Structural reorganisation of biological materials

—Inelastic aspects and fibre reorientation in fibre-reinforced tissues—

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In this series of lectures, I would like to present the principal results of some studies that, within a purely mechanical approach, aim at describing the structural reorganisation of soft, fibre-reinforced biological tissues [1, 2, 3]. The tissues of this type are strongly anisotropic and inhomogeneous, and their material behaviour is tightly connected to the complexity of their internal structure, which is capable of rearranging itself both actively and in response to environmental stimuli. In the biomechanical community, this property is referred to as *remodelling* [4], and may be interpreted as the manifestation of degrees of freedom internal to the tissue, whose activation is related to some generalised concept of stress.

In spite of their complexity, the tissues I will be talking about are often modelled by considering only few constituents, which are typically identified with its cells, extracellular matrix, collagen fibres, and interstitial fluid. Accordingly, the extracellular matrix is viewed as a fibre-reinforced porous medium, in the pore space of which the interstitial fluid is allowed to flow, thereby bringing nourishment to the cells and taking away the products of their metabolism. On the basis of this description, the study of the considered tissues has its roots in the theories of porous media and multi-phasic materials, which have to be duly generalised in order to capture the many facets of the phenomenon of remodelling.

I plan to organise the lectures in three parts:

1. In the *first part*, I will supply the theoretical background required to formulate a mechanical theory of remodelling. To this end, I will recall the most fundamental aspects of the mechanics of porous media and multi-phasic materials, and I will briefly review two papers [5, 6], on which my description of remodelling is based. Moreover, I will summarise the main results of the constitutive description of fibre-reinforced media with statistical directional distribution of the fibres [7, 8, 9, 10]. For this purpose, I will select articular cartilage as the representative element of the class of tissues to which the lectures are dedicated.

2. In the *second part*, I will classify the two types of remodelling addressed in the studies [1, 2, 3], and I will focus on the first type. This is related to the capability of the fibres of changing their orientation pattern, and has been discussed in [1, 2] from two rather different, yet complementary, perspectives. My purpose is to highlight the conceptual differences between these two approaches and to connect the idea presented in [2] to the need of forecasting the fibres' directional distribution in articular cartilage [11]. The main point is that the fibres' orientation pattern is governed by a set of "remodelling parameters" that are distributed inhomogeneously throughout articular cartilage. According to the model developed in [2], this inhomogeneity is accounted for constitutively by generalising the tissue's Helmholtz free energy density. This, indeed, is prescribed to feature one term depending on the deformation of the tissue, one term depending explicitly on the material gradient of the remodelling parameters, and one term that assigns an energy to each distribution of fibres. One of the principal properties of this approach is that the latter term, referred to as "structural energy" in [2, 3], is nontrivial also in the undeformed configuration of the tissue. In particular, I will comment on the definition of the structural energy given in [2, 3], and compare it with that supplied in [12].

3. In the *third part*, I will address the second type of remodelling presented in [3], i.e., the reorganisation of the tissue's internal structure that may occur in terms of distortions of the extracellular matrix, through the breakage and restoration of the bonds linking the cells with one another [13], or through the nucleation of micro-cracks [14] due to traumatic events or degenerative diseases. I will assign an inelastic character to this type of remodelling, and I will describe it by exploiting the Bilby-Kröner-Lee decomposition of the tissue's deformation gradient tensor (see e.g. [15]). Within this framework, my concern will be the establishment of a *configurational* coupling among the inelastic remodelling of the tissue, its deformation, the reorientation of the fibres, and the flow of the fluid [3]. The ultimate scope of this study will be the analysis of the impact of remodelling on the permeability and the elastic properties of the tissue.

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