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NUMERICAL SIMULATION OF THE INFLUENCE ON INTERSTITIAL FLUID FLOW AND ION TRANSPORT OF THE VISCOUS MECHANICAL BEHAVIOUR OF HUMAN SKIN IN VIVO

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The human skin is the external protection of the human body. It protects the body against external chemical, biological, mechanical and thermal influences. From the skin outer surface inward, it is composed of several layers: the epidermis (consisting of the stratum corneum and the viable epidermis), the dermis and the hypodermis [1]. Each layer has a unique structure and function contributing to the in vivo overall material function of the human skin. Studying the answers of these skin layers is important for clinical and cosmetic research, such as the development of personal care products, the understanding of skin diseases and the consequences of chirurgical actions.

Numerous studies of the mechanical behaviour of human skin have shown that the skin is a stratified non-homogeneous, anisotropic, non-linear visco-elastic material which is subjected to a pre-stress in vivo [2]. In addition its properties vary with age, throughout the body and depending on the health of the person. The properties are also influenced by the structure of each layer, where the cells of the soft tissues are bathed and hydrated by an interstitial tissue fluid which provides them with nutrients and which removes their wastes. Interstitial fluid consists of a water solvent containing sugars, salts, fatty acids, amino acids, coenzymes, hormones, neurotransmiters, as well as waste products from the cells. The composition of interstitial fluid depends upon the exchanges between the cells in the skin layers, the blood and the lymph circulations. This means that interstitial fluid as a different composition in different tissues and in different areas of the body [3]. As a direct consequence, these phenomena are complex to understand and to model due to the strong couplings that exist between them and due to the complex behaviour of the different layers of skin tissues.

Different non-invasive techniques: tensile tests, suction, torsion, indentation are performed on the skin for trying to characterize the mechanical behaviour of human skin in vivo or in vitro or ex vivo. But generally, the experimental device needs to be fixed to the skin all along the test. This modifies the skin’s natural state of stress and gives results that are difficult to reproduce and to interpret. Moreover it is hard to compare results obtained with different measurement conditions. The experimental set-up considered here as support for characterizing in vivo equivalent parameters of human skin without pre-stressing the skin before the test is the LTDS-light load indentation device. It is able to give a better understanding on the mechanical behaviour of the skin by characterizing the mechanical behaviour of several distinct skin layers in vivo including for quite difficult experimental zones on the human body [4].

Within the framework of a general phenomenological thermo-hydro-mechanical and physico-chemical approach of heterogeneous media [5], a tri-phasic skin model is proposed in reference [6] which incorporates a solid phase with four solid materials, a fluid phase with four fluid materials and an ionic component under ambient constant conditions with no electrical effects. In this model, skin is considered as a stratified material with four layers modelling the four outer layers of skin: the stratum corneum, the viable epidermis, the dermis and the hypodermis. These four layers are modelled separately in order to win insights on their own contribution to the overall response of the skin. All layers of the skin model are supposed to be made of fluid-saturated materials. Furthermore each layer is seen as a different solid material within the solid phase and it is described its own behaviour law. In reference [6] the solid material is seen as an isotropic linear elastic material. In the fluid phase, the four fluid materials model the interstitial fluid of each skin layer of soft tissue seen as a Newtonian viscous fluid described by its own behaviour law. The driving forces for transport are the gradients of the chemical potentials of the fluids and of the ions coupled with the stress states of the solids.

This paper proposes an extension of this skin model. Now the solid materials are seen as linear visco-elastic materials, each of them with its own behaviour law. Nine sets of governing partial differential equations (one for each constituent taken into account in the human skin specimen) arise from the equilibrium, the kinematic and the constitutive equations. In order to write a closed mathematical problem, they are solved under varying physically admissible initial and boundary conditions for the ion concentration, the interstitial fluids and the solids proposed for describing in vivo indentation test available in the laboratory. A finite difference analysis is carried out following an iterative procedure that allows to describe the transient interstitial fluids circulations and ion movements through skin after application of a saline solution and to gain insight on the mechanical behaviour of human skin layers separately.

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