Three Dimensional Finite Difference Model to Study the Thermal Stress in Peripheral Regions of Human Limbs Immediately after Physical Exercise

Babita kumari and Neeru Adlakha
Department of Applied Mathematics and Humanities, S.V. National Institute of Technology, Surat Gujarat-395007, India
Email: {babitak54, neeru.adlakha21}@gmail.com

Abstract—**The physical exercise imposes challenges on the human thermoregulatory system, as heat exchange between body and environment is substantially impaired which can lead to decrease in performance and increased risk of heat illness. In view of above a three dimensional finite difference model is proposed to study the effect of physical exercise on temperature distribution in peripheral regions of human limbs under moderate and hot climatic conditions. Human limb is assumed to have cylindrical cross section. The peripheral regions of human limbs is divided into three natural components namely epidermis, dermis and subdermal tissues. The model incorporates the effect of important physiological parameters like blood mass flow rate, metabolic heat generation, and thermal conductivity of the tissues. Appropriate boundary conditions have been framed based on the physical conditions of the problem. Explicit Finite Difference Method (EFDM) has been employed along time and spatial variable to obtain the solution. The numerical results have been used to obtain the temperature profiles in the region immediately after exercise for an unsteady state case. The results have been used to study the thermal stress caused by the different intensities of physical exercise.**

***Index Terms*—metabolic heat generation, blood mass flow rate, thermal conductivity, finite difference method**

I. Introduction

The physical exercise is one of the environments where human thermoregulatory functions are critical for survival and sustenance of work [1]. The exertion of physical exercise poses challenges to thermoregulatory system due to substantial increase in metabolism. During high intensity physical exercise the body core temperature can increase from 37^0C at rest to > 42^0C, which can damage cellular cytoskeleton and impair the functions of organs and central nervous system. Therefore, understanding of temperature distribution in human body tissues due to physical exercise is important for protecting the sportsmen, military persons and labour intensive workers from heat injury and other disorders caused due to physical exertion [1]-[3]. The thermoregulatory system of human body maintains the body core temperature at almost uniform temperature i.e. 37^0C which is essential for maintaining the structure and functions of human body organs. This thermoregulation is based on balance between metabolic heat generation within the body cells and heat loss from the body to the environment by the conduction, convection, radiation and evaporation. The heat transport from body core to the body surface takes place through peripheral region of human body by conduction and perfusion of blood [4], [5]. Thus the peripheral region of human body namely Skin and Subcutaneous Tissues (SST) is the medium of interaction between the body and the environment. The peripheral region is a non homogenous medium consisting of three natural layers namely epidermis, dermis and subdermal tissue. The properties likes, blood flow, metabolic heat generation and thermal conductivity are found to be different in these three layers [6], [7].

The metabolic activity varies between 1 to 2.9 times of the normal metabolic activity during light intensity activities like sleeping, watching television, writing, typing and slow walking (2.5mph) etc. At moderate intensity activities like bicycling, home exercise, walking (3.5mph) etc, the metabolic activity is 3 to 6 times of that in normal conditions at rest. For high and vigorous intensity activities like jogging, running, roping jumping etc the metabolic activity varies from 6 to 10 times of that in normal conditions at rest. In the same way blood flow is 1 to 2 times for moderate intensity activities and 2 to 4 times of that at rest during vigorous intensity activities [8], [9].

Earlier, experimental investigations were carried out by Patterson [10] to determine temperature profiles in the human peripheral regions. Some theoretical investigations have been carried out during the last few decades by Cooper and Trezek [11], Chao *et al.* [12], Saxena *et al.* [13] and Saxena and Pardasani [14] to study temperature distribution in the SST region using analytical and numerical techniques. These investigations were performed under normal environmental and

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physiological conditions. Also attempts have been made by Pardasani and Adlakha [15] and Agrawal, Adlakha and Pardasani [6], [7] to study problems involving abnormalities like tumors in SST regions of a human body. Khanday and Saxena [16] developed a model to study the effect of body fluid on temperature distribution in different skin and subcutaneous tissues layers and also to study the cold related problems [17] associated with dermal layers in human body. Gurung, Saxena and Adhikary [18], [19] used quadratic shape functions in variational finite element approach to study the temperature distribution in human dermal parts for one dimensional unsteady case. Some models have been developed by Pardasani and Adlakha [20] for temperature variation in human limbs for one and two dimensional steady state cases under normal physiological and environmental conditions. Agrawal *et al.* [4], [5] have developed three dimensional models to study temperature distribution in human limbs. Kumari and Adlakha [8], [21]-[23] have studied temperature distribution in human peripheral regions due to physical exercise for a one dimensional unsteady state case. Torii, Yamasaki and Nakayama [25] studied the effect of exercise on fall in skin temperature during initial muscular work in ten healthy men. Lim, Byrne and Lee [1] has also studied the human thermoregulation during exercise and the measurement of body temperature in clinical and exercise settings. But no attempt is reported in the literature for the study of effect of different intensities of physical activity on three dimensional temperature distribution in human body organs under moderate and hot climatic conditions.

Here a finite difference model is proposed to study the effect of light, moderate and vigorous intensity activities on temperature distribution in peripheral region of human limbs at moderate and high atmospheric temperatures. A human limb is assumed to be of circular cross section. The model is developed for a three dimensional unsteady state case. The outer surface of the limb is assumed to be exposed to the environment and appropriate boundary condition is incorporated.

II. MATHEMATICAL FORMULATION

The heat flow in human body tissues is governed by the following partial differential equation (Perl) [24].

$$\rho\bar{c}\left(\frac{\partial T}{\partial t}\right) = Div(K.gradT) + m_b c_b (T_A - T) + S \qquad (1)$$

The first, second and third term on the right-hand side of equation (1) are, respectively, the Fick's law of diffusion, Fick's perfusion principle and rate of metabolic heat generation. Here, ρ, $\bar{c}$, K and S respectively, denote the density, specific heat, thermal conductivity and rate of metabolic heat generation in tissues. T and T_A denote the tissue and arterial blood temperature, respectively. Also, m_b, and c_b, are the blood mass flow rate and specific heat of the blood respectively and $M = m_b c_b$.

The mathematical model of equation (1) can be expressed in polar cylindrical coordinates for three dimensional unsteady state case as given below,

$$\rho\bar{c}\left(\frac{\partial T}{\partial t}\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(Kr\frac{\partial T}{\partial r}\right) + \left(\frac{K}{r^2}\frac{\partial^2 T}{\partial \theta^2}\right) + K\left(\frac{\partial^2 T}{\partial z^2}\right) + m_b c_b (T_A - T) + S \qquad (2)$$

Using Explicit Finite Difference Method in (2) we get

$$\rho\bar{c}\left(\frac{T^{n+1}_{i,j,k} - T^n_{i,j,k}}{\Delta t}\right) = K\left[\begin{array}{l}\left(\frac{T^n_{i-1,j,k} - 2T^n_{i,j,k} + T^n_{i+1,j,k}}{(\Delta r)^2}\right) + \left(\frac{T^n_{i+1,j,k} - T^n_{i,j,k}}{r(\Delta r)}\right) \\ + \left(\frac{T^n_{i,j-1,k} - 2T^n_{i,j,k} + T^n_{i,j+1,k}}{(r\Delta\theta)^2}\right) + \left(\frac{T^n_{i,j,k-1} - 2T^n_{i,j,k} + T^n_{i,j,k+1}}{(\Delta z)^2}\right)\end{array}\right] + M(T_b - T^n_{i,j,k}) + S \qquad (3)$$

Simplifying (3) we have

$$\begin{aligned} T^{n+1}_{i,j,k} &= T^n_{i,j,k} + \bar{r}_1(T^n_{i-1,j,k} - 2T^n_{i,j,k} + T^n_{i+1,j,k}) + \bar{r}_2(T^n_{i+1,j,k} - T^n_{i,j,k}) \\ &+ \bar{r}_3(T^n_{i,j-1,k} - 2T^n_{i,j,k} + T^n_{i,j+1,k}) + \bar{r}_4(T^n_{i,j,k-1} - 2T^n_{i,j,k} + T^n_{i,j,k+1}) \\ &+ \bar{r}_5(T_b - T^n_{i,j,k}) + \bar{r}_6 \end{aligned} \qquad (4)$$

Where,

$$\bar{r}_1 = \frac{k_i\Delta t}{\rho\bar{c}(\Delta r)^2}, \bar{r}_2 = \frac{k_i\Delta t}{\rho\bar{c}r(\Delta r)}, \bar{r}_3 = \frac{k_i\Delta t}{\rho\bar{c}r^2(\Delta\theta)^2}, \bar{r}_4 = \frac{k_i\Delta t}{\rho\bar{c}(\Delta z)^2}, \bar{r}_5 = \frac{m_i\Delta t}{\rho\bar{c}}, \bar{r}_6 = \frac{s_i\Delta t}{\rho\bar{c}}$$

i= 1,2,...9 , j =0...2π, n=0,1,2,... k= 0, 2,...10

The outer surface of the skin is exposed to the environment and the heat loss from the outer skin surface to the environment takes place by conduction, convection, radiation and evaporation. Therefore, the boundary condition at the outer surface can be written as [2]-[4]:

$$-K\left.\frac{\partial T}{\partial r}\right|_{r=r_9=5.8} = h(T - T_a) + LE \quad at\ x = 0, t > 0 \qquad (5)$$

Where h is the heat transfer coefficient, T_a is atmospheric temperature; L and E are respectively the latent heat and rate of sweat evaporation. The body core which forms the inner boundary is maintained at a uniform temperature ie 37^0C. Therefore, the inner boundary condition is prescribed as given below [4], [23]

$$T(r_0, \theta, z, t) = T_b = 37^0C \quad at\ r = r_0\ and\ t > 0 \qquad (6)$$

Where T_b is the body core temperature, r_0 is the radius of inner core of the limb.

The major heat flow takes place along radial direction of the limb as the radial distances from core of the limb to the outer surface of the limb are very small (few millimetres) as compared to the axial distances. Therefore, the temperature gradient along axial direction will be negligible as compared to the temperature gradient along radial direction of the limb near the trunk. Therefore the following boundary condition is imposed.

$$\frac{\partial T}{\partial n} = 0 \quad at z = a,\ 0 \le \theta \le 2\pi,\ r_0 \le r \le r_8,\ t > 0 \qquad (7)$$

Further the other end of the limb is assumed to be perfectlyinsulated and therefore following boundary condition is imposed.

$$\frac{\partial T}{\partial n}=0 \qquad at\, z=b,\ 0\le\theta\le 2\pi,\ r_0\le r\le r_8,\ t>0 \tag{8}$$

At time t=0, the limb is assumed to be insulated and therefore the following initial condition is imposed.

$$T(r,\theta,z,0)=T_b, r_0\le r\le r_8,\ 0\le\theta\le 2\pi\ and\ a\le z\le b \tag{9}$$

The finite difference equation for equation (5) is given by

$$T_{i,j}^{n+1}=AT_{i,j}^{n}+BT_a-LE \tag{10}$$

Where, $A=(1-\frac{h.\Delta t}{K}), B=\frac{h.\Delta t}{K}$

III. Discretization of the Region

Now the peripheral region of the limb is divided into eight layers with radius r0, r1, r2, r3, r4, r5, r6, r7 and r8. The outermost layer is the epidermis. Below the epidermis are the three layers of dermis followed by four layers of sub-dermal tissues. The innermost part is the limb core consisting of bone, muscles, large blood vessels etc. These layers have been further discretized into 432 nodes. The angular and radial points of each element are the nodes as shown in Figure 1 [5], [6].

The finite difference mesh for circular region is shown in Fig. 1.

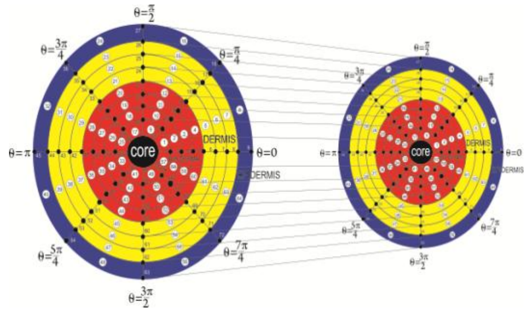


Figure 1. Circular cross-section of peripheral regions in a human limb.

The assumptions regarding K, M and S are taken as given below:

Sub dermal Tissues ($r_0\le r<r_4$): The density of blood vessels is almost uniform in the subdermal tissues. The blood flow, metabolic activity and thermal conductivity [13], [21] are found to be highest and almost constant in subdermal tissues of the peripheral region. Thus in the subdermal tissues the values of K, M and S are taken as constants as given below:

K_i= Ks= Constant, M_i=m, S_i=s i=0(1)4

Dermis ($r_4\le r<r_7$): The density of blood vessels increases as we go down the dermis and it becomes almost uniform in subdermis tissues. The blood flow, metabolic activity and thermal conductivity [13], [21] are maximum in subdermal tissues and minimum in epidermis. Thus we assume the values of these biophysical parameters in dermis as average of that in epidermis and subdermal tissues. Thus we take

K_i= (K_s+ K_e)/2 , M_i=m/2, S_i=s/2 i=4(1)7

Epidermis ($r_7\le r\le r_8$): As there are no blood vessels in epidermis, there is no blood flow and almost negligible metabolic activity in epidermis. The epidermis consists of mainly dead cells with lowest thermal conductivity among the three layers. Thus we take

K_e= Constant, M_i=0, S_i=0 i=7, 8

Here r_i is the radius of the layers.

In the present problem, it is assumed that the subject was doing physical exercise and comes to rest at time t=0. Thus the blood flow and metabolic activity will be maximum at t=0 and will start diminishing as t increases and will approach their minimum normal value as t→∞. So the following exponential variation with respect to time is assumed for m and s [22].

m(t)=m_{max}, where, t=0
m(t)=m_{min}, for t=∞
also, s(t)= s_{max}, for t=0 and s(t)= s_{min}, for t=∞

$$m(t)=C_1+C_2e^{-\lambda_1 t}, \lambda_1\ge 0 \tag{11}$$

$$s(t)=C_3+C_4e^{-\lambda_2 t}, \lambda_2\ge 0 \tag{12}$$

Where, λ_1 , λ_2 , C_1, C_2, C_3 and C_4 are the constants respectively.

A computer program in MATLAB 7.11 has been developed to find numerical solution to the entire problem.

IV. Result and Discussions

The values of biophysical parameters like metabolic heat generation, thermal conductivity, blood mass flow rate, baseline temperature, baseline fitness etc will vary from person to person based on environmental conditions and their demographic characteristics like ethnicity, gender, age, clothing etc. The particular values of these biophysical parameters with respect to the environmental conditions and demographic characteristics of the subjects under study can be substituted in the model to obtain the numerical results. For the purpose of illustration the computations have been performed for two cases of atmospheric temperatures T_a= 23^{0}C and 33^{0}C. The values of M, S and E have been taken as given in Table I [6], [21].

TABLE I. Numerical Values of Physical and Physiological Parameters

Atmospheric Temp T_a (˚C)	$\bar{s}$ (Cal/cm^3-min)	$\bar{m}$ =$m_b c_b$ (Cal/cm^3- min˚C)	E (X10^{-3}Kg.m^{-2}S^{-1})
23	0.018	0.018	0,0.24,0.48
33	0.018	0.0315	0.24,0.48,0.72

Here $\bar{m}$ and $\bar{s}$ are rates of blood mass flow and metabolic activity in tissues when body is at complete rest. The values of other parameters are taken as given below [2], [15], [18].

h = 0.009 cal/cm^2 – min, L=579 cal/gm, K_e = 0.030 cal/cm- min˚C for Epidermis, K_d = 0.045 cal/cm- min˚C for Dermis, K_s =0.060 cal/cm- min˚C for Sub Dermmal

part, T_b= 37^0C, T = 36^0C, $\boldsymbol{\rho}$ = 1.090 gms/cm^2, $\bar{c}$ =0.830 cal/gm-˚C.
r_0=5cm, r_1=5.1cm, r_2=5.2cm, r_3=5.3cm, r_4=5.4cm, r_5=5.5cm, r_6=5.6cm, r_7=5.7cm and r_8=5.8cm, z=0 to 10cm.

The graphs have been plotted for three cases of physical exercise and accordingly the values of blood flow and metabolic activity are taken as given below [21]:

Case I Light intensity physical exercise

$$m_{\min} = \overline{m} \ , \qquad s_{\min} = \bar{s}$$
$$m_{\max} = 1 \times \overline{m} \ , \ s_{\max} = 2.9 \times \bar{s}$$

Case II Moderate intensity physical exercise

$$m_{\min} = \overline{m} \ , \qquad s_{\min} = \bar{s}$$
$$m_{\max} = 2 \times \overline{m} \ , \ s_{\max} = 5.5 \times \bar{s}$$

Case III High/Vigorous intensity physical exercise

$$m_{\min} = \overline{m} \ , \qquad s_{\min} = \bar{s}$$
$$m_{\max} = 4 \times \overline{m} \ , \ s_{\max} = 10 \times \bar{s}$$

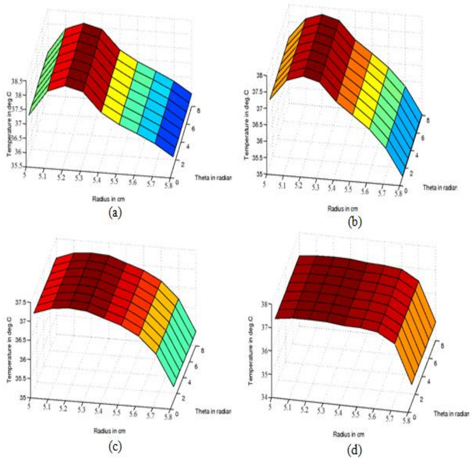


Figure 2. Spatial temperature distribution in peripheral region of human limbs for T_a=23^0C and E=0.24x10^{-3}gm/cm^2-min, θ=0, z=0, case I and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

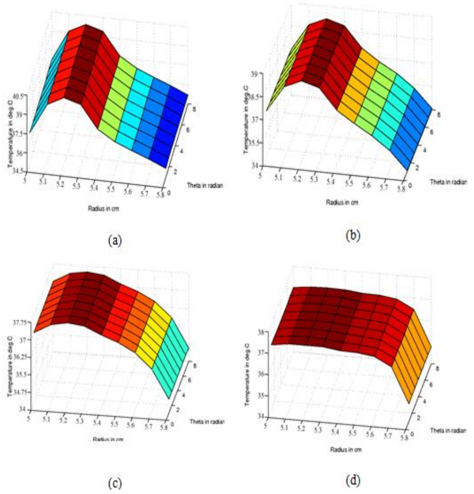


Figure 3. Spatial temperature distribution in peripheral region of human limbs for T_a=23^0C and E=0.24x10^{-3}gm/cm^2-min, θ=0, z=0 case II and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

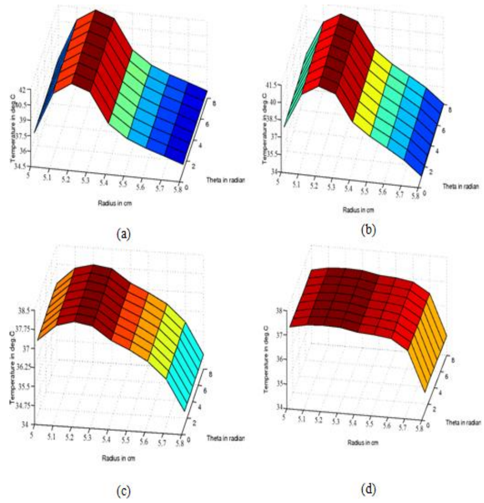


Figure 4. Spatial temperature distribution in peripheral region of human limbs for T_a=23^0C and E=0.24x10^{-3}gm/cm^2-min, θ=0, z=0 case III and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

In Figs. 2, 3 and 4, we observe that initially temperature is increasing and it falls down slowly along radial r and angular θ direction at different time levels and then it falls sharply and it achieves its steady state in 18 min. This is due to the exercise which causes changes in parameters like blood flow and metabolic activity in the peripheral region of human limb. We also observe that highest tissue temperature is 38.23^{0}C, 39.8^{0}C and 41.8^{0}C respectively for case I, II and III in these figures. The outer surface temperature at Ta=23^{0}C, z=0 and E=0.24x10^{-3} gm/cm^2-min in steady state is 34^{0}C.

In Figs. 5, 6 and 7, we observe that initially temperature is increasing and it falls down slowly along radial r and angular θ direction at different time levels and then it falls sharply and it achieves its steady state in 18 min. This is due to the exercise which causes changes in parameters like blood flow and metabolic activity in the peripheral region of human limb. We also observe that highest tissue temperature is 38.22^{0}C, 39.7^{0}C and 41.6^{0}C respectively for case I, II and III in these figures.

The outer surface temperature at Ta=33^{0}C, z=0 and E=0.48x10^{-3} gm/cm^2-min in steady state is 35.02^{0}C.

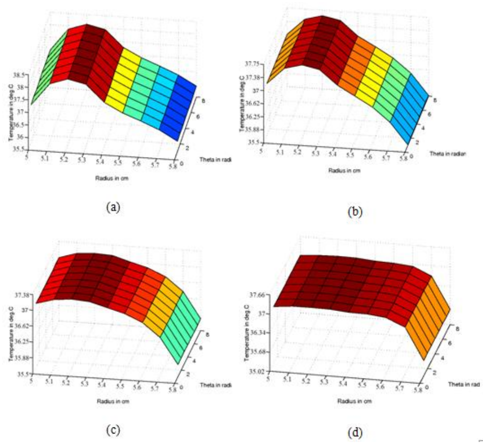


Figure 5. Spatial temperature distribution in peripheral region of human limbs for Ta=33^{0}C and E=0.48x10^{-3}gm/cm^2-min, θ=0, z=0 case I and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

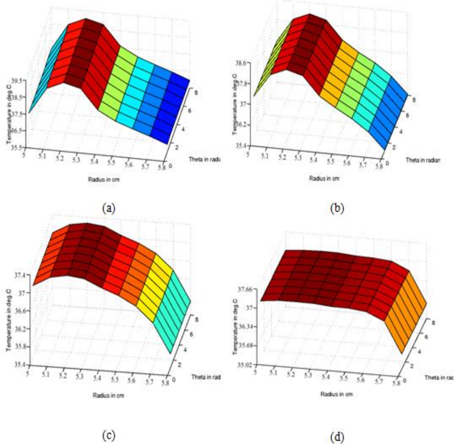


Figure 6. Spatial temperature distribution in peripheral region of human limbs for T_a=33^{0}C and E=0.48x10^{-3}gm/cm^2-min, θ=0, z=0 case II and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

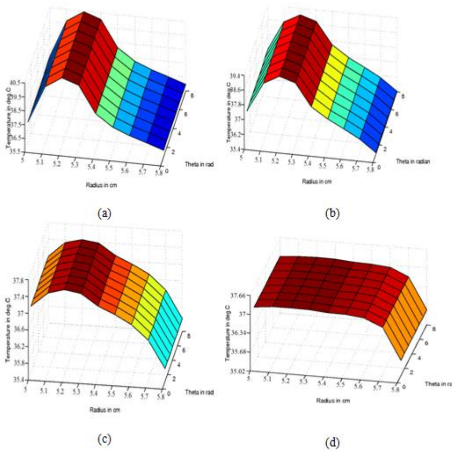


Figure 7. Spatial temperature distribution in peripheral region of human limbs for Ta=33^{0}C and E=0.48x10^{-3}gm/cm^2-min, θ=0, z=0 case III and (a) t=2min, (b) t=6min, (c) t=12min and (d) t=18min.

Fig. 8 shows difference in temperature distribution in peripheral regions of human limbs with and without physical exercise for T_a=23^{0}C and E= 0.24x10^{-3} gm/cm^2-min. Fig. 9 shows difference in temperature distribution in peripheral regions of human limbs with and without physical exercise for T_a=23^{0}C and E= 0.48x10^{-3} gm/cm^2-min. Fig. 10 shows difference in temperature distribution in peripheral regions of human limbs with and without physical exercise for T_a=33^{0}C and E= 0.48x10^{-3} gm/cm^2-min. Fig. 11 shows difference in temperature distribution in peripheral regions of human limbs with and without physical exercise for T_a=33^{0}C and E= 0.72x10^{-3} gm/cm^2-min. The peak temperature difference in figure 8 is 1.3^{0}C for case I, 2.4^{0}C for case II and 2.8^{0}C for case III. The peak temperature difference in figure 9 is 1.1^{0}C for case I, 2^{0}C for case II and 2.3^{0}C for case III. The peak temperature difference in figure 10 is 1.2^{0}C for case I, 2.2^{0}C for case II and 2.5^{0}C for case III. The peak temperature difference in figure 11 is 1^{0}C for case I, 2.1^{0}C for case II and 2.2^{0}C for case III. In these figures 8 to 11, the peak temperature difference increases with increase in intensity of physical exercise. Also the peak temperature difference (see figure 9 and 10) is higher at higher atmospheric temperature. Further the peak temperature difference is lower for higher rate of evaporation at same atmospheric temperature. The results obtained here are in the agreement with the physiological facts. No experimental and theoretical results are available for comparison with the present study.

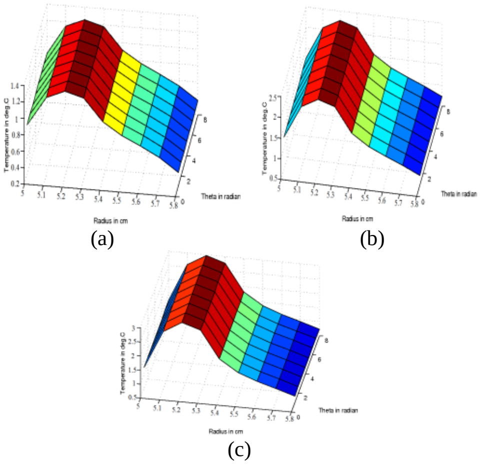


Figure 8. Difference in spatial temperature distribution in peripheral region of human limbs with and without physical exercise for T_a=23^{0}C and E=0.24x10^{-3}gm/cm^2-min at t=2min for (a) case I, (b) case II and (c) case III.

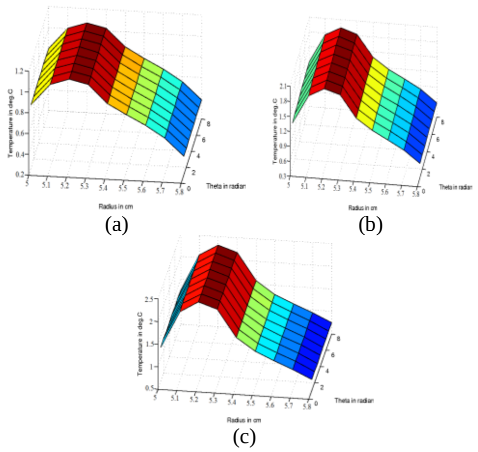


Figure 9. Difference in spatial temperature distribution in peripheral region of human limbs with and without physical exercise for T_a=23^{0}C and E=0.48x10^{-3}gm/cm^2-min at t=2min for (a) case I, (b) case II and (c) case III.

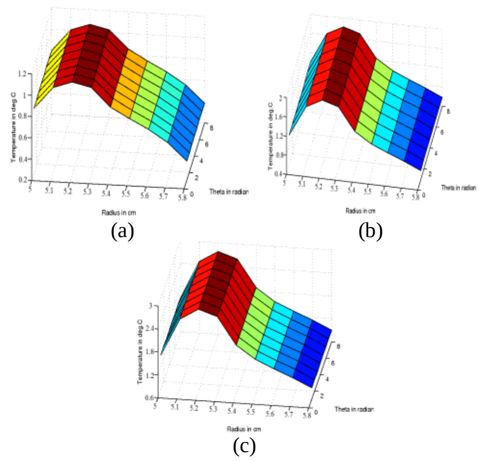
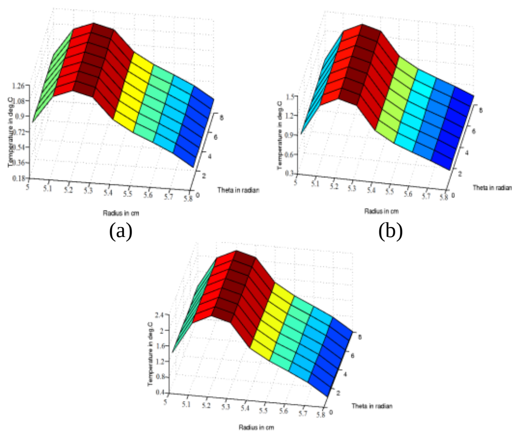


Figure 10. Difference in spatial temperature distribution in peripheral region of human limbs with and without physical exercise for T_a=33^{0}C and E=0.48x10^{-3}gm/cm^2-min at t=2min for (a) case I, (b) case II and (c) case III.



(a) (b) (c)

Figure 11. Difference in spatial temperature distribution in peripheral region of human limbs with and without physical exercise for $T_a=33^0$C and E=0.72x10^{-3}gm/cm^2-min at t=2min for (a) case I, (b) case II and (c) case III.

V. Conclusion

The three dimensional finite difference model is proposed and employed to study the thermal stress in peripheral regions of human limb immediately after exercise under moderate and hot climatic conditions. The proposed finite difference grid is able to effectively take care of non homogenous nature of the peripheral region. From the results it is concluded that the thermal stress increases with increase in intensity of physical exercise and maximum thermal stress occurs in the lower layer of peripheral regions and portion of limb near the trunk of the body. The thermal stress is high initially and diminishes within 18 minutes. The model gives us useful information regarding the magnitude of thermal stress, time period and spatial region in relation to the intensity of physical activity. The information generated from such models can be useful for the developing strategies regarding time period and intensity of physical activity and rest for labourers, sportsmen and military persons etc to protect them from harmful effects of thermal stress. Also the thermal information generated from such models can be useful to biomedical scientists in developing protocols for exploiting therapeutic effect of thermal stress to cure various diseases and physical exercise prescription for the healthy life style.

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Neeru Adlakha is presently working as an associate professor and Head in the Department of Applied Mathematics and Humanities at SVNIT Surat, India. She has supervised ten PhD students in the fields of Mathematics and Computational Biology, Bioinformatics and Computer Applications. She has about 17 years of teaching and research experience. Her current teaching and research interests are in the fields of Modeling and Simulation, Computational Cell Biology, Finite Element Methods, Numerical Methods, Bioinformatics, Data Mining, Optimization Techniques etc.

Babita Kumari did her bachelor of mathematics degree in 2003 from Jiwaji University, Gwalior, MP and master of mathematics (M.Sc) in 2005 from Jiwaji University, Gwalior, MP, India. She has completed her Ph.D. in applied mathematics in 2014 from S. V. National Institute of Technology, Surat, India. Her areas of interest are computational Biology, biomathematics, finite element method, finite difference method etc. She has published 6 research papers in International peer reviewed journals. She has presented 5 research papers in various national and international conferences. She is actively involved in teaching and research.