Three-dimensional analysis model of electric heating fabrics considering the skin metabolism

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Abstract
In low temperature environment, electric heating clothing can provide extra heat for human body through built-in heat source, so it has better thermal insulation effect. The thermal analysis is the initial step for electric heating clothing design. The current thermal analysis of electric heating textiles focuses on the fabric itself instead of the effect of skin tissue metabolism and heat production. In order to improve the accuracy of skin surface temperature prediction, the biological heat transfer need be modeled to analyze the internal temperature distribution of the heating suit system. In this paper, a three-dimensional (3D) thermal analysis model of electric heating clothing combined with human skin tissue is established. Firstly, the coupling analysis of Fourier heat conduction and Pennes biological heat transfer equation is carried out. Then the reliability of the 3D thermal analysis model is verified by finite element analysis (FEA). The results show that the fitting error between the three-dimensional model analysis data and FEA simulation data is 5°C, which proves that the model can accurately predict the system temperature. Finally, we make further research about the effects of ambient temperature, clothing layer thickness, and input power on the maximum skin surface temperature. This study provides theoretical foundation for the design of wearable thermal management fabric.

Keywords
Electric heating clothing, human skin, FEA, Pennes bio-heat transfer

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Introduction
Electric heating clothing is an important barrier for people to resist the cold in life. It provides extra heat for the human body through the built-in heat source to maintain body temperature balance. In order to ensure the thermal comfort and safety of electric heating clothing, the research on its heat transfer mechanism becomes particularly important.

In the design process, not only clothing fibers themselves that keep warm in a passive way, but the design of the heat source is also particularly important.1,2 Nowadays, the commonly used heating wire materials include metal wire, graphene, fiber, etc.3 Carbon fiber is the most widely used because of good flexibility, ductility, and flexible structure.4 The electric heating clothing made of carbon fiber keeps conformal contact with skin under pressure and tension,5 which has great application prospects in the field of biomedicine.

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The electric heating clothing is close to the skin, so it is very important for the thermal analysis of the internal heat transfer to the skin surface, because high temperature will also cause skin thermal damage and adverse reactions. The heat transfer of electric heating clothing is complex, and it is not the sum of a single heat transfer mechanism, but includes heat conduction, convection, radiation, and combined heat transfer with the surrounding environment.

Several scholars use different methods to study the heat transfer mechanism of wearable flexible electronic devices or clothing to improve the user experience and security. Sun et al.\(^8\) used the influence of temperature and heat flux on the cross-section of fabric system by FEA, and found that the transient heat flux loss of fabric in contact with skin is the largest, which can be used as the basis for the prediction of contact comfort. Santo et al.\(^7,8\) used computational fluid dynamics to study the microclimate conditions of cylindrical clothing. The results show that the natural convection increases with the thickness of the microclimate ratio, and the best gap between clothing and skin is 0.1 mm. Gong et al.\(^9\) established a one-dimensional heat transfer model of the fabric, and studied the thermal protection performance of the fabric using ANSYS software. Siddiqui and Sun\(^10,11\) used FEA method to predict the effective thermal conductivity and thermal resistance of fabrics according to the actual parameters of fabrics. Fan et al.\(^12\) proposed a three-layer branched chain structure bionic woven fabric, and analyzed the steady-state heat transfer performance of the fabric by using FEA method. The predicted effective thermal conductivity is in good agreement with the experimental results. Su et al.\(^13\) used organic disguised materials to change the thermal properties of fabrics, designed coated fabrics with bidirectional thermal regulation function, and evaluated their thermal protection and heat dissipation function. The results showed that although the disguised materials had good thermal protection, they improved the thermal hazard. Chen\(^14–17\) analyzed the heat transfer of protective clothing through FPGA simulation software and temperature sensor, and verified the transfer model by comparing with the experimental data. In their research, the thermal comfort performance of protective clothing was optimized, which could protect the skin from the thermal damage caused by low-intensity thermal radiation. However, they ignored that the skin burn can also come from fabric combustion.

The above researches were limited to the fabric itself or only involved the heat transfer performance of the garment in combination with the surrounding environment while ignoring the influence of biological metabolism heat generation on the thermal comfort of the skin. Pennes biothermal equation\(^18–20\) has been widely used to simulate the biological heat transfer of skin tissue and study the thermal damage process of skin. Cui et al.\(^21–23\) had developed the flexible electronic heating equipment combined with skin metabolic heat production, which was used for one-dimensional (1D) and 3D heat conduction analysis to explore the influence of the size, load, and material of the flexible electronic heating equipment on its heat transfer. Udayraj and Wang\(^24,25\) established a 3D heat transfer model to analyze the heat transfer of thermal protective clothing under radiation heat exposure. A computational fluid dynamics model was used to analyze the heat transfer of the air gap between clothing and skin. However, the model ignored the influence of convection and other assumptions on the air gap of cold protective clothing, the deviation of heat transfer analysis and secondary combustion prediction was quite large. Due to the possible delamination between components and skin in practical application, Li et al.\(^26,27\) established an axisymmetric model to analyze the influence of interface thermal resistance on the integrated system of electronic devices and skin. The results of FEA and experimental measurement are in good agreement. However, in all the above researches, only the heating element itself or the coupling analysis of the heating electronic equipment and the skin tissue had been taken into account. These researchers ignored the actual environment when the electric heating fabric was worn inside.

When electric heating clothing is worn on the human body under working conditions, part of the heat generated by the source is transmitted to the environment through the fibers of the garment. The other part is transferred to the skin surface to achieve a dynamic equilibrium with the surface temperature of the body. Compared with only analyzing the heat transfer of heating clothing, it will be more complicated to consider the influence of human biological metabolic heat production on the thermal comfort of heating clothing. In the whole process of thermal analysis, heat transfer is mainly through heat conduction, heat convection, and heat radiation, accompanied by different degrees of heat loss. Given the above two situations, it is of great significance to explore the whole process of thermal analysis by establishing mathematical models.

In the field of clothing design, some scholars have also combined bio-heat transfer to analyze the safety performance of clothing, but only in special scenarios (such as fabric burning, high-intensity thermal radiation, etc.). Their research theories mostly focus on the material properties of clothing and do not involve flexible wearable electronic heating devices. For the bio-integrated application of electronic heating equipment such as electric heating clothing, the classical Fourier heat conduction ignores the influence of skin tissue heat production and blood infusion, and cannot accurately describe the heat transfer within tissues. In order to accurately analyze the bio-integrated applications of electric heating suits, Fourier heat conduction is adopted for electric heating suits, while Pennes bio-heat equation is adopted for skin tissues. There are few studies about the thermal analysis of the bio-integrated applications of heating suits and biological tissues. To accurately simulate the heat transfer mechanism between electric heating clothing and skin tissue, this paper established a three-dimensional...
A 3D analysis model for heat conduction between skin and fabrics

Model establishment

The electric heating fabric is installed on the human body to form a multilayer structure of skin tissue-electric heating fabric-air gap and outer clothing. In order to simplify the model, the skin tissue is set to a single-layer structure (actually a multi-layer complex structure); the electric heating fabric is composed of clothing fibers-fusible interlining-carbon fiber heating elements. The thermal conductivity of carbon fiber heating elements is 600 W/mK, which is much larger than clothing fiber can be modeled as a heat source that is close to a rectangle and has a heat generation power density $Q$ (W/m²). Although the air gap exists between the electrically heated fabric and the outer clothing, the thickness is thin and the flow is stable, so the air gap heat convection and heat radiation can be ignored. In addition, several factors affect the heat transfer of the fabric, such as: fabric, porosity, number of layers, bulkiness, etc. In order to simplify the complexity, the heat transfer model with a multilayer structure and good windproof performance fabrics is placed in an indoor environment. Based on the above-mentioned analysis and assumptions, the air gap is modeled as a uniform solid rectangle with constant thermal conductivity, ignoring the mass transfer through the fabric. The electric heating fabric is composed of clothing fiber and carbon fiber heating elements. The outer garment is a composite material composed of clothing fiber and air. The effective thermal conductivity of this layer is related to the thermal conductivity of clothing fibers, air, and its volume fraction.

In conclusion, an idealized model is shown in Figure 1. The heating plate inside the heating fabric contains wire, carbon fiber, fusible interlining, and fabric. The one-dimensional model is simplified to a five-layer structure, $h_1$, $h_2$, $h_3$, $h_4$, and $h_5$ respectively represent skin tissue, clothing fiber, fusible interlining, carbon fiber heating element, and outer layer composition. As is shown in Figure 2, only a quarter geometry of the analytical model for the heating fabric on the skin need be analyzed by taking the advantage of the symmetry. The bottom center point of the three-dimensional model is the origin of the coordinates, the positive direction of the $z$-axis is from the skin layer to clothes, and the positive $x$-axis and $y$-axis directions.

Figure 1. Conceptual model of 3D analysis model with multi-layered structure: (a) schematic diagram of the layout and structure of heating plate inside the heating fabric and (b) schematic illustration of one-dimensional geometry of the analytic modeled heating fabric-skin system.
follow the length and width directions of the carbon fiber heating element respectively. In the heat transfer analysis, the boundary conditions contain natural convection and heat radiation.

**Coupling analysis of Fourier heat transfer and Pennes biological heat transfer**

In the established three-dimensional model, heat transfer occurs at the interface of each layer, so the temperature difference caused by the heat transfer to each interface is used as the evaluation criterion. In the Cartesian coordinate system, \( h(i = 1–5) \) (Figure 1) respectively represents skin tissue, clothing fiber, fusible interlining, carbon fiber heating element, and outer layer composition, and \( n(i = 1–5) \) (Figure 2) represents the interface of each layer. The temperature difference of the skin tissue layer:

\[
\Delta = -T_{xy}(x, y, z) - T_h(x, y, z).
\]

Among them, \( T(x, y, z) \) is the temperature of the coordinate point \( (x, y, z) \), and \( T_h \) is the heart temperature. In the entire heat transfer process, the heat transfer from the heating source of the electric heating fabric to the outer garment satisfies the Fourier heat conduction equation:

\[
\nabla^2 \Delta T_i = 0 (i = 2, 3, 4, 5)
\]

According to physiological structure, blood is evenly perfused into the entire skin tissue, and the blood temperature is usually close to the body temperature: \( T_b = T_c \). The heat generated by metabolism will maintain the body temperature balance, so healthy people’s temperature can be set as constant. Therefore, the temperature change of the skin tissue layer satisfies the Pennes bioheat equation:

\[
k_i \nabla^2 (\Delta T_i) - \omega_b \rho_b c_b \Delta T_i + q_{met} = 0
\]

Where \( \omega_b \) is the blood infusion rate, \( \rho_b \) is the blood density, \( c_b \) is the blood specific heat capacity, \( q_{met} \) is the skin metabolism, and \( k_i \) is the thermal conductivity of skin tissue.

In the skin tissue layer \( (z=0) \), the skin epidermal temperature is similar to body temperature, while natural convection and thermal radiation occur in the outermost layer \( (z=n_5) \). Based on the theory of natural convection and thermal radiation, the boundary temperature can be obtained:

\[
\Delta T_i |_{z=0} = 0
\]

\[
-k_5 \frac{\partial \Delta T_i}{\partial z} |_{z=n_5} = Q_c + Q_r
\]

\[
Q_c = h_c(T_{\text{cloth}} - T_a), Q_r = \varepsilon \sigma (T_{\text{cloth}}^4 - T_r^4)
\]

Where \( Q_c \) is the natural convection heat, \( Q_r \) is the radiant heat, \( T_a \) is the ambient temperature, \( T_{\text{cloth}} \) is the cloth temperature, \( T_r \) is the radiation temperature, \( \varepsilon \) is the blackbody emissivity, and \( \sigma \) is the Stefan constant.

The outermost layer temperature in the established three-dimensional thermal analysis model is expressed as \( T_{clot} = T_{clot} |_{z=n_5} \). In order to facilitate the calculation, \( Q_c \) and \( Q_r \) have a unified formula, and \( Q_c \) can be:

\[
Q_c = h_c(T_{\text{cloth}} - T_r)
\]

where \( h_c \) is the linear thermal radiation coefficient.

The linear emissivity coefficient is related to the coat temperature and the radiation temperature, so the boundary temperature of the outermost layer can be expressed as:

\[
-k_5 \frac{\partial \Delta T_5}{\partial z} |_{z=n_5} = [h_0(T_z + T_c - T_0)] |_{z=n_5}
\]

\[
h_0 = h_c + h_r, T_0 = \frac{T_a h_c + h_r}{h_c + h_r}
\]

where \( h_0 \) is the total heat transfer coefficient, \( h_c \) is the natural convection coefficient, and \( T_0 \) is the system temperature.

In formula (4), \( k_5 \) is the effective thermal conductivity of the outer garment (a mixture of clothing fiber and air), which is calculated according to the effective medium theory:

\[
\text{Figure 2. The three-dimensional analytical model showing a quarter geometry of the heating fabric device integrated with skin tissue.}
\]
According to the above conditions, skin tissue metabolism, heat production, natural convection, and heat radiation are constant, so it can be used as a one-dimensional heat transfer model along the thickness direction. The governing equation $\Delta T$ can be expressed as:

$$
\begin{align*}
\frac{d^2 \Delta T}{dz^2} - \omega_h \rho c_s \Delta T + q_{met} &= 0 \\
\frac{d^2 \Delta T}{dz^2} - 0(i = 2, 3, 4, 5)
\end{align*}
$$

At the $n=n_{i=1,3,4}$ interface, the temperature transfer continuity and boundary conditions remain unchanged, while in the $n=n_2$ layer, the temperature change can be expressed as:

$$
\begin{align*}
\Delta T_2 |_{z=n_2} &= \Delta T_3 |_{z=n_3} \\
-k_3 \frac{\partial \Delta T_3}{\partial z} |_{z=n_3} + k_2 \frac{\partial \Delta T_2}{\partial z} |_{z=n_2} &= 0
\end{align*}
$$

The expression of the temperature difference at each interface in equation (15) is:

$$
\Delta T_{i+1} = A_{i,1} \exp(n_i \sqrt{\eta/k_i}) + B_{i,1} \exp(-n_i \sqrt{\eta/k_i}) + q_{met}/\eta \\
\Delta T_{i,1} = A_{i,1} + B_{i,1}(i = 2, 3, 4)
$$

Through formulas (3), (7), (8), (14), and (16), the coefficients $A_{i,1}$ and $B_{i,1}$ in the formula can be obtained:

$$
\begin{align*}
C &= h_0 k_2 \left[ \frac{(n_5 - n_4) + (n_4 - n_3)}{k_5} + \frac{(n_4 - n_3) + (n_3 - n_2)}{k_4} \right] + k_2 \\
D &= \frac{\eta}{k_1} \sqrt{\frac{k_1}{k_2}} \\
E &= CD \cos h(n_i \sqrt{\eta/k_i}) + h_0 \sin h(n_i \sqrt{\eta/k_i}) \\
F &= Dh_0 \left[ \cos h(n_i \sqrt{\eta/k_i}) - 1 \right] - \frac{q_{met}}{\eta} \\
&= \cos h(n_i \sqrt{\eta/k_i})(T_c - T_0)
\end{align*}
$$
\[
A_{1,1} = \frac{1}{2} \left( -CD + h_0 \right) e^{-\eta/\sqrt{k_1}} \frac{q_{\text{met}} - h_0}{\eta} - h_0 (T_c - T_o)
\]
\[
B_{1,1} = -\frac{1}{2} \left( CD + h_0 \right) e^{\eta/\sqrt{k_1}} \frac{q_{\text{met}} - h_0}{\eta} - h_0 (T_c - T_o)
\]
\[
A_{2,1} = -\frac{F}{E}
\]
\[
B_{2,1} = \frac{(C + h_0 n_1) D (\cosh(\eta/\sqrt{k_1}) - 1)}{E} q_{\text{met}}/\eta + \frac{h_0 n_1 D \cosh(\eta/\sqrt{k_1}) - h_0 \sinh(\eta/\sqrt{k_1})}{E} (T_c - T_o)
\]

### Carbon fiber heating element under working conditions

The carbon fiber heating element in the electric heating fabric is embedded in the designated area of the clothing fiber/fusible interlining. The thermal analysis of the whole system belongs to the three-dimensional heat conduction problem. The governing equation \( \Delta T \) is:

\[
k_1 \nabla^2 (\Delta T_1) - \omega_b \rho_b c_b \Delta T_1 = 0
\]  

(20)

Except for the skin tissue/clothing fiber interface, the governing equations \( \Delta T \) of the other interfaces are as follows:

\[
\nabla^2 (\Delta T_i) = 0, (i = 1, 2, 3, 4), \quad \text{where the temperature change formulas of each interface are (3), (13), and (14).}
\]

The outermost layer temperature of the coat remains uniform and the expression for:

\[
-k_1 \frac{\partial \Delta T_1}{\partial z} \bigg|_{z = n_1} = h_0 \Delta T_1 \bigg|_{z = n_1}
\]

(21)

According to the Fourier cosine transform of the established spatial rectangular coordinate system along the \( x \)- and \( y \)-axis, we can get:

\[
\Delta T(\alpha, \beta, z) = \int_{0}^{+\infty} \int_{0}^{+\infty} \Delta T(x, y, z) \cos(\alpha x) \cos(\beta y) dxdy
\]

(22)

According to the above formula, the skin tissue layer and the electric heating suit are considered separately and calculated:

\[
\begin{aligned}
\frac{d^2 \Delta T_1}{dz^2} - (\alpha^2 + \beta^2) \Delta T_1 = 0 \\
\frac{d^2 \Delta T_1}{dz^2} - (\alpha^2 + \beta^2) \Delta T_1 = 0, (i = 2, 3, 4)
\end{aligned}
\]

(23)

The boundary temperature of the outermost layer of the 3D model and the heat transfer formula of other interfaces are transformed into:

\[
\begin{aligned}
\Delta T_1 \bigg|_{z = 0} &= 0 \\
\Delta T_2 \bigg|_{z = n_1} &= \Delta T_3 \bigg|_{z = n_1} \\
-k_1 \frac{d \Delta T_3}{dz} \bigg|_{z = n_1} + k_2 \frac{d \Delta T_2}{dz} \bigg|_{z = n_1} &= \frac{P \sin(\alpha a) \sin(\beta b)}{4ab\alpha\beta}
\end{aligned}
\]

(24)

The solution formula of the above-mentioned expression is:

\[
\begin{aligned}
\Delta T_{1,2}(\alpha, \beta, z) &= A_{1,2}(\alpha, \beta) \exp(n_1 \sqrt{(\alpha^2 + \beta^2) + \eta/k_1}) \\
&+ B_{1,2}(\alpha, \beta) \exp(-n_1 \sqrt{(\alpha^2 + \beta^2) + \eta/k_1}) \\
\Delta T_{1,2}(\alpha, \beta, z) &= A_{1,2}(\alpha, \beta) \exp(z_1 \sqrt{(\alpha^2 + \beta^2)}) \\
&+ B_{1,2}(\alpha, \beta) \exp(-z_1 \sqrt{(\alpha^2 + \beta^2)})
\end{aligned}
\]

(25)

The above \( A_{1,2} \) and \( B_{1,2} \) can be determined by equation (24) obtained from the boundary conditions in the heat transfer process and the continuous conditions of heat transfer at each interface, and then:

\[
\begin{aligned}
\mu_1 &= k_1/k_2 \sqrt{(\alpha^2 + \beta^2 + \eta/k_1)/(\alpha^2 + \beta^2)} \\
\lambda_1 &= \mu_1 \sqrt{\alpha^2 + \beta^2 + \eta/k_1} \\
\lambda_1 &= (n_1 - n_{i-1}) \sqrt{\alpha^2 + \beta^2}, (i = 2, 3, 4, 5)
\end{aligned}
\]

(26)

\[
\begin{aligned}
G_1 &= k_1 k_2 \cos(\lambda_1) \sinh(\lambda_1) + k_1 \sinh(\lambda_1) \cos(\lambda_1) \\
G_2 &= k_1 k_2 \cos(\lambda_2) \sinh(\lambda_2) + k_1 \sinh(\lambda_2) \cos(\lambda_2) \\
H_1 &= k_1 (n_1 \cos(\lambda_1) \sinh(\lambda_1) + \sinh(\lambda_1) \cos(\lambda_1)) \\
H_2 &= k_1 (n_1 \cos(\lambda_2) \sinh(\lambda_2) + \sinh(\lambda_2) \cos(\lambda_2)) \\
I_1 &= k_1 (H_1 \cos(\lambda_1) + H_1 \sin(\lambda_1)) \\
I_2 &= k_1 (H_2 \cos(\lambda_1) + H_1 \sin(\lambda_1)) \\
J_1 &= k_1 (I_1 \cos(\lambda_1) + I_1 \sin(\lambda_1)) \\
J_2 &= k_1 (I_2 \cos(\lambda_1) + I_2 \sin(\lambda_1))
\end{aligned}
\]

(27)
\[
A_{1,2} = \frac{P \sin(\alpha a) \sin(\beta b)}{8ab\sqrt{\alpha^2 + \beta^2}}
\]
\[
\left\{ G_0 + G_0 \frac{h_0}{\sqrt{\alpha^2 + \beta^2} k_0} \cosh(\lambda_0) + \left[ G_0 + G_0 \frac{h_0}{\sqrt{\alpha^2 + \beta^2} k_0} \sinh(\lambda_0) \right] \cosh(\lambda_0) + \left[ J_2 + J_2 \frac{h_0}{\sqrt{\alpha^2 + \beta^2} k_0} \sinh(\lambda_0) \right] \sinh(\lambda_0) \right\}
\]
\[
B_{1,2} = -A_{1,2}
\]
\[
A_{2,2} = \frac{A_{1,2} (n_1 \cosh(\lambda_1) + \sinh(\lambda_1))}{e^{\alpha \sqrt{\alpha^2 + \beta^2}}}
\]
\[
B_{2,2} = \frac{A_{1,2} (n_1 \cosh(\lambda_1) - \sinh(\lambda_1))}{e^{\beta \sqrt{\alpha^2 + \beta^2}}}
\]

The calculation formula for the temperature difference at each interface is obtained through the Fourier arc cosine pair equation (25) conversion:

\[
\Delta T(x, y, z) = \frac{4}{\pi^2} \int_0^\infty \int_0^\infty \Delta T(\alpha, \beta, z) \cos(\alpha x) \cos(\beta y) d\alpha d\beta
\]

The expression formula for the temperature difference at \( z = n_2 \) is:

\[
\Delta T_{2,2}(x, y, z) = \frac{4}{\pi^2} \int_0^\infty \int_0^\infty \left[ A_{2,2}(\alpha, \beta) \exp(n_2 \sqrt{\alpha^2 + \beta^2}) \right] \cos(\alpha x) \cos(\beta y) d\alpha d\beta
\]

\[
+ \frac{4}{\pi^2} \int_0^\infty \int_0^\infty \left[ B_{2,2}(\alpha, \beta) \exp(-n_2 \sqrt{\alpha^2 + \beta^2}) \right] \cos(\alpha x) \cos(\beta y) d\alpha d\beta
\]

In the thermal analysis, the temperature of the carbon fiber heating element and the maximum temperature of the human skin surface need to be considered. The skin layer \((x, y, z) = (0, 0, n_f)\) is brought into the equation:

\[
\Delta T_{\text{skin}} = \frac{8}{\pi^2} \int_0^\infty \int_0^\infty A_{1,2} \sinh(\lambda_1) d\alpha d\beta
\]

The temperature outside the carbon fiber heating element/clothing fiber contact area \((z = n_f)\) can be calculated by the formula (32):

\[
\Delta T_{\text{carbon}} = \frac{16}{\pi^2 [2ab + (a+b)h_{\text{carbon}}]} \int_0^\infty \left[ A_{1,2} \frac{H_2}{k_3} \sin(\alpha a) \sin(\beta b) \right] \frac{d\alpha d\beta}{\alpha \beta}
\]

**Analyze the above two situations together**

According to the mathematical model of the carbon fiber heating element embedded in the electric heating fabric under working and non-working conditions, the linear superposition method is used to calculate the temperature calculation formula of the carbon fiber heating element/ clothing fiber interface and the electric heating fabric/skin tissue contact surface:

\[
T(x, y, z) = T_h + A_{2,1} n_2 + B_{2,1} + \Delta T_{2,2}(x, y, z)
\]

**Results**

*Simulation analysis based on ANSYS*

In order to verify the validity and feasibility of the established analysis model, steady-state thermal simulation
verification is performed through ANSYS. Outerwear is a mixture of clothing fiber and air, in which the air volume fraction is 75%.\textsuperscript{31,32} According to equations (9) and (10), the thermal conductivity of the outerwear ($k_i$) can be calculated. The thermal conductivity and thickness of other layers are shown in Table 1.\textsuperscript{20,33,34}

In order to ensure that the contact area of each layer is large enough to get a good convergence result, the length, width, and height are set as 14 mm × 14 mm × 6.2 mm. The size of the carbon fiber heating element embedded in the fabric is: $2a \times 2b \times H_{\text{carbon}} = 0.2 \text{ mm} \times 4 \text{ mm} \times 0.2 \text{ mm}$. The geometric model is divided into a mapped grid, and the grid cell size is 0.1 mm. Before the simulation, material parameter definition and boundary condition constraints are required. Under standard atmospheric pressure, the setting parameters and constant values\textsuperscript{21,33,35–38} are shown in Table 2. The above linear thermal radiation coefficient $h_r$ can be calculated by formula (12),\textsuperscript{34,39} the external environment temperature is set to $T_a = 283 \text{ K}$, the physical properties of blood tissue under the skin tissue surface:

\[
\begin{align*}
\rho_b &= 1069 \text{ kg/m}^3, \quad c_b = 3659 \text{ J/(kg} \cdot \text{K}), \quad 22,28,40,41 \\
o_b &= 0.0005 \text{ ml/(ml} \cdot \text{s}).
\end{align*}
\]

In order to understand the heat transfer state in the electric heating fabric-skin tissue, the heat source temperature inside the electric heating fabric is transferred to the skin surface and the external environment.\textsuperscript{42,43} Taking the center point of the bottom layer as the origin of the coordinates, the horizontal and vertical coordinates are $x$ and $y$. When the input power is 50 mW, the thermal map distribution along the $y$-axis is shown in Figure 3. The heat is transferred to the outermost boundary, causing the temperature of each part to be different, causing the surrounding cold and hot air to flow relatively, the hotter part of the airflow rises, the colder part of the airflow drops, circulating flow. The temperature is transferred down to the surface of the skin to reach thermal steady-state equilibrium.

**Thermal analysis model and finite element data fitting**

We used finite element calculation to verify the correctness of the established three-dimensional thermal analysis model, which is consistent within the allowable error range. When the input power is $P = 50 \text{ mW}$, the temperature distribution of the finite element calculation and thermal analysis model at the interface ($z = n_z$) of the fusible interlining and the clothing fiber along the positive direction of the $x$- and $y$-axis varies with distance as shown in Figure 4. As shown in Figure 4(a) and (b), the analysis and prediction results are in good agreement with the finite element analysis results, and the error is about 0.5°C, thus verify the feasibility of the established three-dimensional thermal analysis model. The maximum temperature occurs inside the region of the carbon fiber heating plate and keeps as a uniform value at around 58.3°C. Outside the heating plate region, the temperature decays quickly as far from the boundary of the heating plate and then begins to flatten gradually.

**Discussion**

In this paper, a three-dimensional thermal analysis model of metabolic heat of biological tissues and heating clothing is established based on the real environment. For the thermal analysis model of clothing and biological tissue, several scientists come from different fields have different research focuses and adopt different methods. Santos et al.\textsuperscript{7} established a two-dimensional model of the horizontal cylindrical structure of skin and clothing based on fluid dynamics. Shen et al.\textsuperscript{44} simulated the thermal resistance of the fabric heat transfer and established a new heterogeneous model, the transverse and longitudinal heat transfer can be processed in parallel. Cui et al.\textsuperscript{21} analyzed blood infusion rate and adipose decompose biological heat by one-dimensional thermal analysis model. Compared with the above model, the three-dimensional FEA model can predict the skin surface temperature more accurately.

Moreover, the model verifies the heat transfer to the skin surface is affected by the thickness of the garment. For a planar heat source, the geometric size, input power, and ambient temperature are kept constant. The results predicted from the analytical model in formal\textsuperscript{56} agree well with FEA (Figure 5), which validate the reliability of the model. The thickness of the clothing fiber layer increases from 0.1 to 0.5 mm, the maximum temperature change for heat transfer to the skin surface is from 38.4°C to 34.1°C. The thickness of fabric increases from 0.1 to 0.4 mm, the maximum skin surface temperature decreased by about 4.3°C. But the thickness exceeds 0.4 mm and the temperature is maintained at around 34°C, the skin surface temperature is no longer affected by

| Table 1. Thermal conductivity and thickness of each material. |
|---------------------------------------------------------------|
| **Thermal conductivity (W/m/K)** | **Thickness (mm)** |
| Skin tissue | 0.470 | 4.0 |
| Carbon fiber heating element | 700 | 0.2 |
| Fiber (95% cotton) | 0.049 | 0.3 |
| Fusible interlining | 0.420 | 0.3 |
| Air gap | 0.023 | 0.1 |
| Outer layer | 0.0282 | 1.5 |

| Table 2. Parameters setup. |
|-----------------------------|
| **Variables** | **Symbols** | **Values** |
| Natural convection coefficient | $h_c$ | 15 W/m$^2$/K |
| Skin metabolism | $q_{\text{met}}$ | 368 W/m$^2$ |
| Ambient temperature | $T_a$ | 283 K |
| Blackbody emissivity | $\varepsilon$ | 0.95 |
the thickness of clothing. The maximum temperature at the heating fabric/skin interface varies with the thickness of the clothes fiber, which is very helpful to design the electric heating clothing integrated with human skin. Zhu and Lu\textsuperscript{45} pointed out that the critical temperature of thermal pain which can be felt by human is 39°C, while Lovik et al.\textsuperscript{46} considered 43°C as the threshold of tissue injury. By simulating a more realistic environment, the maximum temperature of the heating fabric/skin interface was respectively 38.6°C and 38.4°C in the analytical model and FEA. On the basis of previous research, more accurate and safe temperature predictions are demonstrated. It can be understood that if the clothing is thicker and the porosity is higher, the thermal performance of electric heating clothing will be reduced.

Although we verified the influence of a single variable on the distribution of skin surface temperature, we further...
explored the influence of different input power and ambient temperature on the distribution of skin surface temperature. As the ambient temperature changes, and the input power is 50 and 70 mW, the temperature in the skin tissue/clothing layer decrease with the x-axis as shown in Figure 6(a) and (b). When the ambient temperature is −5°C, 5°C, and 15°C,\textsuperscript{47–49} FEA analysis is in good agreement with the analytical model, and the influence trend on the temperature is consistent. The lower the ambient temperature, the higher the input power can improve the insulation efficiency of the electrically heated fabric. Therefore, the insulation effect can be achieved in a low temperature environment by adjusting the heating power to increase the heat. For example, as the rated power is 70 mW and the ambient temperature drops from 15°C to −5°C, the maximum skin surface temperature drops by around 17.6°C after the heat transfer reaches the steady-state equilibrium.

Due to the simplification of heat radiation, heat mass transfer, and air gap heat convection, a three-dimensional thermal analysis model of electric heating fabric and biological tissue is established under the premise of natural convection air and airtight clothing. The accuracy of FEA calculation is affected by the simplification of physical model, material properties, and environmental boundary conditions. The thermal characteristics and blood infusion rate of biological tissues vary from person to person, and the convection coefficient is affected by the environment. To ensure the accuracy of the above thermal prediction, the uncertainty caused by the skin thermal characteristics and blood infusion rate should be considered. Several scholars have discussed the uncertainty problem.\textsuperscript{50–52} Here we consider conditions with uncertain values (input power, ambient temperature, and clothing thickness). Figure 6(a) and (b) presents the largest differences in the temperatures for the three conditions are approximately 9.5°C, which means that these factors are sensitive to the maximum surface temperature of the skin. In the actual environment, more factors can affect the heat preservation effect, therefore a more comprehensive and widely applicable model needs to be developed for electric heating suits.

**Conclusions**

In this paper, an integrated three-dimensional thermal analysis model of electric heating fabric and human skin is established, the temperature distribution of the skin surface is predicted. Under the condition of constant power and environmental temperature remain unchanged, the biological heat transfer of the skin tissue and the Fourier heat conduction in the electric heating clothes are introduced for coupling analysis, and the calculated prediction results fit well with the finite element simulation data, thus verifying the feasibility of the three-dimensional thermal analysis model. The formula for calculating skin surface temperature is obtained from the above, and the influence of clothing thickness, ambient temperature, and input power of electric heating clothing on skin surface temperature is studied. The research results can be used to quantitatively evaluate the thermal comfort of human skin, which can avoid adverse reactions such as heat damage to the skin caused by excessively high temperature of the electric heating clothes. The research results provide new ideas and methods for the design of wearable electric heating devices to reduce adverse thermal effects and power consumption in bio-integrated applications. Theoretical results discussed above also provide new ideas for the thermal design of bio-electronic devices.

**Author contributions**

Xiao Li: Investigation, Methodology, Writing – original draft, Writing – review and editing, Project administration, Funding
acquisition. Bo Kuai: Investigation, Methodology, Formal analysis, Visualization, Writing – review and editing. Xikai Tu: Resources, Formal analysis, Supervision, Validation. Jiahao Tan: Investigation, Conceptualization, Methodology, Writing – original draft. Xuan Zhou: Methodology, Writing – original draft.

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