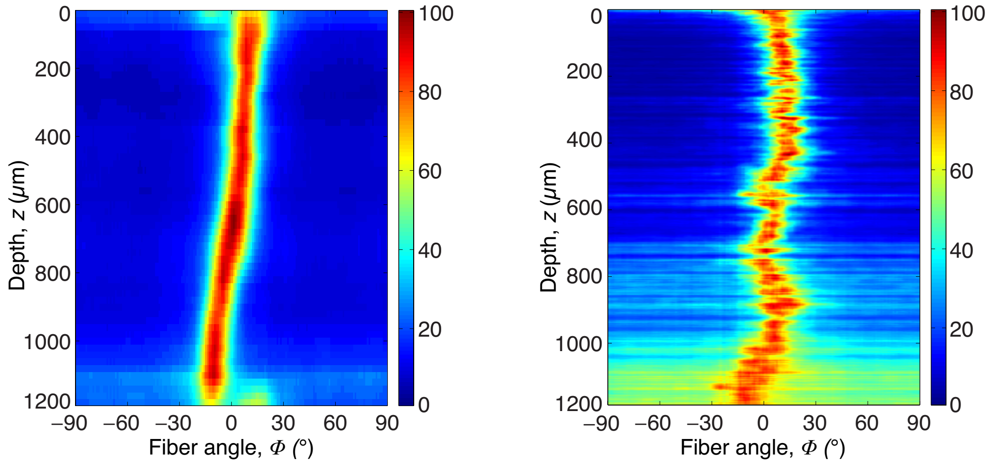

Figure 2: Typical intensity plots of the three-dimensional myocyte fiber orientations in-plane (left panel) and out-of-plane (right panel). The color ranges from dark blue (0%) to dark red (100%) corresponding to the relative amplitudes of the angles displayed on the x-axis. Red areas show the preferred fiber orientations and thus, a high density of fibers in the indicated direction, whereas blue areas display orientations with a low fiber density.

References

[1] G. Sommer, A.J. Schriefl, M. Andrä, M. Sacherer, C. Viertler, H. Wolinsky, S.D. Kohlwein, G.A. Holzapfel, Biomechanical properties and microstructure of human ventricular myocardium, submitted.

[2] G.A. Holzapfel and R.W. Ogden, Constitutive modelling of passive myocardium. A structurally-based framework for material characterization. *Philos. T. Roy. Soc. A* 367:3445–75, 2009.