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On the Thermo-Visco-Hyperelasticity of Electro-Active Biological Tissues

Alessio Gizzi[1], Christian Cherubini[1], Simonetta Filippi[1] and Anna Pandolfi[2]

[1] Campus Biomedico, via A. del Portillo 21, 00128 Rome, Italy,
A.Gizzi@unicampus.it, C.Cherubini@unicampus.it, S.Filippi@unicampus.it

[2] Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy,
anna.pandolfi@polimi.it

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Thermoelastic-electroactive (TEA) media represent a wide range of materials and physical systems sensitive to mechanical forces, electric fields and thermal stimuli. Upon the application of an electric field TEA media deform spontaneously. Viceversa, if mechanical forces are applied, the induced deformations perturb the original electric configuration. Time and temperature dependence are additional recurrent features of such materials. The behavior of fiber reinforced active tissues, namely the excitation-contraction coupling (typical of myocardium, intestine, vascular walls, etc.), is due basically to the nonlinear interplay between the passive elastic tissue (mainly the extracellular collagen) and the active muscular network. The observed macroscopic dynamics derives as the emergent behavior of a complex multiscale architecture spanning several length scales: from the nanometer molecular actin-myosin calcium mediated interaction, going through the micrometer single cell contraction, up to the centimeter scale of the whole organ. Experimental evidences have demonstrated that the temperature strongly affects the macroscopic behavior of biological TEA systems. Isolated arterial strips in dog, as an example, have been shown to be characterized by an entropic retractile force, with negligible volume changes but with a significant internal energy contribution to the total force. Force-elongation nonlinear relations were also characterized in the large strain regime at various temperatures [1]. Even more complicated results the inotropic behavior of the cardiac muscle [2]. Cardiomyocytes, in fact, are able to adjust their contractile strength both to the beating rate and to the thermal state. In particular, tension tends to become maximum at lower temperature via the inhibition of active chemical processes, controlled by the concentration of free calcium ions. Recent experimental and theoretical studies, moreover, have shown that human colonic smooth muscle strips respond in a similar fashion to the thermal state: increased basal tone, diminished contraction amplitude and frequency are recorded at lower temperature [3,4]. Despite the wide literature on the subject, a few studies explored the role of stresses induced by the temperature on the electromechanical coupling. In this work we refer to a fiber reinforced TEA material model of myocardium. We consider an extended MEF behavior and introduce the thermal feedback via a generalized thermodynamic approach, that accounts also for viscosity [5] In particular we provide the general theoretical framework of the thermo-electromechanical problem with time-dependent behaviors. We derive the constitutive relationships by assuming a decoupled expression of the Helmholtz free energy density and the multiplicative decomposition of the deformation gradient. We specialize the formulation to a simplified phenomenological material model, validating the response against experimental measurements and providing a few representative numerical applications.

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