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One Dimensional Model to Study the Effect of Physical Exercise on Temperature Distribution in Peripheral Regions of Human Limbs

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Abstract

The purpose of the present investigation is to develop a numerical model to study the effect of physical exercise on temperature distribution in peripheral layers of circular shaped human limb. The model has been developed for a one dimensional unsteady state case. The model incorporates the effect of thermal conductivity, blood mass flow rate and rate of metabolic heat generation in the tissues. The outer surface of the limb is assumed to be exposed to the environment and heat loss takes place by conduction, convection, radition, and evaporation. Appropriate boundary conditions have been framed. The finite difference method is employed to compute the results foor two cases. (i) The subject comes to rest after doing physical exercise and (ii) the subject is periodically doing exercise and rest respectively. MATLAB 7.11 has been used to simulated the model and obtain numerical results.

Keywords: Metabolic heat generation, Blood mass flow rate, Thermal Conductivity, Finite Difference Model

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1 Introduction

Human body survives in cold and hot temperature, weather and environmental changes by skin and core temperature regulation. Survival in severe hot and cold environment means adjusting to very high and low temperatures quickly. The body core temperature is maintained at 98.6 degrees or 37 degree C. Activities like exercise and aerobics cause corresponding increase in energy production and body temperature: vasodilatation of blood vessels increases blood circulation leading to sweating and evaporation, bringing down skin and core temperature. In this way regulates its temperature [19, 28].

The peripheral region namely (Skin and Subcutaneous tissue) plays an important role in temperature regulation of the human or animal body which maintains the structure and function of the body organs. The skin consists of three layers namely epidermis, dermis and subcutaneous tissues. There are no blood vessels in the epidermis, so there is no blood flow and metabolic activity in this outermost layer. The density of the blood vessels increases as we go down to the dermis and becomes almost uniform in the layer below the dermis namely sub dermal tissues. A human body maintains its body core temperature at a uniform temperature under the normal atmospheric conditions [19, 20].

Metabolism is the chemical action by which the cells of an organism transform energy from one cell to another cell and maintain their identity. The factor which increases the chemical activity in the body also increases the metabolic heat generation rate. Some of these factors are shown below: i) Exercise ii) Shivering iii) Change in atmospheric temperature iv) Energy required for the daily activity. Heat is lost and gained, through convection, radiation, and conduction, while evaporation contributes only to heat loss. Even for humans, the standard thermodynamic laws of physics apply. The rate at which the body looses heat depends on the temperature difference between the skin and the environment. In the cold, therefore, the aim is to reduce the skin temperature as much as possible, whereas in the hot climate the skin temperature should be as high as possible [28]. When the human body is at rest, there is normal blood flow and metabolic activity but the influence of external pressure during exercises, running, jumping etc there is abnormal blood flow and metabolic activity.

Earlier experimental investigations were made by Patterson [1] to obtain temperature profiles in the SST region under normal physiological and environmental conditions. Some theoretical investigations have been carried out during the last few decades by Cooper and Trezek [27], Chao et al. [7], Saxena et al. [28, 29, 31], Mitchell et al. [6], Pardasani and Adlakha [11, 12], Pardasani and Saxena [23], Adlakha and Pardasani [1] and Agrawal et al [2, 5 ,6] to study temperature distribution in SST region under normal environmental and physiological conditions. Also attempts have been made by Saxena and Pardasani [30], Pardasani and Saxena [17], Pardasani and Adlakha [9, 10], Pardasani and Jas [8], Pardasani and Shakya [13, 14, 15] and Agrawa et al. [20, 21] to study problems involving abnormalities like tumors in SST regions of human body. Khanday and Saxena [24] developed a model to study the body fluid in different Skin and Subcutaneous Tissues layers and also to study the cold related problems associated with dermal layers in human body, Gurung, Saxena and Adhikary [4] used quadratic shape functions in Variational Finite Element approach to study the temperature distribution in human dermal parts for one dimensional unsteady case. Torri et al. [25] studied the changes in skin temperature during initial muscular work in ten healthy men, Lim et al. [3], Folk et al. [5] and Gisolfi and Mora [2] have also studied human thermoregulation during exercise and the measurement of body temperature in clinical and exercise settings.

From above literature survey , it is evident that very little attention has been paid to the study of temperature distribution in a human or animal body under thermal stresses due to physical exercise and various other physical and phsiological conditions. In order to determine the amount of rest required by subject after exercise, it is necessary to understand the temperature variation in human body under thermal stress caused by physical exercise. This thermal stress will depend on amount of physical exercise, environmental conditions, the baseline, fitness, baseline temperature and biophysical parameters of an individual depending on this demographic characteristics like ethnicity, sex, age, clothing etc. In view of a above an attempt has been made in this paper to develop a model of temperature distribution in peripheral regions of circular shaped human limbs during and immediately after physical exercise. Here the analysis is conducted for the one dimensional unsteady state case to study relationships among the temperature, the blood flow and metabolic activity during physical exercise. Initially it is assumed that the subject is doing exercise at time t=0 and then goes to state of rest for $t > 0$. Further it is assumed that skin surface is insulated at time t=0 and no heat loss takes place form outer surface of human body i.e initially temperature is 37°C, throughout the layers of skin. For t>0, the insulation is removed and heat loss takes place at the outer skin surface. The finite difference method is employed to obtain numerical solution.

2 Mathematical Formulation

The mathematical model for heat flow in body tissues for a one dimensional unsteady state case is as given below [32]:

$$\rho\bar{c}\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + m_b c_b \left(T_a - T\right) + S \tag{1}$$

Where ρ, $\bar{c}$, K and S are respectively the density, specific heat, thermal conductivity and rate of metabolic heat generation in tissues; m_b, c_b, and T_A are the blood mass flow rate, specific heat of the blood and arterial blood temperature respectively and M= $m_b c_b$. 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 [19, 20, 21, 22, 23]:

$$K\frac{\partial T}{\partial x} = h\left(T - T_a\right) + LEatx = 0, t > 0 \tag{2}$$

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°C. Therefore, the inner boundary condition is prescribed as given below [12]

$$T = T_b\ t \geq 0,\ x = b \tag{3}$$

Where T_b is the body core temperature and b is the thickness of the skin layers. It is assumed that at time t=0 the outer surface of the body is perfectly insulated. Thus, the initial condition is given by

$$T(x, 0) = T_b \tag{4}$$

In the present study it is assumed that the heat stress caused by physical exercise is not so much that it can disturb the body core temperature and therefore body core is maintained at a uniform temperature 37°C. The present study is performed for peripheral regions (SST) of circular shaped human limbs. The region has been divided into ten annular subregions with internal and outer radii equal to r_1 and r_{10} respectively. The SST region has been divided into three natural components epidermis, dermis and subdermal tissues. The assumptions regarding K, M and S are as given below:

Sub dermal ($r_1 \leq r < r_3$):

In the subdermal tissues the values of K, M and S are taken as constants as given below:

K_i= K_s= Constant, M_i=m, S_i=s i=1(1)3

Dermis ($r_3 \leq r < r_8$):

The density of blood vessels increases as we go down the dermis and it becomes almost uniform in subdermis tissues. Thus blood flow, metabolic activity and thermal conductivity 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)8

Epidermis ($r_8 \leq r \leq r_{10}$):

As there are no blood vessels in epidermis, there is no blood flow and almost negligible metabolic activity in epidermis. Thus we take

K_e= Constant, M_i=0, S_i=0 i=9,10

Here m and s are functions of time. K_e and K_s represent thermal conductivity in epidermis and subdermal tissues respectively. The finite difference mesh for circular region is shown in figure 1

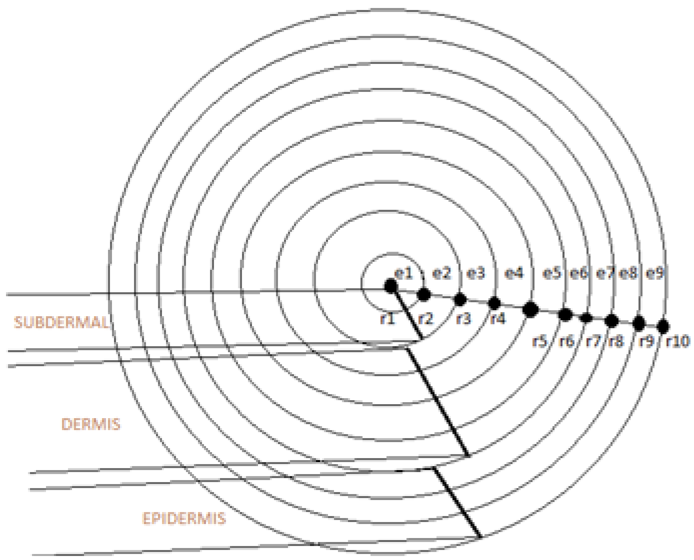

Figure 1: **Finite Difference mesh for circular region**

The study has been performed for two cases as mentioned below:

CASE 1

It is assumed that initially the human subject was doing physical exercise and he comes to rest at time t=0 so the blood flow and metabolic activity will be maximum at time t=0 and they will be go on decreasing as the time passes (ie for $t > 0$) and reach their normal values in steady state condition. Therefore as a special case we assume following exponential variation of blood mass flow rate and metabolic activity in SST region with respect to time:

m(t_0)=m_{max} where, t_0=0

m(t_α)=m_{min} t_α=∞

also, s(t_0)= s_{max} for $t_0 = 0$ and s(t_α)= s_{min} for t_α=∞

$$m(t) = C_1 + C_2 e^{-t} \tag{5}$$

$m_{max} = C_1 + C_2$

$m_{min} = C_1$

$$s(t) = C_3 + C_4 e^{-t} \tag{6}$$

Where, C_1, C_2, C_3 and C_4 are the constants which are determined by the conditions defined at t_0 and t_∞ respectively.

CASE 2

It is assumed that the human subject does a physical exercise for some period of time and then takes rest for a period of time and again repeats the cycle of physical exercise and rest during alternate periods. Thus the blood flow and metabolic activity also keeps on increasing and decreasing in alternate periods. In view of above as a special case the following periodic variation of blood mass flow rate and rate of metabolic heat generation with respect to time has been assumed.

m(t_0)=m_{max} where, t_0=0

m(t_α)=m_{min} t_α=∞

also, s(t_0)= s_{max} for $t_0 = 0$ and s(t_α)= s_{min} for t_α=∞

$$m(t) = C_1 sin(\pi/l)t + C_2 cos(\pi/l)t \tag{7}$$

$m_{max} = C_1 + C_2$

$m_{min} = C_1$

$$s(t) = C_3 sin(\pi/l)t + C_4 cos(\pi/l)t \tag{8}$$

Where, C_1, C_2, C_3 and C_4 are the constants which are determined by the conditions defined at t_0 and t_∞ respectively.

Here l is a period of time for which the subject does exercise and rest alternatively.

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

$$\rho\bar{c}\frac{\partial T}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(Kr\frac{\partial T}{\partial r}\right) + m_b c_b\left(T_a - T\right) + S \tag{9}$$

or

$$\rho\bar{c}\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial r^2} + \left(\frac{K}{r}\frac{\partial T}{\partial r}\right) + m_b c_b\left(T_a - T\right) + S \tag{10}$$

By using the Schmidt method, the diffusion equation evaluated at (i, n) grid point is given by [18]

$$(\frac{\partial T}{\partial t})_i^n = \alpha(\frac{\partial^2 T}{\partial x^2})_i^n \tag{11}$$

$$\frac{T_i^{n+1}-T_i^n}{\Delta t}=\alpha[\frac{T_{i-1}^n-2T_i^n+T_{i+1}^n}{\Delta x}] \tag{12}$$

where $R=\alpha\frac{\Delta t}{\Delta x}$ and simplifying
From (10) and (12) we get

$$\rho\bar{c}\frac{T_i^{n+1}-T_i^n}{\Delta t}=k_i[\frac{T_{i-1}^n-2T_i^n+T_{i+1}^n}{(\Delta r)^2}]+\frac{k_i}{r}[\frac{T_{i+1}^n-T_i^n}{(\Delta r)}]+M_i\left(T_A-T_i^n\right)+S_i \tag{13}$$

Simplifying (13) we have

$$T_i^{n+1}=(1-2r_1-r_2-r_3)T_i^n+(r_1+r_2)T_{i+1}^n+r_1T_{i-1}^n+(r_3T_b+r_4) \tag{14}$$

$i=1,2,3...10,\ n=0,1,2,...$
where, $r_1=\frac{\Delta tK_i}{(\Delta r)^2\rho\bar{c}}$, $r_2=\frac{\Delta t}{r\Delta r\rho\bar{c}}$, $r_3=\frac{\Delta tM_i}{\rho\bar{c}}$, $r_4=\frac{\Delta tS_i}{\rho\bar{c}}$
The outer boundary condition is given by

$$K\frac{\partial T}{\partial x}|_{r=r_{10}=5.9}=h\left(T-T_a\right)+LE \tag{15}$$

and
The inner boundary condition is given by

$$T=T_b\ for\ t\geq 0\ at\ r=r_0 \tag{16}$$

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

3 Numerical Results and Discussion

The computations have been performed for two cases of atmospheric temperatures T_a = 15°C and 23°C. The values of M, S and E have been taken accordingly from the table given below [4, 15, 20].

Table 1

Atm Temp) T_a (^oC)	**S** (Cal/cm^3min)	**M=m$_b$c$_b$** (Cal/cm^3min^oC)	**E** $\times 10^{-3}$ $(Kg.m^{-2}S^{-1})$
15	0.0357	0.003	0
23	0.018	0.018	0

The values of other parameters are taken as given below [4,15, 20].

h $=0.009 cal/cm^2 min$,**L** $=579$ cal/gm, $\mathbf{K}_e = 0.030\ cal/cm - min$°C for Epidermis, $\mathbf{K}_d = 0.045\ cal/cm{-}min$°C for Dermis, $\mathbf{K}_s = 0.060\ cal/cm{-}min$°C for Sub-dermmal part, $\mathbf{T}_b = 37$°C,ρ= $1.090 gm/cm^2$ and $\overline{c} = 0.830 cal/gm-$°C.

For a particular case of thickness of skin layers of human body we take the following values of $r_i (i = 1(1)10)$ radius r_1=5.0cm, r_2=5.1cm, r_3=5.2cm,r_4=5.3cm, r_5=5.4cm, r_6=5.5cm, r_7=5.6cm, r_8=5.7cm, r_9=5.8cm, r_{10}=5.9cm.

The results have been computed for two cases (i) A person was doing exercise initially and stops doing exercise at t=0 (ii) The person does exercise periodically with a period of l i.e he does exercise for period l and takes rest for period l alternatively. Graphs have been plotted between temperature and time for normal conditions and for subjects doing exercise.

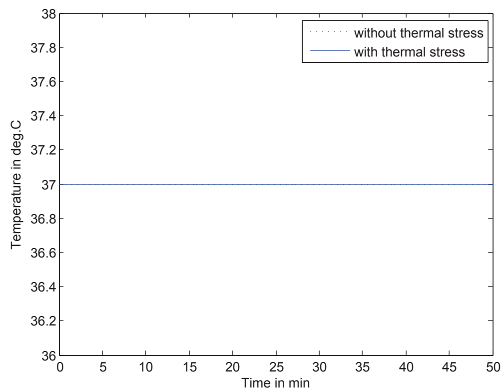

Figure 2: Graph between temperature T and time t for $\mathbf{r_1}$= 5.0cm representing boundary condition at $\mathbf{T_a} = \mathbf{15}$°C

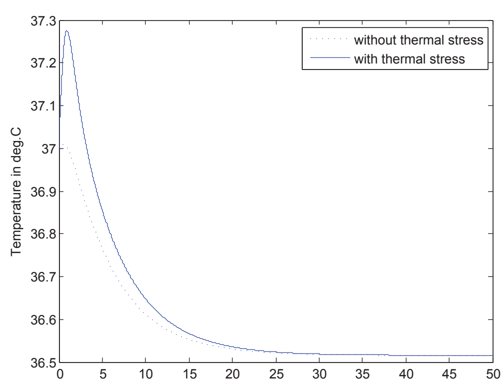

Figure 3: Graph between temperature T and time t for $\mathbf{r_2}$= 5.1cm representing boundary condition at $\mathbf{T_a} = \mathbf{15}$°C

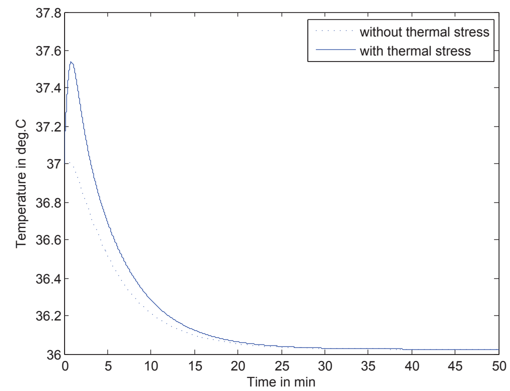

Figure 4: Graph between temperature T and time t for $\mathbf{r_3}$= 5.2cm representing boundary condition at $\mathbf{T_a} = \mathbf{15}$°C

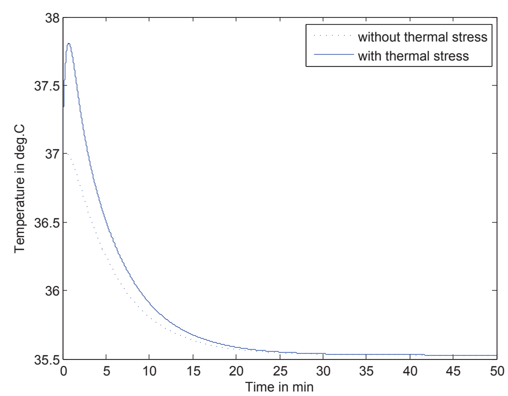

Figure 5: Graph between temperature T and time t for $\mathbf{r_4}$= 5.3cm representing boundary condition at $\mathbf{T_a} = \mathbf{15}$°C

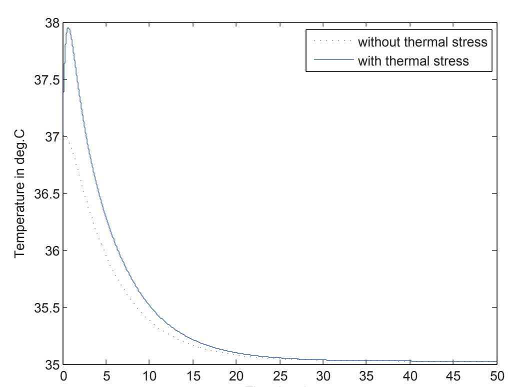

Figure 6: Graph between temperature T and time t for $\mathbf{r_5}$= 5.4cm representing boundary condition at $\mathbf{T_a} = \mathbf{15}$°C

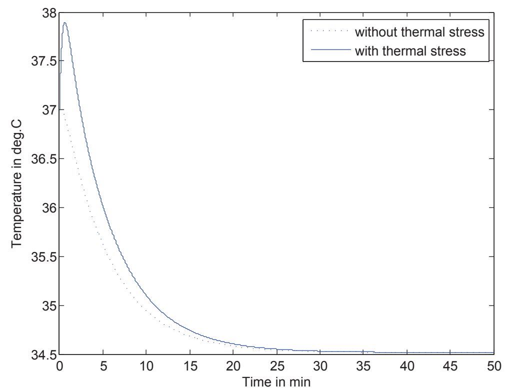

Figure 7: Graph between temperature T and time t for $\mathbf{r_6}$= 5.5cm representing boundary condition at $\mathbf{T_a = 15}$°C

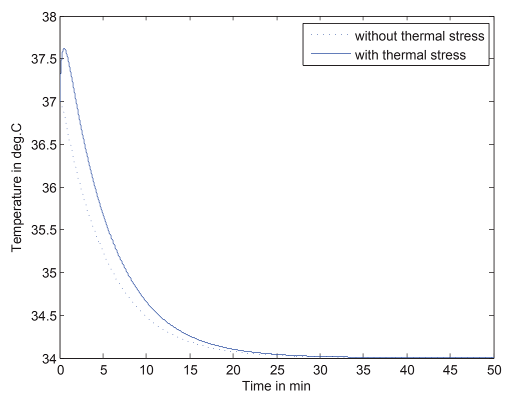

Figure 8: Graph between temperature T and time t for $\mathbf{r_7}$= 5.6cm representing boundary condition at $\mathbf{T_a = 15}$°C

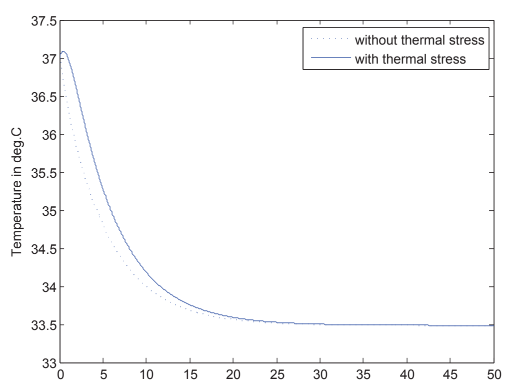

Figure 9: Graph between temperature T and time t for $\mathbf{r_8}$= 5.7cm representing boundary condition at $\mathbf{T_a = 15}$°C

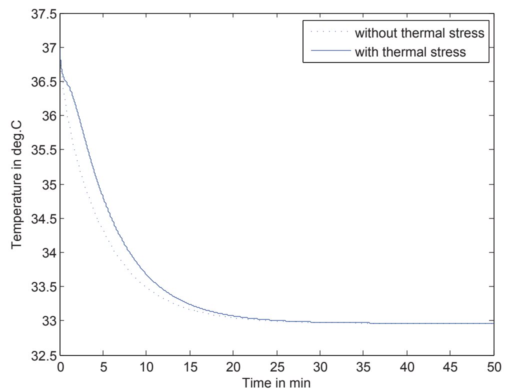

Figure 10: Graph between temperature T and time t for $\mathbf{r_9}$= 5.8cm representing boundary condition at $\mathbf{T_a = 15}$°C

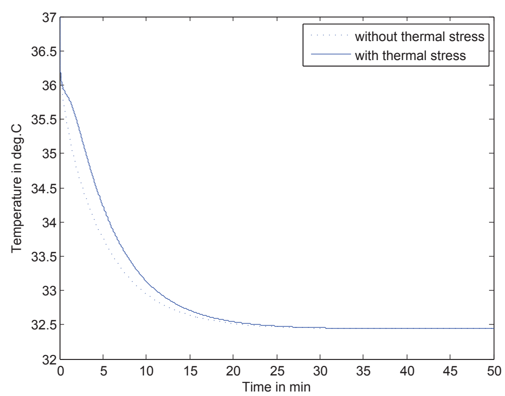

Figure 11: Graph between temperature T and time t for $\mathbf{r_10}$= 5.9cm representing boundary condition at $\mathbf{T_a = 15}$°C

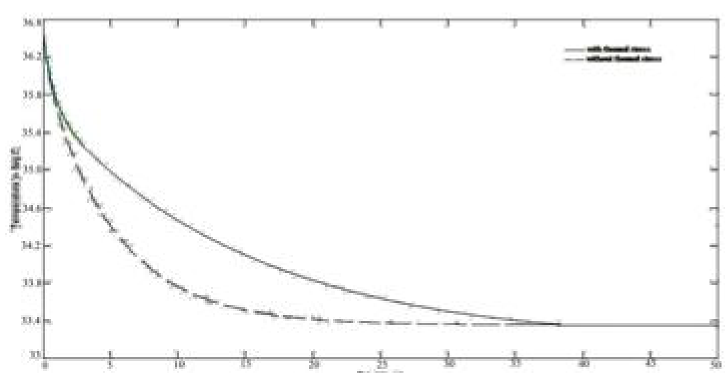

Figure 12: Graph between temperature T and time t for $\mathbf{r_10}$= 5.9cm representing boundary condition at $\mathbf{T_a = 23}$°C

CASE-1

The graphs have been plotted between temperature and time at different positions r_i=1(1)10 as shown in figures 2 to 12 at atmospheric temperature T_a = 15°C and 23°C. The continuous line represents temperatures profiles under the condition of thermal stress due to exercise and broken lines represent temperature profiles under normal condition without any thermal stress for a person at rest Figure 2 and 12 at atmospheric temperature T_a = 15°C and 23°C respectively represent the boundary condition taken as uniform core temperature of 37°C. It can be clearly seen in all the figures 2 to 12 that thermal stress caused due to exercise has significant effect on temperature profiles in the skin layers. In figures 2 to 12 we observe that the temperature falls down sharply during first 10 minutes and this fall in temperature is gradual and smooth after t = 10 minutes. The elevation in temperature profiles is observed initially caused by thermal stress due to physical exercise and the effect of thermal stress on the profiles becomes negligible around t=40 minutes and beyond. The temperature profiles due to thermal stress achieve steady state around 40 minutes and converge into steady state temperature profiles of a subject without thermal stress. Also the temperature profiles of the subject without thermal stress reach steady state in 25 minutes. Thus by comparing the temperature profiles of subjects with thermal stress due to physical exercise and subject with thermal stress can be used to infer the magnitude of thermal stress, its relation with magnitude of thermal effect on temperature distribution and the time period of rest required to completely remove the effect of thermal stress on the human body. Same behaviour of temperature profiles is observed in figures 2 to 12 at atmospheric temperature T_a=15°C and 23°C. The outer surface temperature at T_a=15°C and $E = 0gm/cm^2 - min$ in steady state is 32°C and for T_a = 23°C and $E = 0gm/cm^2 - min$ it is 33°C. The gaps between the curves are different in different layers of skin which is due to the different insulation or conduction properties of each skin layer. The gaps between the curves decrease as we move away from the body core and are least near and at the skin surface. This is due to the fact that heat loss takes place from skin surface to the environment in proportion of the gradient of temperature at and near the skin surface there by reducing the gap between the curves.

CASE-2

In this case the human subject is doing exercise for a certain interval of time. He does the physical exercise for an interval of time and comes to rest for some small period of time and again resumes the exercise for a period of time and this process of exercise and then rest and this process of exercise and rest continues for a longer period of time. As a special case these intervals are assumed to be equal and periodic. The blood flow and metabolic activity keeps on changing dynamically from their maximum to minimum values alternatively at fixed periods of time. As a special case we take the period l=2.5min, 5min and 7.5min.

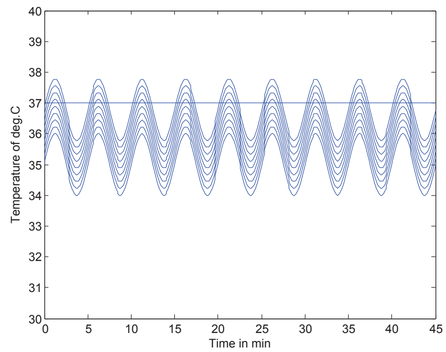

Figure 13: Graph between temperature T (in deg C) and time t (in min) at $T_a = 15°$C and $E = 0gm/cm^2$-min at different positions $r_i(i = 1(1)10)$ for a subject doing exercise and rest periodically at intervals of 2.5 minutes

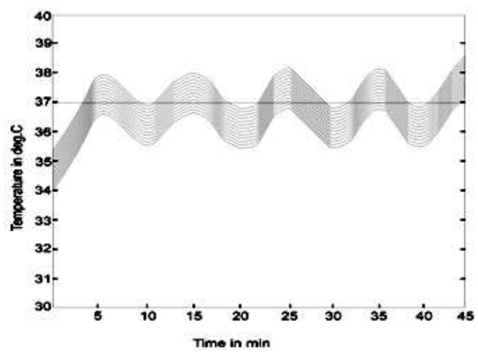

Figure 14: Graph between temperature T (in deg C) and time t (in min) at $T_a = 15°$C and $E = 0gm/cm^2$-min at different positions $r_i(i = 1(1)10)$ for a subject doing exercise and rest periodically at intervals of 5 minutes

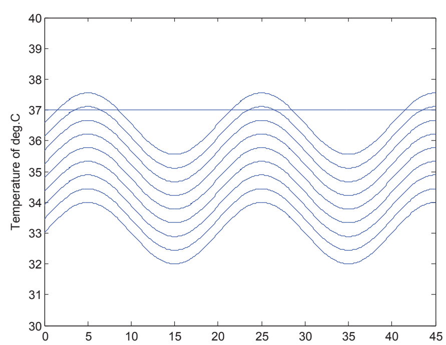

Figure 15: Graph between temperature T (in deg C) and time t (in min) at $T_a = 15°$C and $E = 0gm/cm^2$-min at different positions $r_i(i = 1(1)10)$ for a subject doing exercise and rest periodically at intervals of 7.5 minutes

The graphs have been plotted for temperature T (in deg C) and time t (in min) at $T_a = 15°C$ and $E = 0gm/cm^2{-}min$ at different radial positions/ layers $r_i(i = 1(1)10)$ of SST region of human limb respectively. In figures 13, 14 and 15, we observe that there is elevation in temperature profiles during different period of time 2.5min, 5min and 7.5min respectively due to the thermal stress as the subject is doing exercise. In figure 13 at time t= 2.5 minutes we observe the change in the slope of the curve because the subject stops exercise at time t= 2.5 minutes and takes rest for next 2.5 minutes. Thus between time t=2.5 minutes to t= 10 minutes we observe the fall in temperature and again the slope of the curve changes at t=10 minutes as the subject starts doing exercise for next 2.5 minutes. The pattern of increase and fall in temperature profiles is observed periodically with a period of 2.5 minutes in the figure 13. Same pattern of increase and fall in temperature profiles is observed periodically with a period of 5 minutes and 7.5 minutes in the figure 14 and 15 respectively. The outer surface temperature at $T_a = 15°C$ and $E = 0gm/cm^2 - min$ at different positions $r_i(i = 1(1)10)$ for a subject doing exercise and rest periodically at intervals of 2.5min in steady state is 35°C and for 5min it is 34°C and for 7.5min it is 33°C. Thus the thermal effect of physical exercise and rest periodically is clearly visible in figure 13, 14 and 15 respectively and it gives us idea about the magnitude of thermal effect of physical exercise and rest on temperature profiles in the skin layers.

Conclusion

The Mathematical models developed for the temperature distribution in SST region of human limbs during exercise by using Finite Difference Method was used to predict the effect of thermal stress. The thermal effect of physical exercise is quite significant. Such mathematical models can be developed to predict the magnitude of effect of thermal stresses in relation to magnitude of physical exercise and rest. Further such models can be used to generate thermal information for developing strategies regarding physical work and rest for Labourers, sportsmen and military persons etc based on their biophysical and demographic characteristics like age, sex, ethnicity, baseline fitness, clothing etc.

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