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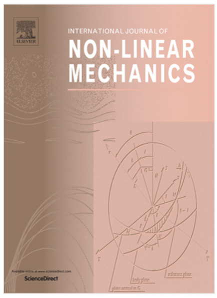

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Martine Ben Amar

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Nonlinear visco-elasticity of soft tissues under cyclic deformations

Martine Ben Amar[1]

Laboratoire de Physique Statistique, Départemant de Physique de l'ENS,PSL Research University, CNRS,Sorbonne Université, 75005 Paris

Sorbonne Université,Institut Universitaire de Cancérologie, Faculté de médecine, 75013 Paris, France

Abstract

Nowadays, new experimental set-ups allow to determine the strains which appear in biological tissues under small controlled solicitations as stretch (uniaxial and bi-axial) or shear. Automatically recorded by camera, these data exhibit hysteresis even for very slow and weak forcing. The aim of this work is to revisit the modeling of hyper-elasticity and visco-elasticity for tissues with a rather disordered structure. Despite the weakness of the imposed stretch values, strong nonlinearities are observed for these tissues that polymeric gels do not show under the same conditions. Various classical models have been tested on surgical mammary tissues and it turns out that the simplest Neo-Hookean model with its viscous counter-part explain perfectly the data. Viscosity and elasticity compete quite equivalently showing that, in the selected range of forcing values, visco-elasticity cannot be discarded.

Keywords: Finite elasticity and visco-elasticity; cyclic cycles, hysteresis, living fibrotic tissues

1. Introduction

As the description of fibrous tissues evolves and makes progress [1, 2], experimental set-ups have also been improved allowing the automatic determination of stress-strain results which can be compared to modelling of complex hyper-elastic tissues. Some theoretical models originate from a microscopic analysis of the structural properties of the sample under tension and the changes which may occur when a tensional state is applied. The case of elongation of tendons is an example [3, 4]; the micro-structures have been analyzed in details, the link existing between the main components: collagen fibers, extra-cellular matrix and proteo-glycans, has been incorporated in the formalism with the aim to deduce a stress-strain compared to experimental data [5, 6]. Elaborated models can be established where the involved parameters rely on microscopic quantities as done for composite materials [7] . Hysteresis and plasticity behaviors can also be recovered. Such studies require a profound knowledge of the biological structures and of the evolving interactions between them under stress conditions. However, they remain specific to the system under study and need to be validated by stress-strain experimental curves, when they are available.

Using different approaches, biophysics groups have elaborated a characterization of the material properties going from individual cells [8] to tissues. After investigated in detail isolated cell behavior during mitosis for example or migration of connected cells in an epithelium on a solid substrate [9], they show that collections of cells, interacting with each other and/or with the extra-cellular matrix, may exhibit emergent properties, which do not necessarily mirror the properties of their constitutive elements. An integrated approach is then necessary at the scale of the tissue leading to continuous visco-elastic modelling where fibers are treated using the formalism of nematic liquid crystal [10, 11]. Nonetheless, not all biological tissues exhibit a well defined organization. Let us mention the brain and fat tissues, [12, 13, 14], or fibrotic tissues [15] which play an important role in organogenesis but also in the development of pathologies: wound-healing [16, 17], capsules around implants [18], sarcoma (the generic word for cancer of tissues) and various tumors of the brain. Even if these tissues present an order at the microscopic scale, like bundles of fibers with an averaged orientation [1], phenomenological constitutive laws with a small number of parameters can be derived. Often, they intervene in the complex geometry of organs and a simplified constitutive law takes all its value to understand biological processes such as growth [19, 20] in embryo-genesis or in pathologies.

Parameters of constitutive laws may be experimentally deduced from compression/tension-shear tests under a sequence of multiple cycles [21]. These experiments exhibit hysteretic cycles which suggest that visco-elasticity plays an important role. However, if macroscopic constitutive laws exist for tissues like the Mooney-Rivlin [22], Ogden [23, 24], Gent [25], or the GOH [1] models, macroscopic viscoelasticity [26] do not offer the same diversity.

Indeed, a brief history of nonlinear dissipation modeling can be found in [27], going back to the beginning of the last century and a presentation of the so-called Landau model, commonly used in acoustics [28]. In the spirit of Landau, the theory of visco-elasticity rests on the definition of a dissipation energy rate, formulated in the same way as the elastic energy density, then introducing two new "Lamé" parameters for the visco-elastic part. But, as shown by Destrade and coworkers, to de-

Email address: benamar@lps.ens.fr (Martine Ben Amar)

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