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Influence Of Exercise Condition On Tissue Blood Temperature Using Whole Body Model

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ABSTRACT

Predicting thermal responses of the human body accurately during different exercise conditions is of increasing importance. Computing changes in the core body temperature (T_c) during exercise require detailed modeling of both the body tissue temperature and the time-dependent blood temperature. Predicting changes in T_c is challenging because the model needs to respond effectively to the changes in perfusion or sweating. Our study was to demonstrate the ability of a recently developed whole body heat transfer model. It simulates the tissue-blood interaction to predict the thermal response of the human body under different exercise intensities. The cases simulated were of a human being walking on a treadmill at 0.9, 1.2 and 1.8 m/s for 30 minutes. It was shown that T_c was effectively regulated within 0.17 °C of the steady state value of 37.23 °C for the three cases by means of adjusting the cardiac output; varying between 15 to 25 liters per minute.

INTRODUCTION

In this study, the previously developed whole body model that simulates tissue-blood thermal interaction [1] was used to compute the thermal response of the body under different exercise conditions. The whole body model comprises of two components: the Pennes bioheat equation to simulate the temperature distribution in the body (T_t), and an energy balance equation to determine the change in blood temperature (T_{blood}) during a process. The Pennes equation (1) is defined as

$$\rho c \frac{dT_t}{dt} = k_t \nabla^2 T_t + q_m + (\rho c)_{blood}\, \omega (T_{blood} - T_t) \text{ - (1)}$$

where ω is the blood perfusion. A theoretical blood energy balance equation was employed to compute the change in blood temperature using Pennes bioheat equation. The governing equation (2) for T_{blood} was written as

$$(\rho c V)_{blood} \frac{dT_{blood}}{dt} = -(\rho c \omega_{avg})_{tissue} V_{body} (T_{blood} - T_{wt}) \text{ - (2)}$$

where ω_{avg} is average blood perfusion and T_{wt} is the weighted average tissue temperature. As shown in equation 2, T_{blood} will increase if the right side of the equation becomes positive. During exercise, the increase in T_{wt} leads to heat gain by the blood during its circulation. Since both equations are coupled, they are solved simultaneously, updating both T_{blood} and T_{wt} during the simulation process.

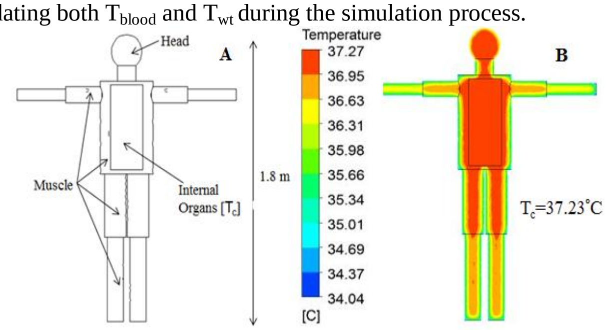

Figure 1: Geometry of a realistic human model (A) and initial temperature field in 25 °C air (B).

METHOD

Geometry. The human body model was made comparable to the previous study [1] with a height of 1.8 m, weighing 80 kg and having a body surface area of 1.90 m^2. There are three major components in the model namely muscle, head, and internal organs.

Physical and Physiological Parameters. For the entire body, the thermal conductivity was kept constant at 0.5 W/m-°C whereas the density was fixed at 1060 kg/m^3 and the specific heat was maintained at 3800 J/kg-°C. During exercise about 90% of heat produced is in the muscles [2]. Hence, changes in the metabolic rate and perfusion rate were made only for muscle, as shown in Figures 2 and 3. The parameters for organs and head were kept the same as that in the previously described study [1]. Increase in perfusion is a bodily response to the increase in metabolic rate. It was assumed to lag the rise in metabolic heat rate by 120 seconds.

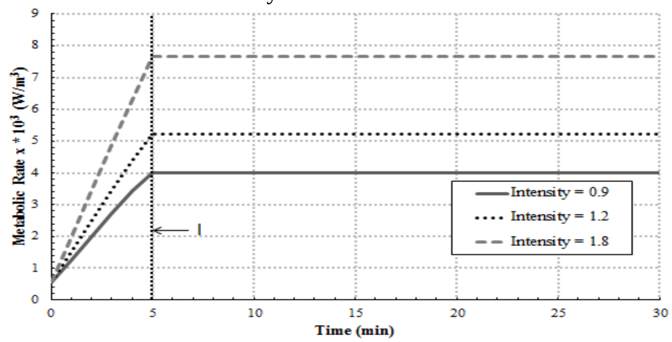

Figure 2. Variation in Metabolic Rate for muscle during exercise.

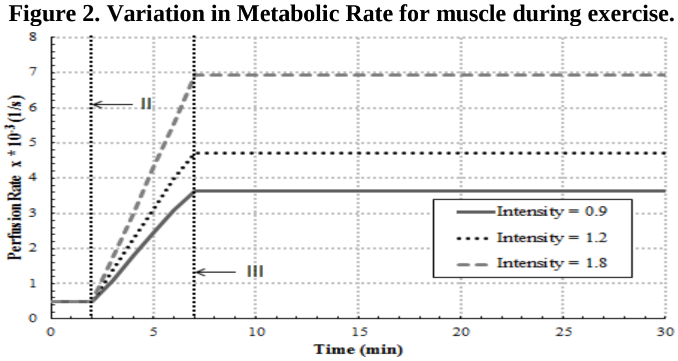

Figure 3. Variation in Perfusion Rate for muscle during exercise.

The equation used to calculate the heat loss due to sweating (E_{sw}, W/m^2) is shown in Figure 4. This was developed for maximum possible evaporative heat loss in the absence of clothing from previously described sweating equations [2, 3]. Values for the evaporative heat transfer coefficient were estimated using the Lewis relation [3]. These were calculated to be 103, 115 and 135 W/m^2.kPa for cases 1, 2 and 3 respectively. Sweating was activated when T_c reached 37.23 °C; however sweating was restricted for 7 minutes until the perfusion rate in muscle had achieved its maximum value.

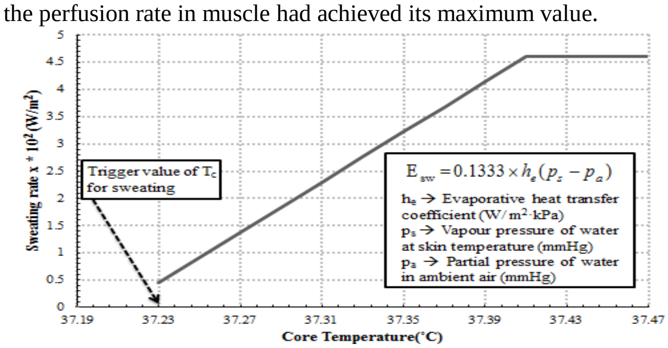

Figure 4. Illustrative Sweating rate during exercise.

Boundary and Initial Conditions. The heat transfer from the body to the environment by evaporation, convection, and radiation is represented by an overall heat transfer coefficient (h). In ambient conditions of 25 °C air, h was determined to be 5.1 W/m^2-°C without evaporation. This value of h was chosen such that T_{wt} is equal to the initial blood temperature of 37 °C. When sweating was activated, the heat loss due to sweating was incorporated into the boundary condition as an additional heat flux term. The steady state temperature field of the human body in 25 °C air, as shown in Fig 1B, was defined as the initial condition. The model was analyzed for different exercise intensities with walking speeds of 0.9, 1.2, and 1.8 m/s [3].

Solution Method. An implicit method was used to solve the governing equation for blood and tissue temperatures [1]. The model was solved using a combination of subroutines and a finite volume solver (Ansys Fluent, v13.0). Different exercise intensities were simulated by changing the metabolic and perfusion rates of the muscle and inclusion of sweating as heat flux term, when applicable. The transient response of the body temperature and blood temperature was then solved for each case.

RESULTS

During exercise, the increase in metabolic rate causes an increase in the blood temperature. Although this causes a rise in T_c, there is a noticeable time lag. Figure 5 shows the change in T_c for the three cases analyzed. Once perfusion is allowed to vary, there is an observed 0.06-0.08 °C drop in T_c. The corresponding increase in perfusion is able to check the increase in T_c over a period of time. The dip in T_c starts a little over 2 minutes and falls till around 7-10 minutes depending on the intensity of exercise. Beyond this, the blood perfusion is unable to regulate the rise in T_c due to high metabolic rate. Advent of sweating allows the corresponding escalation of T_c to be restricted. However, the resulting dip in T_c is observed only after the sweating rate has peaked around 20-27 minutes. The drop in T_c observed due to changes in perfusion and sweating compares relatively well with that observed in detailed whole body model [4]. The cardiac outputs for the three cases were calculated to be 15.1, 18.5, and 25.3 liters per minute, respectively.

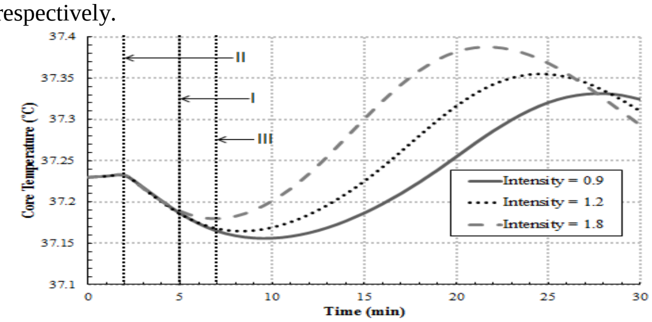

Figure 5. Computed T_c for human body model during exercise.

CONCLUSION

The ability of the relatively simple whole body model to predict changes in T_c during various exercise conditions was established in this study. The model is adept in accurately responding to temperature fluctuations due to changes in perfusion and sweating. The computed values of T_c by the model were between 37.39 °C and 37.16 °C, a small deviation from the normal T_c due to sweat induced evaporation on the skin surface.

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