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Sweat effects on the thermal analysis of epidermal electronic devices integrated with human skin

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ABSTRACT

Epidermal electronic devices (EEDs) are widely used in many applications especially directly integrated with human skin tissue to monitor the vital signs of human body. The thermal management of EEDs is very critical because the excessive temperature increase may cause discomfort or damage to human skin. Sweating can also significantly change the thermal environment of EED/skin system due to its function on the thermal transport process. A three-dimensional heat transfer analytical model is established to predict the thermal characteristics of EED/skin system considering the bio-heat transfer and effects of sensible sweat. In this model, the heat conductions in EEDs and in human skin are taken into account with Fourier heat transfer equation and Pennes bio-heat transfer equation, respectively, including the transport process of sweating. The results are validated by finite element analysis (FEA) and parameters studies such as velocity of sweat, thermal conductivity and thickness of substrate have been investigated. The results can help guide the thermal management of EED/skin system considering effects of sensible sweat.

1. Introduction

Since first brought forward in 2011, epidermal electronic devices (EEDs), as a new category of stretchable electronics, can be integrated directly on top of human skin tissue in the manner of mechanical invisibility because their effective mechanical properties (such as elastic modulus, and bending stiffness) are very close to those of human skin [1]. With ingeniously mechanical design [2–6], EEDs can indeed undergo stretching, twisting, bending or the combinations of them without any failure or damage, which makes the EEDs conformal incorporation with human skin tissue possible.

EEDs are consisted of laminated layers containing electronic functional components and stretchable circuits, which can be employed to monitor human vital signs (e.g., blood oxygen [7], blood pressure [8–11], blood flow [12], heart rate [13,14], body temperature [15–17]), on top of polymer substrates and encapsulated with elastomers for protection. With strain or pressure sensor components, EEDs can measure heart rate, pulse and movement of human body. Dagdeviren et al. [18–20] conducted a series of investigations on the pressure sensors basing on piezoelectric materials directly integrated with soft biological tissues and organ systems for force sensing or energy harvesting. Zhang et al. [17] utilized temperature sensors and analytical model to identify the temperature of human core body easily and accurately. Webb et al. [16], Tian et al. [21] and Gao et al. [15] adopted the temperature sensors to achieve the hydration of human skin tissue with different EEDs, respectively.

These above EEDs are the apyretic, but other EEDs such as micro-scale inorganic emitting diodes [7] can generate enormous heat when working. In order to measure the blood oxygen of human body invasively, Li et al. [7] designed and fabricated an epidermal inorganic optoelectronic device. Webb et al. [12] developed a new EED to detect the blood flow rate with temperature sensor array for temperature imaging. Thermal management is a critical problem for this type of EEDs because the redundant heat generation can cause discomfort or lesion of human skin and poor efficiency of EEDs.

In order to obtain the thermal behaviors for the EED/skin system, the bio-heat transfer in human skin tissue is necessarily considered, which has been investigated in many articles [22–27]. Human skin can be divided into three layers: epidermis layer, dermis layer and fat layer from outside to inside, whose thermal parameters (e.g. conductivities and diffusivities) are totally different. Bio-heat

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characters such as metabolism and blood flow effects can also be considered in the Pennes bio-heat transfer equation which takes the general form of $\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \varpi_b \rho_b c_b (T_a - T) + q_{met}$ [24]. Many researchers also studied the bio-heat transfer and thermo-mechanical analysis of the skin tissues [28,29]. Cui et al. [30] firstly established a one-dimensional analytical heat transfer model to illustrate the thermal characteristics of flexible electronic devices integrated with human skin tissue. However, all the investigations above can only provide the results of normal state for the human body. When human body is sweating, the thermal properties of the system will be significantly changed because the sweat can cause evaporative heat dissipation [24,31,32]. Therefore, the thermal management of EED/skin system can be significantly affected by the sweating process.

Physiological studies of sweat gland and sweating process have been reported in literatures [24,33,34]. In general, the highly coiled and tubular sweat gland consists of three parts: the secretory potion located deeply inside the tissue, the excretory duct located in the dermis and the spiral duct located in the epidermis [33]. Based on the heat pipe theory of the eccrine sweat gland [34], Xu et al. [24] considered evaporative heat dissipation caused by body's sweating of latent sweat and sensible sweat, respectively. They employed porous biological heat transfer model [35–37] to describe the flow of sweat in the skin. For latent sweat, the sweat evaporates in the secretory portion firstly and flows through excretory duct into spiral duct. Then the sweat is stored into spiral duct after liquefaction due to the low temperature and low pressure. In other word, the sweat oozed to the skin surface forms no distinct liquid drop or layer. The heat transfer model considering latent sweat in skin tissue is given as [24,32]

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T - \rho_s c_s \overline{V}\nabla T + q_s + q_{met} \qquad \text{(Epidermis)}, \tag{1-a}$$

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \varpi_b \rho_b c_b (T_a - T) + q_{met} \qquad \text{(Dermis)}, \tag{1-b}$$

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + q_{met} \qquad \text{(Fat)}, \tag{1-c}$$

where T_a and T are the temperatures of blood and skin tissue; $\nabla^2 T = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}$ and $\nabla T = \left(\frac{\partial T}{\partial x}, \frac{\partial T}{\partial y}, \frac{\partial T}{\partial z}\right)$ represent the Laplace operator and the gradient of the skin temperature T, respectively; t denotes time; k, ρ, c are the thermal conductivity, density and heat capacity; $\overline{V}$, ρ_s and c_s are velocity vector, density and heat capacity of sweat; q_s denotes the heat which the sweat absorbs in secretary portion and releases in the spiralled duct; ϖ_b, ρ_b and c_b are perfusion rate, density and heat capacity of the blood; $\varpi_b \rho_b c_b (T_a - T)$ represents the effect of blood perfusion, which is derived by the difference between the heat generated by arterial blood and the heat taken away from venous blood [32]; q_{met} is the effect of metabolism in the skin tissue.

As for sensible sweat, the sweat flows into the skin surface as liquid state and then evaporates. Relevant heat transfer model is presented as [24,32]

$$\begin{cases} \rho c \frac{\partial T}{\partial t} = k\nabla^2 T - \rho_s c_s \overline{V}\nabla T + q_{met} & \text{(Epidermis)} \\ \rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \varpi_b \rho_b c_b (T_a - T) + q_{met} - \rho_s c_s \overline{V}\nabla T & \text{(Dermis)} \\ \rho c \frac{\partial T}{\partial t} = k\nabla^2 T + q_{met} & \text{(Fat)} \end{cases}. \tag{2}$$

In general, the existence of sensible sweat on the interface of EED and skin is unacceptable since the liquid sweat may affect the performance of electronic device. Recently, a kind of breathable and stretchable temperature sensor designed by Chen et al. [38] provide a solution to this problem. The temperature sensors possess excellent permeability of air and high quality of water-proof by using porous designed substrate [38]. Thus, the sensible sweat effect on the thermal management of EED/skin system adopting porous substrate can be investigated. The heat transfer in skin tissue satisfies Eq. (2) while the heat transfer in the EED follows Eq. (1-a) with $q_{met} = 0$ since the heat dissipation process through porous substrate is just the same as latent sweat in the epidermis.

In this paper, a three-dimensional analytical model is established to solve this problem with combination of Fourier heat transfer equation and Pennes bio-heat transfer equation, which is validated via FEA by COMSOL software. Section 2 is the modeling of the system, Section 3 shows the results and discussion and conclusions are in Section 4.

2. Mathematic modeling of the system

2.1. Governing equations and boundary conditions

A typical EED integrated with human skin is shown in Fig. 1a. Functional sensors are linked by the serpentine mesh interconnects [17], which are widely used in the flexible sensors and actuators to provide stretchability [16,17,21,39]. Since the thermal analysis of serpentine mesh electrodes is cumbersome and difficult to develop analytically, an equivalent method is adopted to consider a rectangular heating component with the same heat flux

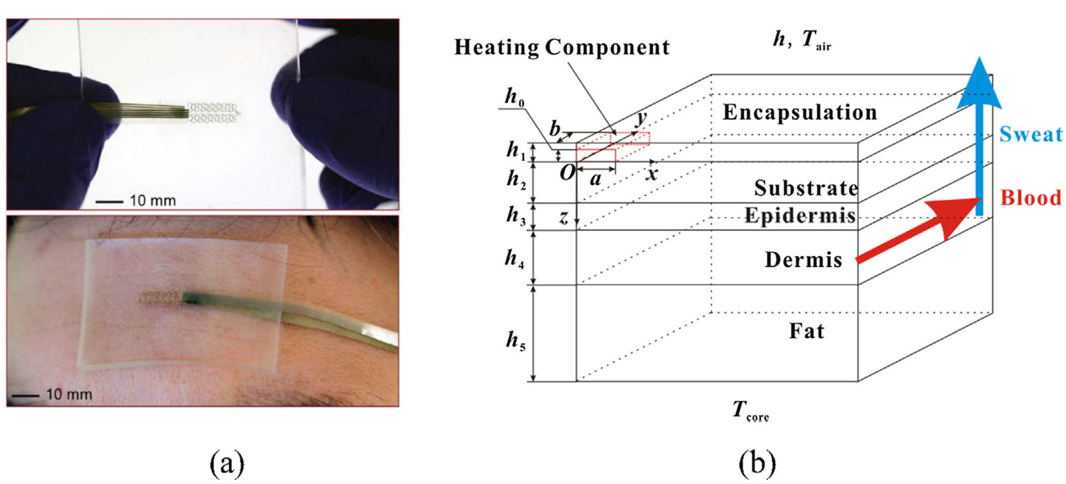

Fig. 1. Schematic diagram of (a) a typical EED integrated with human skin [17], (b) the three-dimensional analytical model showing a quarter geometry of EED/skin system.