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A FEM Approach to Evaluate Thermoregulation in the Human Body during Cycling Due to the Metabolic Effect

Dev Chandra Shrestha[1*], Saraswati Acharya[2]

[1]Department of Mathematics, Baneshwor Multiple Campus, Kathmandu, Nepal
[2]Department of Mathematics, Kathmandu University, Dhulikhel, Nepal
Email: *shresthadev28@yahoo.com, saraswati.acharya@ku.edu.np

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Abstract

The physical properties of convective and evaporative heat loss and thermophysical properties such as blood perfusion, specific heat capacity, thermal conductivity, and metabolic heat generation rate play a significant role in thermoregulation in the human body during cycling. During cycling, skeletal muscles generate a large amount of metabolic energy, which is distributed over different parts of the body through the perfusion process. Surplus heat energy is released from the body through tears and maintains the body during thermoregulation. The temperature profiles of the epidermis, dermis, and subcutaneous tissue were analyzed at various ambient temperatures and sweat evaporation rates. The solution of the model was performed in a one-dimensional steady state using the finite element method (FEM), and the obtained results were simulated graphically.

Keywords

Ambient Temperature, Sweat Evaporation, Metabolic Rate, Threshold Value, Thermoregulation

1. Introduction

Cycling is the physical activity of riding a bicycle or other type of cycle, which constitutes an important part of leisure activities that bring all the body parts into motion. It is practiced worldwide in transportation, pleasure, exercise, and competitive sports. Current weather patterns and other meteorological phenomena have a significant impact on cycling [1]. Low visibility during fog, icy roads, and lightning during thunderstorms all make cycling more dangerous. The ambient temperatures, rainfall, thermal comfort, wind speed, radiation, clothing, and physical activity also affect cycling [1].

Cycling can help protect against serious diseases such as strokes, heart attacks, some cancers, depression, diabetes, obesity, and arthritis. It improves aerobic capacity, blood pressure, lipid profiles, body composition, mental health, and weight loss. Regular cycling reduces body fat mass. Therefore, blood circulation occurs regularly. Blood carries thermal heat energy and dissipates all over the body. Skin blood flow increases the sweating rate and releases heat. During cycling, protein builds damaged muscles and reduces muscle soreness [2]. It is also used to increase general fitness.

Frequent cycling increases lean muscle mass and improves cardiovascular health owing to the burning of more calories. The burning of calories depends on environmental conditions, speed, and distance. The speed of cyclists is also affected by the climate. During cycling, the body burns approximately 9,033 to 12,976 kilocalories of energy per day [3]. The cardiovascular condition is improved by the elevated metabolic rate, which also improves the body's stamina and endurance. In general, the body needs more energy to stay warm in winter, so the speed of cyclists decreases by 10% on average as the speed increases in the summer season [4].

Thermoregulation allows the body to control or maintain the required internal body temperature. It is influenced by environmental factors such as ambient temperature, wind chill, and sunlight. Thermal energy is transferred from the body to the surroundings if the body temperature is higher than the environmental temperature, and the body receives thermal energy if the body temperature is lower than the environmental temperature. Conduction, convection, and radiation are heat transfer processes that transfer heat from the body to the surroundings and vice versa.

The heat exchange among skin layers is dependent upon the skin's thickness, thermal conductivity, anatomical location, and heat transfer coefficient [5]. In sweat evaporation, excess thermal energy loss from the body in the form of sweat controls the body temperature and prevents hyperthermia. During metabolism, the body generates internal heat energy from muscles. When the body temperature is very low, the organs also produce heat energy by thermogenesis and maintain body temperature, preventing the body from hypothermia. During perfusion, the body distributes thermal heat energy over the body, which is generated by the metabolic process.

When the body temperature rises above normal, blood vessels become wider, allowing more heat-carrying blood to the surface. Consequently, the skin temperature increased. At the same time, sweat glands are stimulated, opening the pores of the skin to the passage of body fluids that evaporate onto the surface of the skin, increasing heat loss and causing the body to cool.

When the body temperature is below normal, the outer blood vessels constrict, reducing the blood flow to the skin, which controls the heat loss from the body.

The control device also increases heat production by calling for involuntary muscular activity or shivering.

When the body's intake energy is equal to the output energy, all the internal energy generated by the body dissipates so that the body mechanism easily controls the body temperature and every body organ works properly. However, during cycling, the body consumes a large amount of chemical energy and thus, the body cann't dissipate all the consumed energy. The energy balance could not be maintained. The body stores thermal energy that flows through several skin layers, causing them to heat, and each skin layer and the body's core temperature rise. The thermal energy that occurs in the body during cycling is obtained as the,

$$\text{Intake Energy} = \text{Output Energy} + \text{Storage Energy} \tag{1}$$

Radiative heat loss from the body is independent of the movement of the surrounding air. This occurs when the surrounding objects have a surface temperature lower than the body temperature.

The evaporative heat loss from the body depends on the difference between the water vapor pressure at the skin and the ambient air. This was due to the effect of sweat evaporation and the diffusion of water through the skin. At high ambient temperature and high activity levels, the body releases a large amount of sweat compared to a low ambient temperature and at rest [6]. During cycling, sweat glands become more active, and the body releases approximately 1.2 l/h to 1.93 l/h of sweat [7].

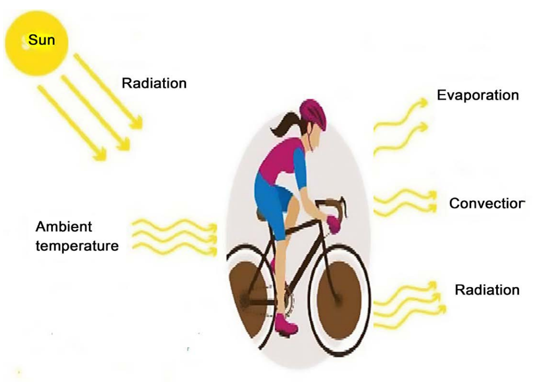

Figure 1. Heat transfer mechanism during cycling [8].

During cycling, owing to the relatively high velocity, the air motion around the cyclist increased and approached the mechanism of convective and evaporative heat loss. In flat terrains, the average speed of the cyclist is greater than 10m/s, which determines the heat loss capacity [9]. The high air speed also facilitates evaporation and stress, and becomes comparable. With environmental conditions of 40˚C, relative humidity 60%, the maximal evaporative cooling capacity for a 70 kg rider cycling at 40 km/h is 2000 W, whereas the same person for 20 km/h may approach a capacity of approximately 1000 W and maintain thermal balance [9]. The heat transfer mechanism in the human body during cycling is shown in **Figure 1**.

Heat energy balance on the body becomes a challenge during uphill cycling. Hyperthermia may arise more frequently in such situations. It is difficult to accurately calculate the convective and evaporative cooling capacities at a given speed and ambient temperature. Heat dissipation is no longer facilitated by high air speeds; therefore, it is a risk to health conditions. Consequently, hyperthermia may become an issue during uphill cycling, where the racing speed is much lower than that during cycling on flat terrains. In the case of a hot environment during cycling, the air temperature is closer to the body's core temperature. When the body temperature is higher, it is controlled by the cooling effect of the hyperpnea.

During cycling, on courses with flat terrains where the velocity is high, the cyclist can maintain temperature balance due to the factors mentioned above, and the evaluated environmental temperature mat proves an advantage for performance. In contrast, during uphill climbing, this may be a disadvantage because heat dissipation is no longer facilitated by the high air speed, and there is only a minimal effect of the lower density.

The average healthy person has a normal body core temperature in the range of 36.1˚C to 37.8˚C, but it may rise to 39.5˚C during exercise [10]. The experimental data indicated that the body core temperature during cycling ranges from 38.5˚C to 39.5˚C; it may also be affected by several physiological factors [7]. When the body temperature exceeds 39.5˚C, the risk of potentially fatal heat stroke is markedly increased [7].

Thermal balance during cycling is also influenced by factors such as ambient temperatures, radiant temperatures, movement and direction of air, humidity, clothing, PPE (Personal Protective Equipment) insulation, work rate, and generation of metabolic heat by the body. Skeletal muscles are the principal sources of metabolic heat energy. Muscle mass determines BMR in the human body. It varies with age, sex, body surface area, and hormone level. The average BMR in a healthy adult is 1114 w/m^3 [11]. With increasing age, BMR also decreases. During cycling, the body consumes a large amount of energy. The experiment data shows that the energy expenditure of the body during cycling in the course of 4000 km is given as 25.40 MJ/day to 35.90 MJ/day [12]. This shows that the maximum metabolic rate of 58 kg body mass was 7163.97 w/m^3 during cycling.

Blood perfusion refers to the delivery of arterial blood to the capillary bed in living tissues. This process works either to dissipate heat or to reheat the cooled area to maintain normal body temperature. Tissue blood flow is the amount of blood flow through the capillaries of the vascular bed of a structure or region.

Moussay *et al.* [13] experimentally observed the body core temperature during cycling and noted that the body core temperature range was 39.3˚C to 41.5˚C. They also suggested that body temperature depends on speed, which depends on the climate.

Shrestha *et al.* [10] analyzed the subcutaneous tissue temperature during vigorous exercises and claimed that the subcutaneous tissue temperature ranged from 38.04˚C to 38.24˚C. They also suggested that body temperature is influenced by thermo-physical properties.

During cycling, heat loss occurs when anything touches the skin. Radiative heat loss occurs when the surrounding temperature is lower than body temperature. In this situation, the heat loss is independent of the air movement or the surrounding air temperature. The sun's radiative heat gain during the day makes the cyclists feel warmer than they would at night with the same ambient temperature.

Metabolic heat generation and heat dissipation balancing from the body determine thermal comfort. The impact of cycling speed on thermal comfort can be analyzed by examining its effects on body heat production and loss. In this study, a metabolic heat generation model was presented, and the temperature of the skin layers, epidermis, dermis, and subcutaneous tissue of cyclists under various environmental conditions was measured.

2. Model Equation of Metabolic Energy

Owing to the increase in the blood flow rate, the metabolic heat generation rate increased during cycling. The metabolic heat energy increases slowly at the beginning and quickly increases in the log phase with poor linear behavior, and reaches a steady state owing to its threshold value. This shows that the metabolic rate has logistics in behavioral behavior during cycling. The metabolic heat generation rate $H_m(t)$ is obtained as [14]:

$$H_m(t) = H_0 + \frac{E_t - H_0}{1 + e^{-\alpha(t - s_m)}} \tag{2}$$

where H_0 is the basal metabolic rate, t is the exercise period, E_t is the activity threshold value of metabolism during cycling, α is the steepness of the curve per unit time, and s_m is the sigmoid midpoint of the curve over time t for extensive exercise.

Figure 2 represents the unsteady behavior of the metabolic rates of the normal human body during cycling in a 2400-s (40 min) period. The figure shows the threshold metabolic value during cycling is 7163.97 w/m^3 at $\alpha = 0.005/\text{s}$, and $s_m = 800\ \text{s}$ with BMR = 1114 w/m^3.

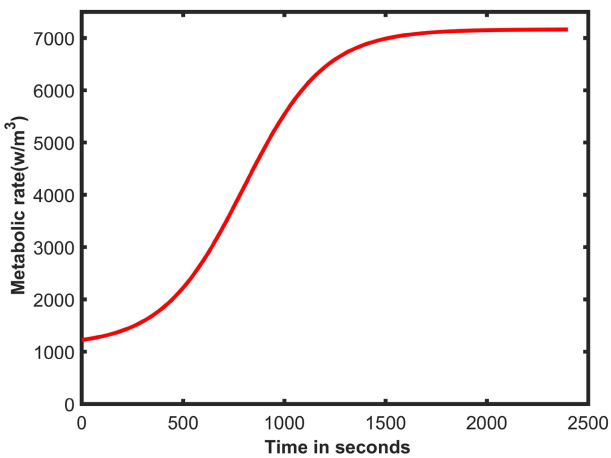

Figure 2. Metabolic rate behavior during cycling.

3. Bioheat Equation and Its Modification

A heat generation model for the human forearm was initially developed by Pennes in 1948. The model was created by a sequence of experiments measuring the temperatures of tissue and arterial blood in the resting human forearm. The model described the rate of heat transfer between the blood and local tissue, provided that the heat transfer rate is proportional to the product of the volumetric perfusion rate and temperature gradient between the arterial blood temperature and the local tissue temperature [15]. In the model, he also explained the effect of thermal diffusion and constant metabolism, which is represented by Equation (3) and is known as Pennes' bioheat equation.

$$\rho c\frac{\partial\theta}{\partial t}=\nabla\cdot\left(K\nabla\theta\right)+\rho_b c_b w_b\left(\theta_A-\theta\right)+H_m\left(t\right) \tag{3}$$

where,

ρ : Tissue density (kg/m³),

c : Tissue-specific heat capacity (J/kg˚C),

K : Tissue thermal conductivity (w/m.˚C),

ρ_b : Blood density (kg/m³),

c_b : Blood specific heat capacity (J/kg˚C),

w_b : Blood perfusion rate (/s),

θ_A : Arterial blood temperature (˚C),

θ : Tissue temperature (˚C),

$H_m\left(t\right)$: Metabolic heat generation rate (w/m³).

During cycling, the body dissipates excess metabolic heat energy to the surroundings. The resulting bioheat equation for generating metabolic energy using Equation (2) modified Pennes' bioheat equation to

$$\rho c\frac{\partial\theta}{\partial t}=\nabla\cdot\left(K\nabla\theta\right)+\rho_b c_b w_b\left(\theta_A-\theta\right)+\left(H_0+\frac{E_t-H_0}{1+\mathrm{e}^{-\alpha\left(t-s_m\right)}}\right) \tag{4}$$

4. Discretization of Domain

The skin is a highly vascularized organ that plays a significant role in maintaining stable internal body temperature through mechanisms such as vasodilation, vasoconstriction, sweating, and metabolism, even under varying environmental conditions. It allows heat through the vasoconstriction mechanism and releases heat energy through the vasodilation mechanism when body temperature rises [16]. Naturally, the skin has three layers: the epidermis (outer layer) is influenced by the environment; the dermis (middle layer), and the subcutaneous tissue (inner layer) is attached to the body core. A geometric diagram of the temperature distribution model in the human body is shown in **Figure 3**.

Let L_1, L_2-L_1, and L_3-L_2 be the thicknesses of the epidermis, dermis, and subcutaneous tissues, respectively. Let θ_0, θ_1, θ_2 and θ_3 be the nodal temperatures at distances of $x=0$, $x=L_1$, $x=L_2$ and $x=L_3$ measured from the outer surface of the skin. $\theta^{(1)}$, $\theta^{(2)}$, and $\theta^{(3)}$ are the temperature functions of the epidermis, dermis, and subcutaneous tissues, respectively.

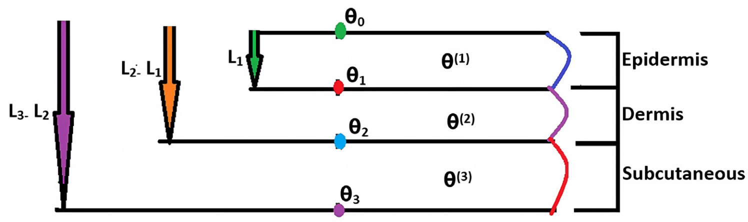

Figure 3. Schematic diagram of three skin layers in the human body.

The thickness of each skin layer varies from person to person and depends on the location of the body. The thickness of the epidermis, dermis, and subcutaneous tissue in the model was obtained from a previously published article, as shown in Table 1.

Table 1. Thickness of skin epidermis, dermis, and subcutaneous tissue in the human body [17].

Skin Layers	Epidermis Layer (L_1) m	Dermis Layer ($L_2 - L_1$) m	Subcutaneous Tissue ($L_3 - L_2$) m
Thickness	1×10^{-3} m	3.5×10^{-3} m	5×10^{-3} m

5. Solution of the Model

The heat regulation in the *in vivo* tissue of the human body during cycling is given by the partial differential Equation (4), which can be written for 1D as

$$\rho c \frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial \theta}{\partial x}\right) + M\left(\theta_A - \theta_\infty\right) + \left(H_0 + \frac{E_t - H_0}{1 + \mathrm{e}^{-\alpha(t - s_m)}}\right) \tag{5}$$

where, $M = \rho_b c_b w_b \left(\mathrm{J/m^3 \cdot s \cdot {}^\circ C}\right)$.

Boundary Conditions

a) Boundary conditions at skin surface ($x = 0$)

The outer surface of the skin is susceptible to the environment. Therefore, the heat flux during cycling was dissipated for $x = 0$, and heat loss occurred from the outer surface by conduction, convection, radiation, and evaporation. Therefore, the net heat flux was determined by the mixed boundary conditions given by Equation (6),

$$K \left.\frac{\partial \theta}{\partial x}\right|_{x=0} = h\left(\theta - \theta_\infty\right) + L_A E \tag{6}$$

where L_A, E, h, and θ_∞ are the latent heat capacity, rate of sweat evaporation, combined heat transfer coefficient of convection and radiation, and atmospheric temperature, respectively.

b) Boundary condition at the body core ($x = L_3$)

During cycling, the body generates a large amount of metabolic heat energy owing to the rapid motion of the muscles. The metabolic heat energy generated by the body cannot dissipate instantaneously. Therefore, some metabolic heat energy is stored in the body during cycling. The stored heat energy is used to raise the body's core temperature to 39.5˚C. So, Dirichlet's inner boundary condition during the cycling period is taken as

$$\theta(L_3) = \theta_b = 39.5^\circ\text{C} \tag{7}$$

where, θ_b is the body core temperature, and L_3 is the total thickness of the skin measured from the outer skin to the subcutaneous tissue.

Using the Euler-Lagrange formula, the modified Pennes' bioheat Equation (5), incorporating the boundary conditions (6), converted into the variational integral form, is given by

$$\begin{aligned} I[\theta] &= \frac{1}{2}\int_L \left[K\left(\frac{\mathrm{d}\theta}{\mathrm{d}x}\right)^2 + M(\theta_A - \theta)^2 - 2H_m(t)\theta \right]\mathrm{d}x \\ &+ \frac{1}{2}h(\theta_0 - \theta_\infty)^2 + LAE\theta_0 \cdot \end{aligned} \tag{8}$$

where, L = domain of skin layers.

The epidermis contains several layers of dead cells and has no blood vessels. The blood flow in this layer is absent. So the epidermis has no metabolism, and arterial temperature is set to zero. The deeper layer, "subcutaneous tissue," is attached to the body core. So in the model, the subcutaneous tissue temperature is taken as the body core temperature.

The physical and physiological parameters of the skin layers of the epidermis, dermis, and subcutaneous tissue of the dermal part varied as in Table 2.

Table 2. Parameters used in the model.

Physical and Physiological Parameters	Epidermis $L_0 \le x \le L_1$	Dermis $L_1 \le x \le L_2$	Subcutaneous $L_2 \le x \le L_3$
K	K_1	K_2	K_3
M	$M_1 = 0$	M_2	M_3
θ_A	$\theta_A^{(1)} = 0$	$\theta_A^{(2)} = \theta_b$	$\theta_A^{(3)} = \theta_b$
$H_m(t)$	$H_{m1} = 0$	$H_{m2} = \frac{1}{2}\left[H_0 + \frac{E_t - H_0}{1+\mathrm{e}^{-\alpha(t-s_m)}}\right]$	$H_{m3} = \left[H_0 + \frac{E_t - H_0}{1+\mathrm{e}^{-\alpha(t-s_m)}}\right]$
$\theta^{(i)}$	$\theta^{(1)} = \theta_0 + \left(\frac{\theta_1 - \theta_0}{L_1}\right)x$	$\theta^{(2)} = \frac{L_2\theta_1 - L_1\theta_2}{L_2 - L_1} + \left(\frac{\theta_2 - \theta_1}{L_2 - L_1}\right)x$	$\theta^{(3)} = \frac{L_3\theta_2 - L_2\theta_3}{L_3 - L_2} + \left(\frac{\theta_3 - \theta_2}{L_3 - L_2}\right)x$

Let I_1, I_2, and I_3 be the integral solutions of epidermis, dermis, and subcutaneous tissue, respectively, with $I = \sum_{i=1}^{n} I_i$. Solving the integrals I_1, I_2 and I_3 with parameters as considered in Table 2, we obtain I_1, I_2 and I_3 as functions of nodal values θ_0, θ_1, θ_2, as given below:

$$I_1 = A_1 + B_1\theta_0 + D_1\theta_o^2 + E_1\theta_1^2 + F_1\theta_0\theta_1 + \alpha_1\frac{\mathrm{d}}{\mathrm{d}t}\left(\theta_0^2 + \theta_1^2 + \theta_0\theta_1\right)$$

$$I_2 = A_2 + B_2\theta_1 + C_2\theta_2 + D_2\theta_1^2 + E_2\theta_2^2 + F_2\theta_1\theta_2 + \alpha_2 \frac{\mathrm{d}}{\mathrm{d}t}\left(\theta_1^2 + \theta_2^2 + \theta_1\theta_2\right)$$

$$I_3 = A_3 + B_3\theta_2 + C_3\theta_3 + D_3\theta_2^2 + E_3\theta_3^2 + F_3\theta_2\theta_3 + \alpha_3 \frac{\mathrm{d}}{\mathrm{d}t}\left(\theta_2^2 + \theta_3^2 + \theta_2\theta_3\right).$$

where, A_i, B_i, D_i, E_i, F_i, and C_j with $1 \le i \le 3$ and $2 \le j \le 3$ are constants whose values depend on the physical and physiological parameters of the skin layers as listed in Table 2. As the next step to the finite element method, we differentiate I_1, I_2, and I_3 concerning θ_0, θ_1, and θ_2 and set $\frac{\mathrm{d}I}{\mathrm{d}\theta_i} = 0$, for $i = 0,1,2$. On simplification, we arrive at the system of equations in matrix form as

$$\boldsymbol{P}\boldsymbol{\theta} = \boldsymbol{R} \tag{9}$$

Equation (9) represents the system of equation in the steady state case. Where,

$$\boldsymbol{P} = \begin{pmatrix} 2D_1 & F_1 & 0 \\ F_1 & 2(D_2 + E_1) & F_2 \\ 0 & F_2 & 2(D_3 + E_2) \end{pmatrix}, \quad \boldsymbol{\theta} = \begin{pmatrix} \theta_0 \\ \theta_1 \\ \theta_2 \end{pmatrix}, \quad \boldsymbol{R} = \begin{pmatrix} -B_1 \\ -B_2 \\ -C_2 - B_3 - F_3\theta_3 \end{pmatrix}$$

6. Numerical Results and Discussion

The threshold value of metabolic rate during cycling is 7163.97 w/m³. The physical and physiological parameter values used in the numerical simulation model are listed in Table 1 and Table 3, respectively.

Table 3. Parameter values used in model [18].

(a)

Parameter	L_A	K_1	K_2	K_3	c_1	c_2	c_3
Values	2.42×10^6	0.209	0.314	0.418	3469.4	1588.4	1588.4
Units	J/kg	w/m˚C	w/m˚C	w/m˚C	J/kg˚C	J/kg˚C	J/kg˚C

(b)

Parameter	M_2	M_3	ρ_1	ρ_2	ρ_3	h
Values	1254	1254	1000	1000	1000	6.27
Units	w/m³˚C	w/m³˚C	kg/m³	kg/m³	kg/m³	w/m²˚C

In general, the atmospheric temperature is below the body's core temperature, so the tissue temperature rises from the skin surface towards the body's core temperature. Therefore, we consider the tissue temperature $\theta(x,0)$ in a linear order given by the following equation

$$\theta(x,0) - \theta_0 = \phi x \tag{10}$$

The body feels comfortable when the operative temperature ranges from 23˚C to 27˚C for fully non-naked people, who are either resting or exercising [19]. Therefore, the skin temperature is considered as 24.91˚C [19]. The value of ϕ use in Equation (10) is 1535.79 that obtained after using $\theta_0 = 24.91^\circ\text{C}$ at $x = 0$, and $\theta_b = 39.5^\circ\text{C}$ at $x = L_3$ during cycling.

Temperature Results

The temperature of the epidermis, dermis, and subcutaneous tissue during cycling is measured in one dimension, in the steady state case at ambient temperatures 15˚C, 25˚C, 35˚C, and sweat evaporation rates 0 kg/m² s, 0.00002 kg/m² s, 0.00004 kg/m² s. The results were simulated in graphs and are listed in a table.

1) Effect of Ambient Temperatures

Figures 4-6 show that the subcutaneous tissue temperature is higher than the epidermis and dermis layer temperatures at each ambient temperature during cycling, while maintaining the sweat evaporation rate constant. This causes the epidermis to be in contact with the surrounding and subcutaneous tissue connected to the body core. If the body cannot produce sweat (an unhealthy body) and the environmental temperature is nearly equal to or more than body core temperature, in this situation, the epidermis and dermis layer temperature becomes higher than subcutaneous tissue temperature due to a fixed body core temperature, which is shown in Figure 4.

Figures 4-6 show that the subcutaneous tissue temperature is higher than the epidermis and dermis layer temperatures at each ambient temperature during cycling, while maintaining the sweat evaporation rate constant. This causes the epidermis to be in contact with the surrounding and subcutaneous tissue connected to the body core.

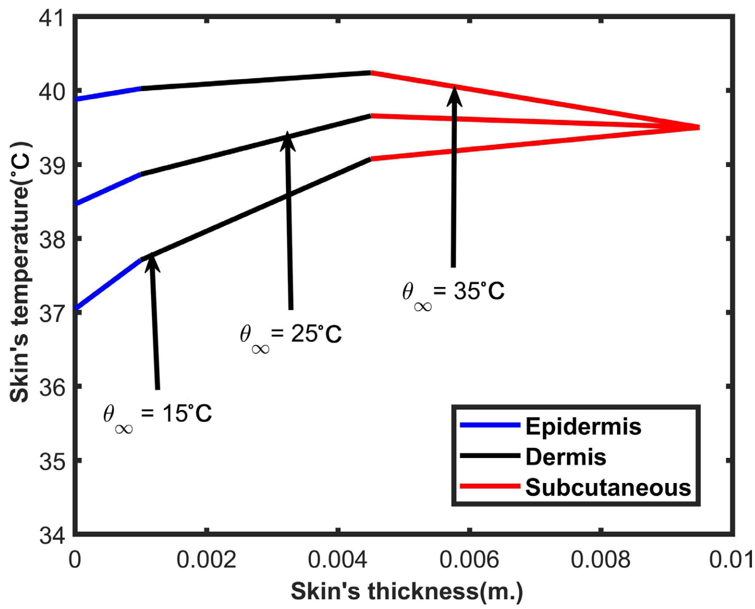

Figure 4. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at $\theta_\infty = 15^\circ\text{C}$, $\theta_\infty = 25^\circ\text{C}$, $\theta_\infty = 35^\circ\text{C}$ and $E = 0\ \text{kg/m}^2 \cdot \text{s}$ during cycling.

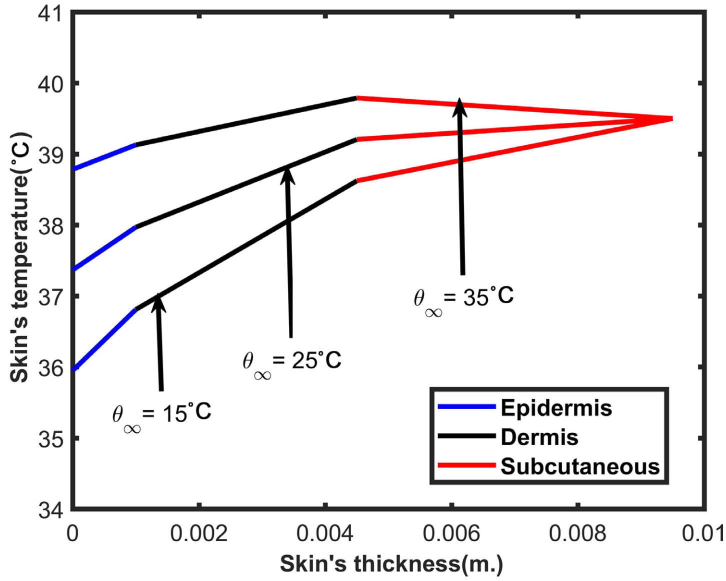

Figure 5. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at $\theta_\infty = 15^\circ\text{C}$, $\theta_\infty = 25^\circ\text{C}$, $\theta_\infty = 35^\circ\text{C}$ and $E = 0.00002\ \text{kg/m}^2 \cdot \text{s}$ during cycling.

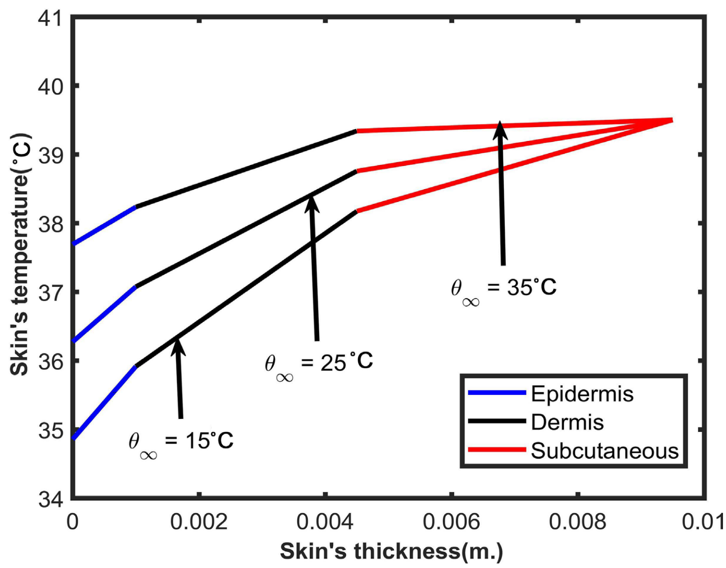

Figure 6. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at $\theta_\infty = 15^\circ\text{C}$, $\theta_\infty = 25^\circ\text{C}$, $\theta_\infty = 35^\circ\text{C}$ and $E = 0.00004\ \text{kg/m}^2 \cdot \text{s}$ during cycling.

The steady-state temperatures of the epidermis, dermis, and subcutaneous tissue were simulated at ambient temperatures $\theta_\infty = 15^\circ\text{C}, 25^\circ\text{C}, 35^\circ\text{C}$ during cycling. These results show that the temperature of each skin layer was higher at 35˚C than at 15˚C and 25˚C at a constant sweat evaporation rate. This is because the body absorbs more energy from the atmosphere at high ambient temperatures through the outer skin surface and more affected epidermis than the dermis and subcutaneous tissue.

2) Effect of Sweat Evaporation

From Figures 7-9, it is observed that each skin layer temperature is higher in the case without sweating than in the case with sweating during cycling. The body loses heat energy in the form of sweat, controls the temperature, and maintains thermoregulation. These results indicate that the temperature distribution in the human body is affected by sweat evaporation.

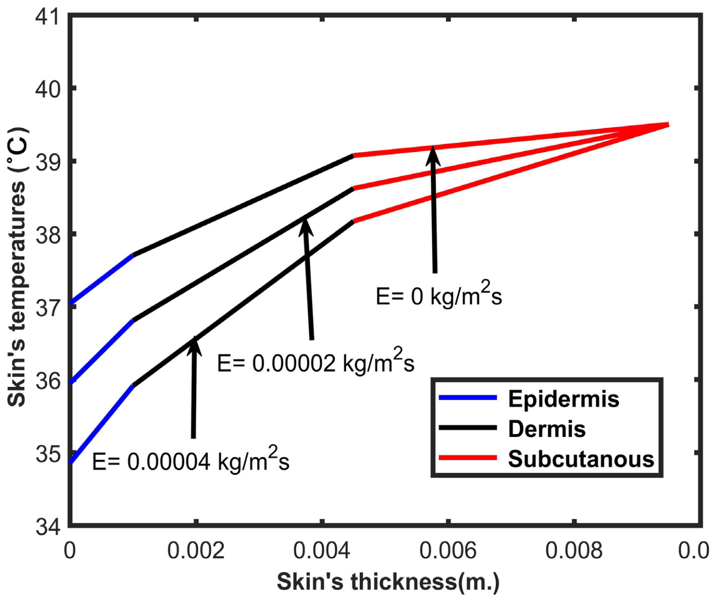

Figure 7. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at E = 0 kg/m^2 s, E = 0.00002 kg/m^2 s, E = 0.00004 kg/m^2 s, and $\theta_\infty = 15^\circ\text{C}$ during cycling.

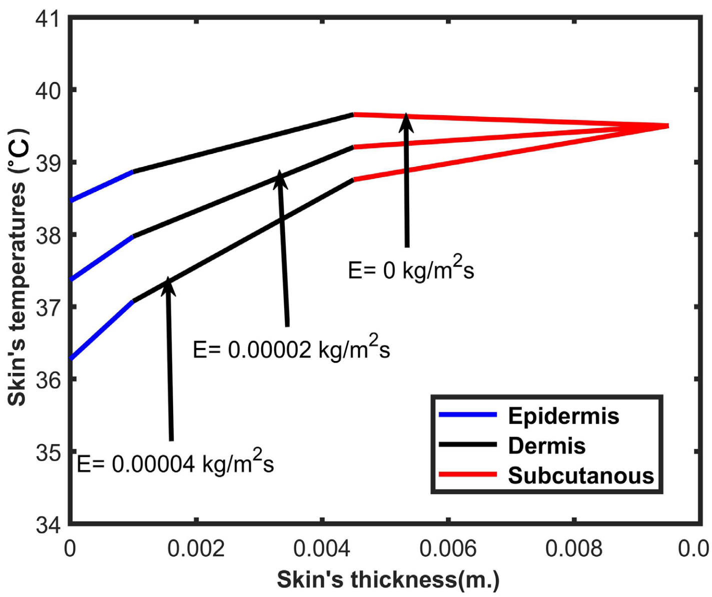

Figure 8. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at E = 0 kg/m^2 s, E = 0.00002 kg/m^2 s, E = 0.00004 kg/m^2 s, and $\theta_\infty = 25^\circ\text{C}$ during cycling.

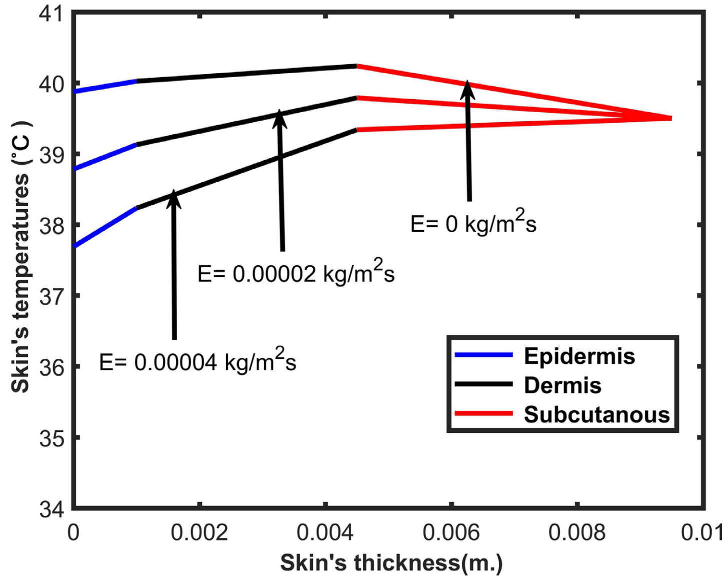

Figure 9. Estimation of epidermis, dermis, and subcutaneous tissue temperatures at E = 0 kg/m^2 s, E = 0.00002 kg/m^2 s, E = 0.00004 kg/m^2 s, and $\theta_\infty = 35^\circ\text{C}$ during cycling.

Table 4 shows the steady temperature of the skin layers during different exercises at various ambient temperatures. The temperature of each skin layer was higher at a high ambient temperature, with no sweat evaporation from the body.

Table 4. Steady state temperature range of epidermis, dermis, and subcutaneous tissue at $\theta_\infty = 15^\circ\text{C}, 25^\circ\text{C}, 35^\circ\text{C}$, with sweat evaporation rates E = 0 kg/m^2 s,0.00002 kg/m^2 s,0.00004 kg/m^2 s during cycling.

Ambient Temp. (θ_∞) (˚C)	Sweat Evaporation Rates (E) kg/m^2 s	Epidermis Temperature (˚C)	Dermis Temperature (˚C)	Subcutaneous Temperature (˚C)
15	0	37.07 - 37.70	37.70 - 39.07	39.07 - 39.50
25	0	38.48 - 38.86	38.86 - 39.66	39.66 - 39.50
35	0	39.88 - 40.02	40.02 - 40.24	39.24 - 39.50
15	0.00002	35.95 - 36.81	36.81 - 38.62	38.62 - 39.50
25	0.00002	37.37 - 37.97	37.97 - 39.20	39.20 - 39.50
35	0.00002	38.78 - 39.13	39.13 - 39.79	39.79 - 39.50
15	0.00004	34.85 - 35.91	35.91 - 38.17	38.17 - 39.50
25	0.00004	36.27 - 37.07	37.07 - 38.75	38.75 - 39.50
35	0.00004	37.69 - 38.23	38.23 - 39.34	39.34 - 39.50

7. Conclusions

The model's results demonstrate that the temperature of each skin layer increases because of the generation of huge metabolic energy by the body during cycling.

The temperature of the skin layers also increases with increasing ambient temperatures. Because the body receives a large amount of heat energy at ambient temperature. However, owing to the upper limit of the metabolic heat generation rate of the body, the body generates sweat and controls body temperature. This revealed that sweat evaporation plays a substantial role in thermoregulation in the body during cycling.

Previously, researchers developed models for temperature distribution in the human dermal part that did not determine the metabolic heat generation rate during cycling. Therefore, this model is prepared for a realistic temperature distribution in the dermal parts of the human body owing to the effect of metabolic rate and ambient temperature. The high temperature of the body is controlled by the release of sweat during cycling. Therefore, this study will be helpful in understanding the body temperature during various exercises. This model also supports the development of temperature distribution models for moderate and high-intensity exercises such as wrestling players, mountain climbers, hikers, painters, and wood cutters, based on their physical and physiological characteristics.

Author Contributions

First author, Dev Chandra Shrestha: Conceptualization, methodology development, investigation, data collection, original draft writing, manuscript editing, computational support, and visualization. Co-author, Saraswati Acharya: Supervision, editing, computational support, and visualization.

Data Availability Statement

Data supporting this research article are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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