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Research Paper

A mechanistic insight into the mechanical role of the *stratum corneum* during stretching and compression of the skin

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ABSTRACT

The study of skin biophysics has largely been driven by consumer goods, biomedical and cosmetic industries which aim to design products that efficiently interact with the skin and/or modify its biophysical properties for health or cosmetic benefits. The skin is a hierarchical biological structure featuring several layers with their own distinct geometry and mechanical properties. Up to now, no computational models of the skin have simultaneously accounted for these geometrical and material characteristics to study their complex biomechanical interactions under particular macroscopic deformation modes.

The goal of this study was, therefore, to develop a robust methodology combining histological sections of human skin, image-processing and finite element techniques to address fundamental questions about skin mechanics and, more particularly, about how macroscopic strains are transmitted and modulated through the epidermis and dermis. The work hypothesis was that, as skin deforms under macroscopic loads, the *stratum corneum* does not experience significant strains but rather folds/unfolds during skin extension/compression.

A sample of fresh human mid-back skin was processed for wax histology. Sections were stained and photographed by optical microscopy. The multiple images were stitched together to produce a larger region of interest and segmented to extract the geometry of the *stratum corneum*, viable epidermis and dermis. From the segmented structures a 2D finite element mesh of the skin composite model was created and geometrically non-linear plane-strain

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finite element analyses were conducted to study the sensitivity of the model to variations in mechanical properties.

The hybrid experimental-computational methodology has offered valuable insights into the simulated mechanics of the skin, and that of the *stratum corneum* in particular, by providing qualitative and quantitative information on strain magnitude and distribution.

Through a complex non-linear interplay, the geometry and mechanical characteristics of the skin layers (and their relative balance), play a critical role in conditioning the skin mechanical response to macroscopic in-plane compression and extension. Topographical features of the skin surface such as furrows were shown to act as an efficient means to deflect, convert and redistribute strain—and so stress—within the *stratum corneum*, viable epidermis and dermis. Strain reduction and amplification phenomena were also observed and quantified.

Despite the small thickness of the *stratum corneum*, its Young's modulus has a significant effect not only on the strain magnitude and directions within the *stratum corneum* layer but also on those of the underlying layers. This effect is reflected in the deformed shape of the skin surface in simulated compression and extension and is intrinsically linked to the rather complex geometrical characteristics of each skin layer. Moreover, if the Young's modulus of the viable epidermis is assumed to be reduced by a factor 12, the area of skin folding is likely to increase under skin compression. These results should be considered in the light of published computational models of the skin which, up to now, have ignored these characteristics.

1. Introduction

In the last few decades, the study of skin biophysics has largely been driven by pharmaceutic, cosmetic and consumer goods industries which aim to offer solutions to reduce the effects of intrinsic and extrinsic ageing factors on skin health and appearance (e.g. using topical agents) and to design products that efficiently interact with the skin (e.g. razors). The surface of the human skin is characterised by ridged features, or skin furrows (*sulci cutis*), varying in length between 70 and 200 μm for the main furrows and 20 and 70 μm for the superficial furrows (Piérard et al., 2004; Shimizu, 2007). These furrows, which represent the natural microrelief of the skin, along with natural or muscle-induced wrinkles, are thought to defect tensional forces thus providing mechanical advantages to the skin. As skin deforms under macroscopic loads it is unclear whether the *stratum corneum* experiences significant local strains (change of length) or simply unfolds/folds during skin extension/compression as suggested by Geerligs (2010). Providing a mechanistic quantitative insight into this question constitutes the main objective of the present study for which an image-based anatomical modelling approach is developed. Understanding the role of the skin microstructure on its response to deformations has the potential to shed light on fundamental questions such as evolutionary aspects concerning the advantages provided by certain skin characteristics or functional abilities. For example, it was recently demonstrated that water-induced finger wrinkles in humans improved the handling of submerged objects (Kareklas et al., 2013), therefore confirming a possible evolutionary mechanical advantage for manipulating objects in submerged conditions (Changizi et al., 2011). An in-depth understanding of the structure-function relationship of the skin also presents many opportunities for practical applications in the aforementioned industrial sectors besides the obvious applications in biomedical and health sciences where the coupling between mechanics and biology (i.e. mechanobiology) is particularly relevant (Brand, 2006).

Being the outermost of the skin layers, the *stratum corneum* is the prime line of defence against environmental threats being they mechanical, thermal, chemical, radiological or biological. Epithelial cells structuring the epidermis replicate in the basal layer and progressively migrate towards the surface of the skin effectively ensuring the regenerative nature of this fundamental layer. In this process, the structure of cells changes as they get deprived of nutrients provided by blood vessels that do not extend beyond the basal layer. The cells eventually die, release their glycolipids into the intracellular space, become flat and finally keratinise to form the *stratum corneum* (Marieb and Hoehn, 2010; Shimizu, 2007). These strong keratinised cells, bonded by desmosomes, form the so-called "brick and mortar" structure (Derler and Gerhardt, 2012; Geerligs et al., 2011) that characterises the *stratum corneum* as a stiff mechanical barrier. In a biotribological context, the nature of physical interactions between the skin and the external environment is strongly conditioned by the propensity of the *stratum corneum* to absorb liquids such as water and lubricants (Bhushan, 2012; Wu et al., 2006) which modify its mechanical and chemical properties, which in turn affect the physical appearance of the skin surface (Raab, 1990) and its mechanical response to deformations. This is due to its complex multi-scale structure, (time-dependent) intrinsic mechanical properties and the nature of its structural and mechanobiological interactions with other skin constituents such as the viable epidermis and underlying dermis.

The sensitivity of the mechanical characteristics of the *stratum corneum* to environmental conditions, particularly relative humidity, is well established (Dauskardt et al., 2006, 2011; Levi and Dauskardt, 2010; Levi et al., 2010; Pailler-Mattei et al., 2007; Wu et al., 2002, 2006) and references therein. This phenomenon results in significant intra-sample variability of its mechanical