Numerical simulation of thermal response of the skin tissues

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Abstract – The aim of this paper is to develop a numerical model for the simulation the heat transfer process and the heat-induced mechanical response of the skin tissues. We present some models using the finite element method in 2D space. A multilayer model is presented and the influence of the environment on the thermal behaviour of the skin tissues is considered. The results of the numerical simulation for some practical cases showed that that the thermomechanical behaviour of the skin tissue is very complex because the biothermomechanics of the skin is highly interdisciplinary involving engineering, biology and neurophysiology.

Although we limit our study to the case of thermomechanics of the skin tissue, the results can be extended for a full coupled system including biology and neurology.

Keywords: Skin tissue; Biothermomechanics; Numerical methods; Thermal systems; Coupled problems; Finite element method.

1 Introduction

Skin is the largest single organ of the human body that plays important roles in the thermoregulation, host defence and sensory system. Accurate evaluation of the spatial and temporal distribution of the temperature in the skin is of great importance in the development and applications of different treatments of the diseases involving the skin tissue. It is obviously that the effectiveness of these treatments is governed by the coupled thermal, mechanical, biological and neural responses of the affected skin tissue.

The analysis of the mechanical and thermal phenomena in a skin is of great importance and contributes to a variety of the medical applications and space and military activities. In Fig. 1 the structure of the skin is presented. This organ is the house of many phenomena including heat transfer, blood circulation, sweating, metabolic heat generation and the interaction with the surrounding environment. The skin properties are influenced by a variety of the factors such as temperature, pressure, damage, age, gender, hydration, site, etc.

The skin is an active, self-regulating system: heat transfer through skin dramatically affects the state of the skin, which can lead to the redistribution of skin blood flow over the cutaneous vascular network, whereby influencing the thermal response of the skin tissue. For example, in a neutral environment, the skin receives 5-10% of the cardiac output, which can be zero in a cold environment and can increase to 50-70% in a hot environment.

There is a natural coupling of the strain, stress and temperature in the skin tissue. A non-uniform distribution of the temperature can cause a thermal stress that contributes to the thermal pain sensation.

The blood perfusion has little effect on thermal damage but large influence on skin temperature distribution, which, in turn, influences significantly the resulting thermal stress field. The stratum corneum is very thin but has a large effect on the thermomechanical behaviour of skin, especially in the modelling of skin thermal stresses. Thus, the thermally induced mechanical stress appears due to the thermal denaturation of the collagen, the major constituent of dry skin. This constituent is macroscopic thermal shrinkage and its hydration level is changed in the denaturation process. Thermal denaturation of a collagenous tissue can lead to important changes of mechanical, thermal, electrical and optical properties of the skin tissue. When collagen is heated, the heat-labile highly organized crystalline structure to a random, gel-like state, which is the denaturation process.
From a simple visual analysis of the Fig. 1 we conclude that each layer has distinct physical properties, especially in the thermal behaviour of the skin. More, even within the same layer, there is a large non-homogeneity and anisotropy due to presence of the blood vessels. Consequently, a linear mathematical model or an analytical solution of the skin behaviour is not possible. Only a numerical model can lead to an approximate solution, can predict the effects of different factors on the skin behaviour.

2 Models for the skin thermomechanics

In the professional literature for the modelling of the human body and thermal comfort, there is a large variety of models on the heat transfer in different tissues of the human body, including the influence of the blood flow in the vascular network. These models can be included in one of these four classes: continuum models, vascular models, hybrid models and models based on the porous media theory.

In the numerical simulation of the skin thermomechanics, numerical models are used because of the large computing power of the advanced computers nowadays. Our work presents a numerical model based on the finite element method (FEM) with emphasis on the thermomechanical phenomena of the skin. The heat transfer in skin tissue is mainly a heat conduction process coupled to complicated physiological processes as blood perfusion that represents a heat source (or a sink). We consider the multi-layer structure of the skin with emphasis on three- and four-layer models. A three-layer structure includes the epidermis, dermis and subcutaneous tissue. A four-layer model is presented in Fig. 1 with stratum corneum, living epidermis, dermis and fat.

3. Modelling of the heat transfer

Mathematical model for the thermal field is Pennes equation of the bioheat [1]. The Pennes bioheat equation describes the thermal behavior based on the classical Fourier’s law:

$$\frac{\partial}{\partial t} (k_x \frac{\partial T}{\partial x} + k_y \frac{\partial T}{\partial y}) + q + w_b c_b (T_b - T) = \rho c \frac{\partial T}{\partial t}$$

Here, $\rho, c$, and $T$ denote density, specific heat, and temperature of tissue. The specific heat and perfusion rate of blood are denoted by $c_b$ and $w_b$, respectively. The heat source is denoted by $q$. $T_b$ is the arterial temperature and we regard as a constant.

The heating source $q$ is viewed as the sum of two components: $q = q_{\text{met}} + q_{\text{ext}}$. The first component $q_{\text{met}}$ is due to the metabolic heat generation in the skin tissue and $q_{\text{ext}}$ is the heat generated by other heating methods.

The equation (1) is solved with specified initial and boundary conditions. Initially, the skin tissue has a temperature distribution ($T(x, y, 0) = T_0$) and at time $t=0$ the skin surface (at $y=L$) is suddenly exposed to a thermal agitation, derived from either a hot contacting plate, a convective medium, or a constant heat flux, whereas on the bottom, $y=0$ the surface is held at the core temperature, $T_c$, or thermally insulated. The effect of blood perfusion is regarded as a heat source.
under heating (or heat sink under cooling) distributed uniformly inside the tissue.

In the model from the Fig. 2, we did not included the hair/fur of the skin, although the hair strands can be so dense that they can trap a layer of air and thus work as an insulation layer. Since the thermal conductivity of hair is about 14 times greater than that of air (about 0.37 W/mK for human hair and 0.026W/mK for air), every single hair strand also works as fin, which enhances the heat transfer from the skin and thus is an unwanted effect in the thermal insulation sense due to the heat loss. In many models the air-hair layer is treated as an orthotropic material, that is, it is considered uniform on the plane parallel to the skin surface.

3.1 Modelling of the sweat gland
Heat is lost from the body through skin by two mechanisms:
- Insensible perspiration
- Sweat vaporization from the skin surface

The first mechanism is called insensible perspiration and is due to the continuous leeching of fluid from the capillaries of the deeper layers of the skin to its dry surface. The sweating contributes significantly to the thermoregulation of the skin.

In Fig. 3 a simple model of the sweat gland is shown and consists in a tubular gland composed of three regions: excretory duct in epidermis, excretory duct in dermis, and secretory portion in dermis. The flow of sweat in the skin is treated as a flow in a porous medium.

The sweating can be:
- latent sweat
- sensible sweat

For latent sweat, in the secretory portion, the sweat absorbs heat and changes to vapor, which flows along the straight dermal duct into the superficial layer of the skin where, due to the low pressure and low temperature, it releases the heat and changes to fluid in the spiraled duct. For sensible sweat, the sweat flows into the skin surface and then evaporates.

4 Modelling of thermal stress
As previously discussed, skin can be modeled as a multi-layer structure. From the mechanical viewpoint the layers are similar, that is the thermal properties have the same order of magnitude. The mechanical properties vary greatly from one layer to another (up to three orders of magnitude). Consequently, the mechanical behavior of the skin can be assimilated to a laminated composite structure, with each layer assumed to be uniform with linear, orthotropic thermoelastic properties.

In a simplified model of the skin tissue, the thermal and mechanical behaviors of the skin can be treated as uncoupled problems, that is, the mechanical behavior has no influence on thermal behavior and vice versa. In this approach, a sequential algorithm can be developed. Firstly, the temperature field in skin tissue is obtained from solving the governing equations of biological heat transfer; which is then used as the input to the mechanical model, from which the corresponding thermal stress field is obtained.

4.1 Skin biothermomechanics
Thermal damage (denaturation) of the skin can be modelled as a chemical rate process. In this area many models were proposed, but most of them have similar format using a first order Arrhenius rate equation. In modelling of the damage we can calculate the time for the appearance of the irreversible damage at temperature T. The damage is related to the rate of protein denaturation and exposure time at a given absolute temperature T.

Skin biothermomechanics is defined as the response of the skin under thermomechanical loading. Collagen is the major thermal constituent of the skin and the thermomechanical loading leads to damage – the thermal denaturation of collagen. The effects of heating on collagen can be reversible or irreversible and the behavior of the collagenous tissue and shrinkage depend on several factors, ones of them being: the collagen content, the maximum temperature reached and exposure time, the
mechanical stress applied to the tissue during heating, and aging.

To measure the thermal denaturation and heating-induced damage a set of metrics were proposed and used, including biological metrics and mechanical metrics. As biological metrics we remember enzyme deactivation and extravasation of fluorescent-tagged plasma proteins; as mechanical metrics we have the thermal shrinkage or optical metrics such as thermally induced loss of birefringence.

5. Some cases of study

We consider some practical cases using 2D models and we seek the solution of the problems for different boundary conditions.

Case 1: a three-layer model for a hot contacting plate

The first case is when the skin is heated at the surface by a heat source with a constant temperature, e.g. in contact with a hot plate, while the bottom of the skin tissue is kept at body temperature, $T_c$. $T_x$ is the ambient temperature.

Because of the symmetry we consider a half of the analysis domain as in Fig. 4 for a three-layer model. The skin is divided into three layers with different properties: the epidermis with thickness of 0.1 mm, dermis with thickness of 1.5 mm, and subcutaneous fat with thickness of 4.4 mm.

In Eqn. (3) $h$ is the convective coefficient with value 7 in our target example. The values of the geometric and thermal physical properties for the thermal analysis are presented in Table 1. For the stress analysis the parameters of the system are presented in Table 2.

The skin is divided into three layers with different properties: the epidermis with thickness of 0.1 mm, dermis with thickness of 1.5 mm, and subcutaneous fat with thickness of 4.4 mm. Epidermis can be divided into 2 layers: stratum corneum and living epidermis so that an idealized skin model has the structure from the Fig. 1.

The initial temperature of the skin tissue is defined by normal parameters. At the initial moment a hot steel plate at the temperature of 90 $^\circ$C is applied on the skin. We consider a transient process for a time interval of 20 s. At the final time the map of the temperature field is shown in Fig. 6.

The distribution of the temperature along the axis $Oy$ is illustrated in Fig. 7. It is obviously that the temperature value decreases in direction of the subcutaneous fat.

![Fig. 4 Analysis domain for case 1](image)

![Fig. 5 Mesh of the analysis domain](image)

Table 1

<table>
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<th>Parameters</th>
<th>Epidermis</th>
<th>Dermis</th>
<th>Fat</th>
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<tr>
<td>Thickness [mm]</td>
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<td>1.5</td>
<td>4.4</td>
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<td>Density [Kg/m³]</td>
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<td>1111</td>
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<td>Specific heat [J/Kg K]</td>
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<td>$\dot{q}_{\text{mean}}$ [W/m²]</td>
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<td>368.1</td>
<td>368.3</td>
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Table 2

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<td>Thermal expansion coefficient</td>
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<td>Young’s modulus</td>
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In the numerical simulation we used the finite element method [3]. The analysis domain is divided in finite elements as in Fig. 5.

The temperature versus time can be computed in different interest points. For example, at the interface epidermis-dermis, in the point (0, 5.9) the temperature vs. time is shown in Fig. 8 for a time interval of 20 s.

Case 2: a two-layer model

In many medical treatments for a multitude of diseases and injuries involving skin tissue, the heating is mainly limited to the top of epidermis layer (laser heating) due to the exponential decrease of heat generation along skin depth. In other words the stratum corneum layer dominates the thermomechanical response of skin tissue so that the analysis domain can be limited to epidermis.

The skin is reduced at two layers (Fig. 9): corneum with thickness of 0.00002 m and living epidermis with thickness of 0.00008 m. The spectrum of temperature and vectors of the heat flux are presented in Fig. 9. The temperature along the axis Oy is linearly (see Fig. 10) so that 1D-models can be used in the prediction of the temperature distribution in the medical treatments. More, analytical solutions can be used for temperature distribution in the skin tissue.
6 Conclusions
Thermally induced damage plays an important role in causing thermal pain so that the evaluation of the temperature distribution in the human skin, the heat transfer between different compartments of the human body and related thermomechanics in skin, play an important role in the study of the causes of pain and its relief.

The main reason for numerical simulation of the thermomechanics of skin tissue is the complex structure of the skin tissue that limits the accessibility needed for a detailed experimental solution and theoretical solutions. An accurate analysis of the thermal response in biological tissues is not possible because of the internal mechanisms that maintain body temperature, such as blood flow and metabolic generation. Almost all models in the thermomechanics of the skin tissue are developed for a specific type of therapy (hypothermia, hyperthermia, cryosurgery) and the numerical results are applied only to a specific treatment. Many aspects of the bioheat transfer during thermal therapy remain to be elucidated.

The objective of this paper was to understand the mechanisms of the biothermomechanics of the skin by using theoretical and numerical methods and to apply these results to special treatments as the thermal therapies. The difficulty of the development of accuated models of the human body leads to the idea that the numerical results must be compared with clinical data to validate or not our models.

References