Comparison Between Experimental and Heart Rate-Derived Core Body Temperatures Using a Three-Dimensional Whole Body Model

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Determination of core body temperature (T_c), a measure of metabolic rate, in firefighters is needed to avoid heat-stress related injury in real time. The measurement of T_c is neither routine nor trivial. This research is significant as thermal model to determine T_c is still fraught with uncertainties and reliable experimental data for validation are rare. The objective of this study is to develop a human thermoregulatory model that uses the heart rate measurements to obtain T_c for firefighters using a 3D whole body model. The hypothesis is that the heart rate-derived computed T_c correlates with the measured T_c during firefighting activities. The transient thermal response of the human body was calculated by simultaneously solving the Pennes' bioheat and energy balance equations. The difference between experimental and numerical values of T_c was less than 2.6%. More importantly, a ± 10% alteration in heart rate was observed to have appreciable influence on T_c, resulting in a ± 1.2 °C change. A 10% increase in the heart rate causes a significant relative % increase (52%) in T_c, considering its allowable/safe limit of 39.5 °C. Routine acquisition of the heart rate data during firefighting scenario can be used to derive T_c of firefighters in real time using the proposed 3D whole body model. [DOI: 10.1115/1.4041594]

Keywords: whole body model, core body temperature, cardiac output, stroke volume, sweating

Introduction

Firefighters are exposed to adverse thermal conditions, leading to heat-related stress (or injury) during firefighting. Uncompensable heat stress and its effect on the firefighter's body can be manifested as intense changes in their physiological response, including increased heart rate, elevated sweating, and incorrect subjective responses [1]. Inability to dissipate the body heat leads to increase in body temperature, which is detrimental to the firefighter's health and can result in heat-related illnesses, including heat stroke and sudden cardiac events. Unfortunately, the measurement of core body temperature (T_c) is neither routine nor trivial. Therefore, the determination of T_c in firefighters is needed to avoid heat-stress related injury in real time.

To effectively dissipate the excess body heat, the options are (1) use of cooling mechanisms, (2) limiting the duration of the activity, or (3) doing both. The limit for the duration of activity can be predicted with the help of algorithms based on experimental data [2], human body simulators [3,4], or computational models [5,6]. Experiment-based algorithms are developed based on the average response of the human subjects tested in controlled environmental simulators. The changes to the local environment are limited based on the capacity of the experimental setup. Conversely, using a computational model includes the advantages of (1) better manipulation of the human body shape and size, and (2) the possibility to impose and test unfavorable environmental conditions such as exposure to fire.

The earliest whole body model was developed by Wissler [7]. The temperature distribution for various subdomains of the model, e.g., the head and limbs, was obtained with the help of Pennes' bioheat equation [8]. Other researchers have also developed whole body models [5,9,10], which focused mainly on analyzing the thermal response of the human body under moderate heat and cold stress environments. However, only a limited number of numerical studies analyzed thermal adverse conditions, such as firefighting scenarios.

Researchers have developed a predictive heat strain (PHS) model [11] and compared the predicted numerical core body temperature (T_{c_N}) with the experimental core body temperature (T_{c_E}) for six human subjects, including one firefighter who was wearing a personal protective equipment. Despite PHS being an international standard (ISO7933), this study reported that PHS was not suitable for determining T_{c_N} for common heat stress scenarios at work places, especially during firefighting. Further, Kim et al. [6] developed a computational model to predict T_{c_N} in firefighters. The model evaluated the thermal response of the firefighters during exercise on a treadmill. The results showed a maximum difference of 0.6 °C between T_{c_N} and T_{c_E}. The experimental setup for this study involved controlled experimental and ambient conditions, which do not replicate the thermal conditions associated with real-life firefighting scenarios.

Our group has previously reported a computational model to assess the thermal response of a human being during exercise and cold water immersion [12–14]. For the exercise conditions, the model simulated a realistic human being exercising on a treadmill at walking speeds of 0.9, 1.2, and 1.8 m/s for 30 min. For the cold water immersion conditions, the thermal response of the body while immersed in cold water with water temperatures of 18.5,

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10, and 0 °C was analyzed. The results for cold water immersion compared well with Wissler's experimental data [7] (maximum difference of 0.6 °C).

Another of our recently published research [15] reported that the tissue parameters, such as density, ρ, thermal conductivity, k, specific heat, c, and resting metabolic rate, M_0, had lesser (secondary) influence on T_{c_N}. The effect of physiologic changes in ρ, k, c, and M_0 on T_{c_N} was less than ± 0.2 °C [15]. However, the interdependence of heart rate with T_{c_N} during different firefighting scenarios (e.g., multiple firefighters) was not assessed.

Therefore, this research is *significant* as thermal model to determine T_{c_N} is still fraught with uncertainties and reliable experimental data for validation are rare. The *objective* of this study is to develop a human thermoregulatory model that uses the heart rate, a measure of metabolic rate (discussed in Metabolic Rate and Perfusion section), to obtain T_{c_N} for firefighters using a whole body model. The *hypothesis* is that the heart rate-derived computed T_{c_N} correlates with the measured T_{c_E} during firefighting activities. This research is *novel* because heart rate-derived T_c in firefighters can be assessed in real time; therefore, heat-stress related injury can be avoided.

Methods

A realistic whole body model was developed to compute the thermal response of three firefighters using datasets from the literature describing firefighting drills. These drills consisted of alternating periods of firefighting and rest scenarios. The de-identified datasets included the heart rate, the experimental core body temperature, T_{c_E}, and the physiological parameters of firefighters 1, 2, and 3 [16,17]. Additional details such as the age and weight of the firefighters are listed in Table 1.

The computational analysis of firefighter 1 is detailed in the main text, whereas the Appendix section includes relevant information regarding firefighters 2 and 3. The human subject data from firefighter 1 were obtained during test firefighting scenarios reported in the study by Horn et al. [16]. This study was approved by the University of Illinois Institutional Review Board. The parameter T_{c_E} of firefighter 1 was measured (not a routine procedure) using an integrated system of ingestible temperature transmitter pill (MiniMitter Vital Sense, Philips Respironics), which has an overall accuracy of ± 0.1 °C with 0.01 °C resolution. Experimental data of the cardiac output and the stroke volume of firefighter 1 at the start and end of the firefighting training drills [16,18] were also available for comparison.

Whole Body Model and Firefighting Gear: The computational model was divided into three subdomains: the head, the internal organs, and the muscle (Fig. 1). The firefighting gear was 7 mm thick [19,20] and was split into two zones: (1) the jacket worn over the torso and hand regions and (2) the firefighting pants covering the legs. The entire firefighting gear was worn during the firefighting scenarios, whereas only the jacket was removed during the rest scenarios. The material properties for the gear and the human body are detailed in Table 2.

The *whole body model* developed in our lab [12] is composed of the Pennes' equation to calculate the temperature distribution in the tissue subdomains, and an energy balance equation to determine the change in the blood temperature (T_{blood}) during each time-step. The Pennes' simplified equation is defined as

$$\rho_t c_t \frac{\partial T_t}{\partial t} = k_t \nabla^2 T_t + q_m + \rho_{\text{blood}} c_{\text{blood}} \omega (T_{\text{blood}} - T_t) \quad (1)$$

Table 1 Age and weight of the firefighters

Firefighter	Age (years)	Weight (kg)
1	20	73.5
2	37	89.4
3	33	86.7

where ω is the blood perfusion, k_t is the conductivity of tissue, ρ is the density, c is the specific heat, T_t is the tissue temperature, and q_m is the volumetric heat generation rate due to metabolism. A *novel* theoretical blood energy balance equation was employed to compute the change in T_{blood} over time with the help of the *perfusion weighted average tissue temperature* (T_{wt}) and the *volumetric average blood perfusion rate per unit volume of tissue* (ω_{avg}). The governing equation for T_{blood} is given by

$$\rho_{\text{blood}} c_{\text{blood}} V_{\text{blood}} \frac{dT_{\text{blood}}}{dt} = -\rho_t c_t \omega_{\text{avg}} V_{\text{body}} (T_{\text{blood}} - T_{\text{wt}}) \quad (2a)$$

where the *simplified* and *novel* parameters, T_{wt} and ω_{avg}, are defined as

$$\omega_{\text{avg}} = \frac{1}{V_{\text{body}}} \iiint_{V_{\text{body}}} \omega \, dV_{\text{body}} \quad (2b)$$

$$T_{\text{wt}} = \frac{1}{\omega_{\text{avg}} V_{\text{body}}} \iiint_{V_{\text{body}}} \omega T \, dV_{\text{body}} \quad (2c)$$

Heart Rate Time Series: Figure 2(*a*) depicts the experimentally obtained temporal changes in heart rate for firefighter 1. The figure is divided into two segments: (1) "Sc," indicating the firefighting scenarios and (2) "R," indicating the rest scenarios.

Metabolic Rate and Perfusion: The metabolic rate was calculated from the heart rate of the firefighter using the following equation reported in ISO 8996 [22]:

$$M = M_0 + \frac{\text{HR} - \text{HR}_0}{\text{RM}} \quad (3)$$

where M is the current metabolic rate, M_0 is the resting metabolic rate, HR is current heart rate, HR_0 is the experimentally recorded baseline heart rate, and RM is the increase in heart rate per unit metabolic rate. RM is defined as

$$\text{RM} = \frac{\text{HR}_{\max} - \text{HR}_0}{\text{MWC} - M_0} \quad (4)$$

where $\text{HR}_{\max}$ is the maximum heart rate and MWC is the maximum working capacity [22], which for men is defined as

$$\text{MWC} = (41.7 - (0.22A))W^{0.666} \quad (5)$$

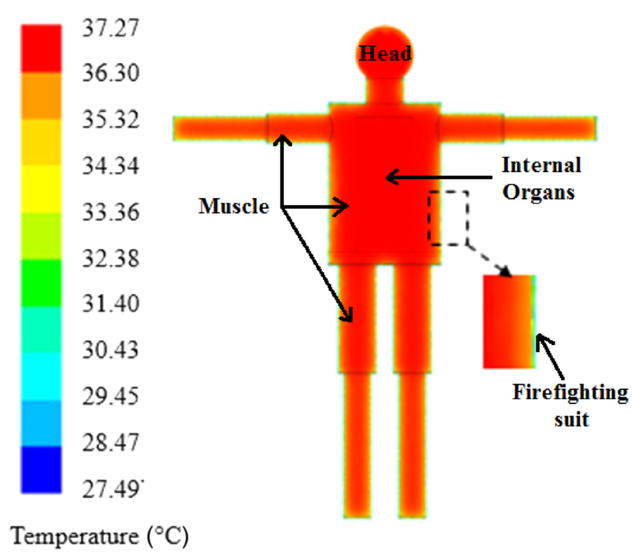

Fig. 1 Schematic of the whole body model with a temperature contour plot at steady-state

Table 2 Material properties for the whole body thermal model

Zone	Material Property	Value
Body tissue (head, internal organs, and muscle) [7,9,10,21]	Thermal conductivity, k	0.5 W/m °C
	Density, ρ	1060 kg/m^3
	Specific heat, c	3165.65 J/kg °C
Blood [12]	Thermal conductivity, k	0.5 W/m °C
	Density, ρ	1060 kg/m^3
	Specific heat, c	3800 J/kg °C
Firefighter ensemble [19,20]	Thermal conductivity, k	0.03454 W/m °C
	Density, ρ	135.96 kg/m^3
	Specific heat, c	1335.36 J/kg °C

where A is the age in years and W is the weight in kilograms. In the computational model, 92% of the increase in metabolic rate (q_m in Eq. (1)) was added to the muscle subdomain, whereas 8% was assigned to the organ subdomain [23]. In this study, T_{c_N} was defined as the average tissue temperature of the organ subdomain within the human body [24]. Changes in perfusion for the organ and the muscle domains were directly proportional to the increase or decrease in the metabolic rates of respective subdomains [25]. The perfusion values were limited to a range between 0.0005 and 0.0115 1/s based on the physiologic changes in cardiac output, which are between 5 and 40 L/min. Equation (3) was observed to have a precision of ±10%. Thus, two limiting sets of transient core body temperatures, $T_{c\_N\_lower}$ and $T_{c\_N\_upper}$, were computed for the firefighters by decreasing and increasing the individual heart rate by 10% at each time point.

Sweat Evaporation: When the increase in local blood perfusion is unable to regulate body temperature within its acceptable range, the evaporation of sweat is utilized to increase the removal of heat generated in the exercising muscles [12]. The original boundary condition at the body surface is defined as

$$-k_t \frac{\partial T_t}{\partial n}\bigg|_{\text{at surface}} = h(T_t - T_{\text{air}})|_{\text{at surface}} + E \qquad (6)$$

where n is the normal direction of the skin surface, while E represents the heat loss due to the evaporation of sweat. The firefighter ensemble consists of a moisture barrier layer that impedes the evaporation of the generated sweat. Thus, it was assumed that there was no heat loss due to sweating during the firefighting scenarios. However, since the firefighting jacket was removed during the rest scenarios, the evaporation of sweat was permitted on the surfaces of the torso and the head regions. The parameter E was calculated as a function of the evaporative heat transfer rate (h_e), skin wettedness factor (w), intrinsic clothing thermal efficiency (f_{cl}), the vapor pressure of water (p_{skin}) at the skin temperature, and the partial pressure of water vapor (p_{air}) in the ambient air. Further details regarding p_{skin} and p_{air} are reported in our previous study [12]. The equation for E [26] is

$$E = 0.1333\left[\frac{\text{kPa}}{\text{mmHg}}\right] \times w \times f_{\text{cl}} \times h_{\text{e}}(p_{\text{skin}} - p_{\text{air}}) \qquad (7)$$

where w refers to the amount of sweat generated that is available for evaporation on the surface of the skin and it varies between 0 and 1 [26]. Being a retrospective study, the details of sweating were not available/recorded for firefighters. Therefore, perturbed w values were calculated based on the decrease in T_{c_E} during the rest scenarios, the duration of the rest scenario, and the value of T_{c_E} at the beginning of the subsequent firefighting scenario. The value of f_{cl} was chosen to be 0.36 to incorporate the maximum evaporative heat loss in the absence of the firefighting jacket [26].

Cardiac Output and Stroke Volume: The cardiac output was defined as the volumetric addition of the perfusion in the human body. The equation for cardiac output is defined as

$$\text{cardiacoutput} = (\omega_{\text{h}} \times V_{\text{h}}) + (\omega_{\text{mu}} \times V_{\text{mu}}) + (\omega_{\text{io}} \times V_{\text{io}}) \qquad (8)$$

The subscripts h, mu, and io refer to the head, the muscle, and the internal organs, respectively. The stroke volume was calculated as the ratio of the cardiac output to the heart rate.

Results

The results of this retrospective study included the temporal changes of the computational core body temperature (T_{c_N}), the cardiac output, and the stroke volume of firefighter 1. Figure 1 shows the geometry with temperature contour at steady-state. The relevant and abbreviated results for firefighters 2 and 3 are reported in the Appendix.

Change of Core Body Temperature (T_c): The parameter T_{c_E} was compared with T_{c_N} for firefighter 1 in Fig. 2(*b*). The perturbed w values for firefighter 1 were computationally determined to be 0.49, 0.35, 0.13, and 0.58 for rest scenarios R1, R2, R3, and R4, respectively. The maximum percentage difference between T_{c_E} and T_{c_N} defined by

$$\text{percentage difference} = \{[T_{\text{c\_E}} - T_{\text{c\_N}}] \times 100\%\}/T_{\text{c\_E}} \qquad (9)$$

for firefighter 1 was calculated to be between −2.2% and +2.0%. Further, the maximum percentage difference between T_{c_E} and T_{c_N} for firefighters 2 and 3 was calculated to be between −2.0% and +2.6% (Fig. 3(*c*)), and −0.7% and +0.9% (Fig. 3(*d*)), respectively. Appendix can be referred to for further details.

The parameter T_{c_N} based on perturbed heart rate values ($T_{c\_N\_lower}$ and $T_{c\_N\_upper}$) for firefighter 1 is shown in Fig. 2(*b*). A maximum change of ±1.2 °C was observed in T_{c_N} for firefighter 1 due to ±10% change in the heart rate. Considering the maximum safe limit of T_c for firefighters being 39.5 °C, the allowable maximum percentage difference in T_c is ∼6.75% (={[39.5 − 37] × 100}/37). On a similar note change of ±1.2 °C in T_{c_N} due to ± 10% change in the heart rate leads to a percentage difference of ∼3.24% (= {1.2 × 100}/37). *Therefore, a 10% increase in the heart rate causes a significant relative % increase (52% = {[6.75 − 3.24]×100}/3.24) in T_c, considering its allowable/safe limit of* 39.5 °C.

On a similar note, ±10% change in the heart rate resulted in a change within ±0.4 °C and within ±1.0 °C in T_{c_N} for firefighter 2 (Fig. 3(*c*)) and firefighter 3 (Fig. 3(*d*)), respectively. Appendix can be referred to for more details.

Cardiac Output and Stroke Volume. For firefighter 1 (Fig. 2(*c*)), the cardiac output varied between 4.8 L/min and 21.4 L/min, while the stroke volume varied between 80 mL/beat and 100 mL/beat. The experimentally reported [18] values of the cardiac output and the stroke volume, measured by an external ultrasound probe, at the beginning of the training drill for firefighter 1 were 3.8 L/min, which are somewhat lower than the physiologic range of 5–40 L/min and 71.3 mL/beat, while the computational values were 6.0 L/min and 89.6 mL/beat. The measurement of stroke volume by such external ultrasound probe is known to have appreciable errors. Inaccuracies in the stroke volume measurement introduce error in the calculation of cardiac output which is the stroke volume multiplied by the heart rate. Similarly, the experimental values of cardiac output and stroke volume at the end of the firefighting training drill (380 min) for firefighter 1 were 5.1 L/min and 47.0 mL/beat. Again, the computed values were relatively higher (10.4 L/min and 96.8 mL/beat, respectively) when compared to the experimental data [18].

Discussion

This retrospective study has demonstrated a methodology to predict T_{c_N} using measured heart rate for firefighters during firefighting training drills. Alterations in the heart rate and therefore, changes in metabolic rate, with T_{c_N} were also assessed in this study. Therefore, routine acquisition of the heart rate data during firefighting scenario can be used to derive T_c of firefighters in real time using the proposed 3D whole body model.

Core Body Temperature (T_c). The comparison between the numerical core body temperature (T_{c_N}) and the experimental core body temperature (T_{c_E}) showed a maximum difference of 0.9 °C (Sc3, Fig. 2(*b*)) for firefighter 1. The previous studies [3,4] have reported a difference of 0.2–0.6 °C in the calculation of T_{c_N} by using their respective models. However, these models simulated the human body experiments inside a closed and controlled environment, but not firefighting scenarios.

Cardiac Output and Stroke Volume. The computed range of cardiac output and stroke volume in this study was mostly within the physiological range (Fig. 2(*c*)), but higher than the experimental data [18]. Further, the measured cardiac output (3.8 L/min) prior to the firefighting scenario was found to be lower than the physiological range of 5–40 L/min. It is well known that the accurate field measurement of cardiac output using external ultrasound probes is challenging.

With the evaluation of additional datasets from statistically determined sample sizes using a prospective study, details regarding heat acclimatization status of the firefighter to unfavorable environmental conditions, and better correlations for perfusion and sweating can further enhance the efficacy of the computational model.

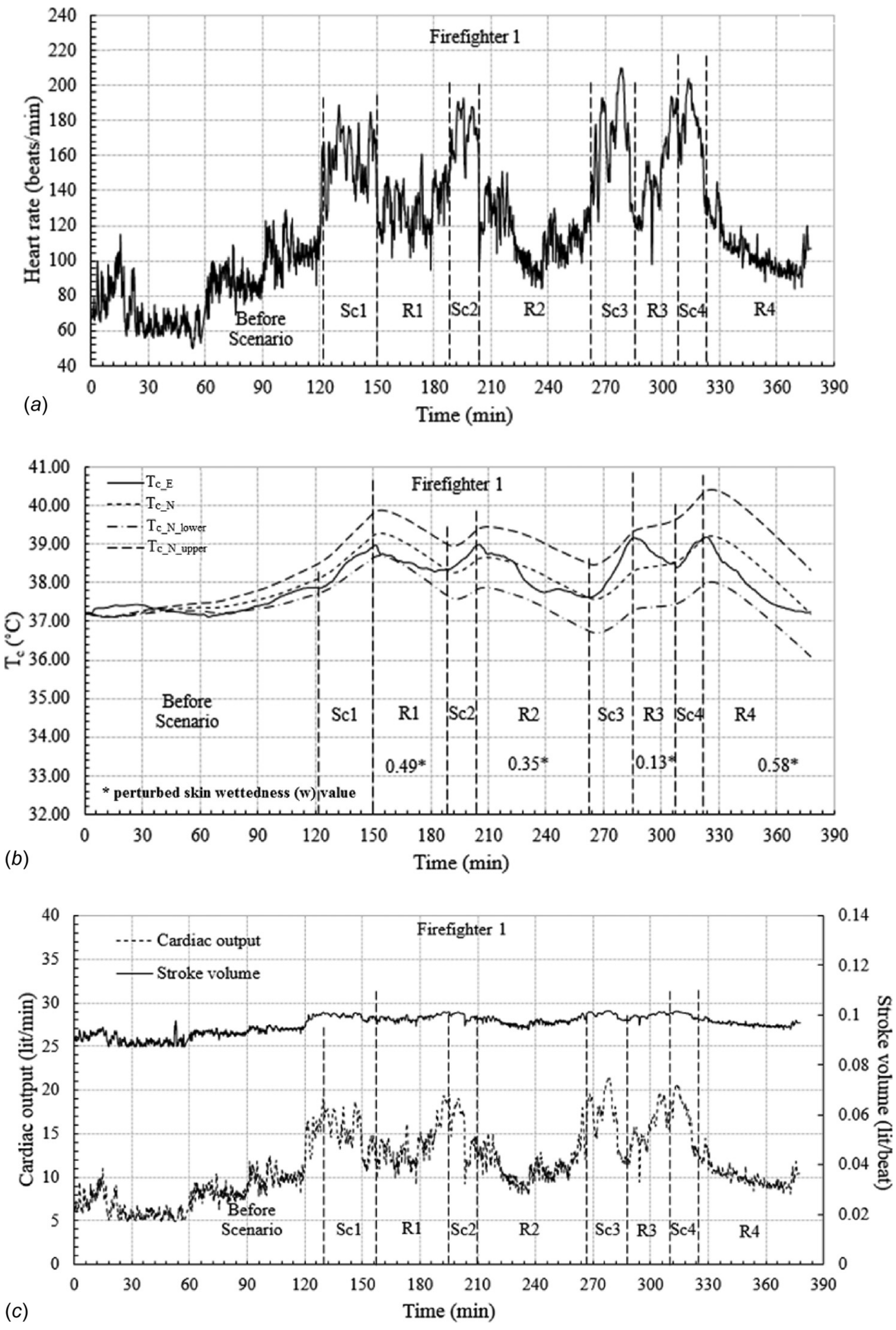

Fig. 2 (*a*) Heart rate time series for firefighter 1 during the entire firefighting training drill, (*b*) change in T_{c_N}, T_{c_E}, and T_c based on perturbed heart rate ($T_{c\_N\_upper}$ and $T_{c\_N\_lower}$) for firefighter 1 during the firefighting training drill, and (*c*) changes in cardiac output and stroke volume over time for firefighter 1

Conclusions

The transient changes in T_{c_N} for firefighters 1, 2 (Appendix), and 3 (Appendix) were compared with T_{c_E} with the aid of a whole body model. The percentage difference between the values of T_{c_N} and T_{c_E} was calculated to be within 2.2% for firefighter 1. Furthermore, the percentage difference between T_{c_N} and T_{c_E} was found to be within 2.6% and within 0.9% for firefighter 2 and firefighter 3, respectively. While the tissue parameters such as density, thermal conductivity, specific heat, and metabolic rate had lesser effect on T_{c_N} [15], the heart rate was observed to have significant influence on T_{c_N} (±1.2 °C for firefighter 1, ±0.4 °C for firefighter 2, and ±1.0 °C for firefighter 3), affirming the hypothesis. For example, for firefighter 1, a 10% increase in the heart rate causes a significant relative % increase (52%) in T_c, considering its allowable/safe limit of 39.5 °C. Therefore, using the heart rate data, the whole body model can potentially be used as a predictive computational tool for deriving the thermal response of firefighters in real time during live-burn activities. Additional applications for the whole body model include testing the effectiveness of protective apparels for soldiers and firefighters.

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Authors' Contributions

R. Banerjee, with the help of R. Kalathil, rewrote the current content of the manuscript that was focused to highlight the correlation between the heart rate and the core body temperature. S. Zachariah, in collaboration with A. Paul and under the supervision of R. Banerjee, revised the original numerical code [12] and obtained results that constituted his MS dissertation, leading to the current version of the manuscript.

Nomenclature

A = age (years)
c = specific heat capacity (J/kg °C)
E = heat loss due to the evaporation of sweat (W/m^2)
f_{cl} = intrinsic clothing thermal efficiency (dimensionless)
h = overall heat transfer coefficient (W/m^2 °C)
h_e = evaporative heat transfer coefficient (W/m^2 kPa)
HR = heart rate (beats/min)
k = thermal conductivity (W/m °C)
M = metabolic rate (W/m^2)
MWC = maximum working capacity (W/m^2)
p = vapor pressure of water (mmHg)
q = volumetric heat generation rate (W/m^3)
R = rest scenario
RM = increase in heart rate per unit metabolic rate (beats m^2/W min)
Sc = firefighting scenario
t = time (seconds)
T = temperature (°C)
V = volume (m^3)
w = skin wettedness factor
W = weight (kg)
ρ = density (kg/m^3)
ω = volumetric blood perfusion rate per unit volume of tissue (1/s)

Subscripts

avg = average
c_E = experimental core body temperature
c_N = numerical core body temperature
c_N_lower = numerical core body temperature based on perturbed (−10%) heart rate
c_N_upper = numerical core body temperature based on perturbed (+10%) heart rate
t = tissue
wt = perfusion weighted average tissue
0 = rest

Appendix

The human subject data of firefighter 2 and firefighter 3 were obtained during firefighting training drills in the study reported by Mani et al. [17], which was performed with the approval of the University of Cincinnati Institutional Review Board. The

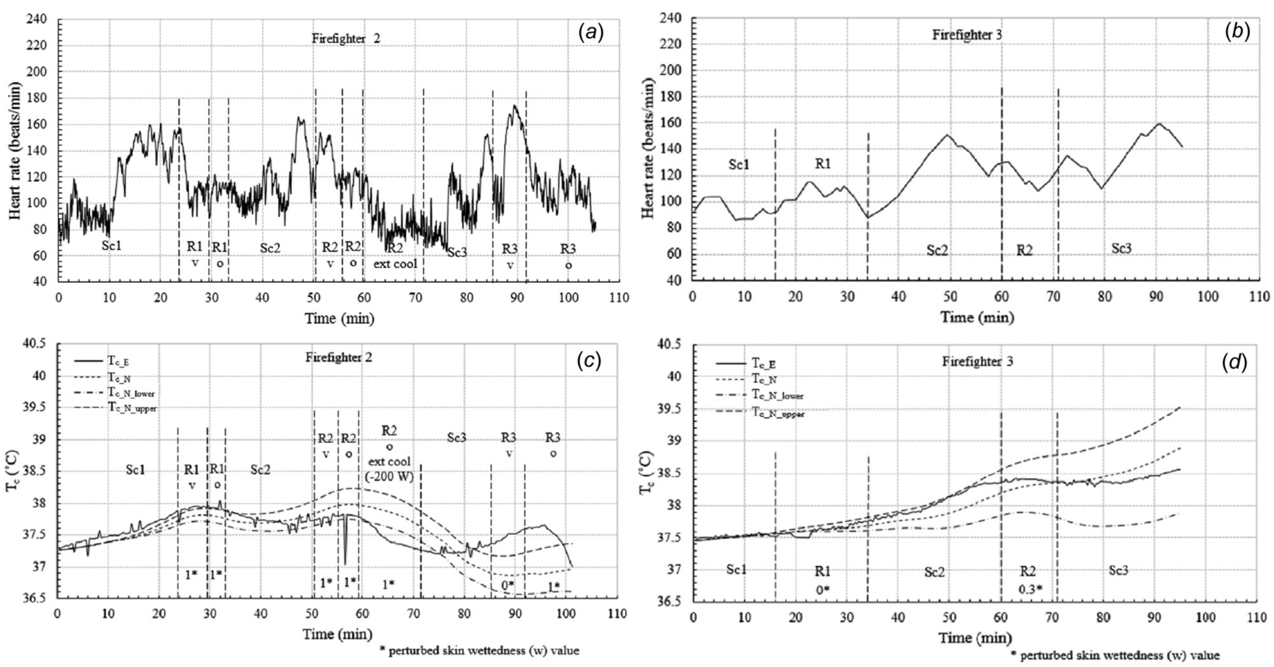

Fig. 3 Heart rate of (*a*) firefighter 2 and (*b*) firefighter 3. Change in T_{c_N}, T_{c_E}, and T_c based on perturbed heart rate ($T_{c\_N\_upper}$ and $T_{c\_N\_lower}$) for (*c*) firefighter 2 and (*d*) firefighter 3.

parameter T_{c_E} in this study was measured using a radio pill (CorTemp, HQ Inc.) which was ingested by the firefighter prior to the firefighting training drill. The radio pill sensor unit/system was accurate to $\pm 0.1\,^{\circ}$C.

Heart Rate and Core Body Temperature (T_c) for Firefighters 2 and 3. Figures 3(*a*) and 3(*b*) show the experimentally obtained temporal change in heart rate for firefighters 2 and 3, respectively. Figure 3(*c*) compared the change in T_{c_E} with T_{c_N} for firefighter 2. The w values for the rest scenarios R1, R2, and R3 were computationally determined to be 1, 1, 0 (inside van) and 1 (outside van), respectively. The change between T_{c_N} and T_{c_E} was calculated to be between -2.0% and +2.6%. Figure 3(*d*) compared T_{c_E} and T_{c_N} for firefighter 3. Based on the marginal increase in T_{c_E} during R1 and a moderate decrease in T_{c_E} during R2, the w values were determined to be 0 and 0.3, respectively. The percentage difference between T_{c_N} and T_{c_E} was between -0.7% and +0.9%. Additionally, $T_{c\_N\_lower}$ and $T_{c\_N\_upper}$, based on perturbed heart rates ($\pm$10%) for firefighters 2 and 3, are shown in Figs. 3(*c*) and 3(*d*), respectively.

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