Uncertainty Analysis of the Core Body Temperature Under Thermal and Physical Stress Using a Three-Dimensional Whole Body Model

Heat stress experienced by firefighters is a common consequence of extreme firefighting activity. In order to avoid the adverse health conditions due to uncompensable heat stress, the prediction and monitoring of the thermal response of firefighters is critical. Tissue properties, among other parameters, are known to vary between individuals and influence the prediction of thermal response. Further, measurement of tissue properties of each firefighter is not practical. Therefore, in this study, we developed a whole body computational model to evaluate the effect of variability (uncertainty) in tissue parameters on the thermal response of a firefighter during firefighting. Modifications were made to an existing human whole body computational model, developed in our lab, for conducting transient thermal analysis for a firefighting scenario. In conjunction with nominal (baseline) tissue parameters obtained from literature, and physiologic conditions from a firefighting drill, the Pennes’ bioheat and energy balance equations were solved to obtain the core body temperature of a firefighter. Subsequently, the uncertainty in core body temperature due to variability in the tissue parameters (input parameters), metabolic rate, specific heat, density, and thermal conductivity was computed using the sensitivity coefficient method. On comparing the individual effect of tissue parameters on the uncertainty in core body temperature, the metabolic rate had the highest contribution (within \( \pm 2.0^{\circ}C \)) followed by specific heat (within \( \pm 0.10^{\circ}C \)), density (within \( \pm 0.07^{\circ}C \)), and finally thermal conductivity (within \( \pm 0.01^{\circ}C \)). A maximum overall uncertainty of \( \pm 0.23^{\circ}C \) in the core body temperature was observed due to the combined uncertainty in the tissue parameters. Thus, the model results can be used to effectively predict a realistic range of thermal response of the firefighters during firefighting or similar activities.

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Keywords: uncertainty analysis, whole body model, core body temperature, tissue parameters, firefighting

Introduction

Firefighters often perform strenuous physical activity while enduring intense heat during firefighting scenario. Heat generated by the body, compounded by the ineffective heat dissipation away from the body due to the presence of firefighting protective ensemble, causes heat stress in the body [1]. Heat stress, and the consequent elevation in body temperature, increases the heat strain. This can lead to adverse health effects, including unconsciousness and cardiac arrest. Thus, the accurate prediction of thermal response of the human body during firefighting scenarios is of high importance.

Significance of Tissue Parameters. Multiple factors are known to have an effect on the thermal response including physical characteristics of the human body, body dynamics, as well as environmental conditions. In particular, tissue parameters such as metabolic rate, \( q \), specific heat, \( c \), density, \( \rho \), thermal conductivity, \( k \), and blood perfusion, \( \alpha \), are known to play an important role in the determination of thermal response in the human body [2].

More importantly, these tissue parameters show significant variation among different individuals at resting condition [2–5]. Therefore, an accurate estimation of the thermal response computed over a physiologic range of tissue parameters is critical for preventing an adverse or fatal condition during firefighting.

Evaluation of Tissue Parameters. A number of studies have listed the physical parameters of tissues. For example, several studies have reported the values of thermal conductivity [6–9], specific heat [7,10,11], density [12–15], and metabolic rate [16,17] of human tissue. Furthermore, comprehensive databases of tissue parameters obtained by consolidating the values reported in literature are also available. An extensive review of physical properties of mammalian tissue, mainly thermal conductivity, specific heat, and thermal diffusivity, has been conducted by Duck [4]. Along with the physical properties of tissues, the techniques for the measurement of these properties have also been discussed in the study. Further, McIntosh and Anderson [2,3] conducted a comprehensive review of tissue parameters of humans at rest condition. The values and the statistical information about the spread of data for the parameters, \( q \), \( c \), \( \rho \), and \( k \), of a number of tissues were quantified. These data can be utilized as inputs to computational models to analyze the temperature distribution in the human body.
Computational Analysis. Computational analysis is an effective means for conducting a parametric study; such analysis provides the flexibility to manipulate the geometry and physiological parameters of the human body and simulate adverse events like unfavorable environmental conditions. The earliest computational thermal model was developed by Pennes [18] to predict the temperature distribution in a human arm. Subsequently, several whole body computational models were developed for several applications, including firefighting applications and incorporated the Pennes’ bioheat equation to assess the temperature distribution. A predictive heat strain (PHS) model [19] was developed to evaluate the physiological responses of human subjects while wearing different protective garments, which included a firefighting suit. The temperature predicted after walking on a treadmill at 1.25 m/s for 63 min was found to be 1.8 °C higher than the observed value [19]. Further, a thermoregulatory model to predict the skin and core temperatures in firefighters was developed by Kim et al. [20]. The study compared the temperatures predicted by the model with the thermal responses of subjects who had worn the firefighting suit while exercising. A maximum difference of 0.6 °C was observed between the computed and experimentally obtained core temperatures. Although these studies predicted the thermal response of firefighters, they failed to analyze the effect of variation in tissue parameters on the body temperature.

More recently, a few numerical studies have assessed the effect of variation in tissue parameters on the temperature distribution in different regions of the human body. A heat transfer model of the skin tissue was developed by Cetingul and Herman [21] for the detection of lesions by analyzing the transient thermal response of the skin layers. The effect of variation in \( q, c, k, \omega \) and thickness of the skin layers on the surface temperature distribution were investigated in this study. As the variations in these parameters were less for the skin layers, the corresponding variability in temperature was also found to be less. A human brain electromagnetic–thermal dosimetry model was developed by Cvetković et al. [22]. The temperature rise due to the absorption of the electromagnetic energy and the sensitivity of steady-state temperature to the variations in tissue parameters was assessed. The parameters considered for the sensitivity analysis were the arterial blood temperature, tissue parameters like \( q, \omega, k \) and \( \text{boundary conditions} \) like heat transfer coefficient and ambient temperature. However, these studies focus on only specific regions in the human body and not on the whole body.

Our group previously developed a whole body computational model to analyze the thermal response of humans at exercise and cold water immersion scenarios [23–25]. We further modified the whole body computational model [23] to predict the thermal response of a firefighter during a firefighting training drill [26,27]. Using this computational model in conjunction with available physiologic tissue parameters obtained from literature, we conducted an uncertainty quantification analysis to evaluate the effect of variability in tissue parameters on the numerical core body temperature, \( T_c \). The objective of this research was to determine the uncertainty in \( T_c \) due to (1) individual and (2) combined variability in tissue parameters: \( q, c, \rho, r, \) and \( k \).

Methods

Details of the firefighting drill, the computational model, and the methodology used for conducting the uncertainty analysis are described in the following paragraphs.

Firefighting Training Drill. Experimental data from the previous studies describing a firefighting training drill were used to develop the human whole body computational model. A typical training drill consisted of alternating firefighting scenarios and rest periods [28,29]. The firefighting scenarios consisted of (1) search for the origin of flame, (2) hose advancement, and (3) search and rescue of the victim. De-identified datasets including the heart rate, experimental core body temperature \( (T_{c,e}) \), and physiological details of a single firefighter (age = 33 yr, weight = 86.7 kg) were obtained from Mani et al. [29] and used in this study. The experimental study, conducted by Mani et al. [29], was approved by University of Cincinnati Institutional Review Board and the firefighter provided informed consent prior to participating in the study. The \( T_{c,e} \) was measured using a radio pill (CoreTemp, HQ, Inc., Palmetto, FL), which was ingested by the firefighter prior to the drill. The heart rate of the firefighter was recorded at an interval of 20 s. Figure 1 represents the experimentally obtained heart rate values of the firefighter recorded during the firefighting training drill. In the figure, “Sc” represents the firefighting scenario and “R” represents the rest periods.

Whole Body Geometry and Firefighting Suit. The 3D whole body computational model, shown in Fig. 2(a), comprised of several geometric shapes including cylinders, cuboids, and a sphere to represent the limbs, torso, and head, respectively [23,26]. Four domains constituted the whole body model: head, muscle, organ, and gut. An additional suit layer was incorporated to simulate the effects of the firefighting suit at extreme atmospheric conditions. The firefighting suit, comprising of a jacket covering the torso and hands, and pants covering the legs, was modeled as an external layer of 7 mm thickness (Fig. 2(a)). The 3D model with the entire firefighting suit layer was used for computations throughout the firefighting scenario while the model ignored the influence of the suit (jacket layer) for computations during the rest periods.

Governing Equations. Based on the previous model developed by our group [23], the Pennes’ bioheat equation and the energy balance equation (please see Eqs. (A1) and (A2) in the Appendix section) were simultaneously solved in order to determine the thermal response of the whole body. For the firefighting application evaluated in this study, additional modifications were made to the previous model which are described below.

Tissue and Firefighting Suit Properties. All the tissues and organs were categorized into four groups corresponding to four domains (head, organ, muscle, gut) of the whole body model. Details of the tissue parameters including the mean values and percentage uncertainties are presented in Tables 1 and 2. The metabolic rate and perfusion for each domain were determined by calculating the mass weighted average of metabolic rate and perfusion values of all the tissues (e.g., heart, lungs, liver, etc.) belonging to each domain. Further, the mass weighted average value of thermal conductivity, \( k \), specific heat, \( c \), and density, \( \rho \),
were computed for the whole body. Since each tissue property had a range of values, the minimum, maximum, and nominal (baseline) mass weighted average tissue property value for a domain/body were calculated using Eqs. (1)–(3), respectively.

\[
X_{\text{min}} = \frac{\sum x_{\text{min, tissue}} m_{\text{tissue}}}{\sum m_{\text{tissue}}} \tag{1}
\]

\[
X_{\text{max}} = \frac{\sum x_{\text{max, tissue}} m_{\text{tissue}}}{\sum m_{\text{tissue}}} \tag{2}
\]

\[
X_n = \frac{X_{\text{min}} + X_{\text{max}}}{2} \tag{3}
\]

The uncertainty, \( u_X \), of a tissue property was calculated using Eq. (4).

\[
u_x = \frac{X_n}{C_0} \tag{4}
\]

It may be noted that the uncertainty in metabolic rate was determined by assessing the resting metabolic rate of the whole body for different subjects [17]. In order to determine the resting metabolic rate for each domain of the whole body model, the resting metabolic rate values of individual tissues (e.g., heart, lungs, liver, etc.) [2,3,16] were utilized. The mass-weighted average metabolic rate calculated using this method was about 3200 kcal/day. However, this value was found to be higher than the physiologic average metabolic heat generation of 2000 kcal/day (96.85 W), reported [23,30,31] for a resting human being. Therefore, the metabolic rate value of each domain was scaled down to obtain the physiologic average energy consumption value. Corresponding to the two sets of metabolic rate values, two numerical core body temperatures were determined: \( T_{c,N} \) and \( T_{c,N} \), based on the metabolic rate values obtained from literature, \( q_\text{m} \), and \( T_{c,N} \), based on the scaled-down metabolic rate values, \( \hat{q}_i \). \( T_{c,N} \) and \( T_{c,N} \) in the current study were defined as the average tissue temperature of the gut region. The material properties of the firefighting suit were unavailable and were considered as proprietary information. Therefore, the material properties of the suit were based on the literature [32,33] and are reported in Table 3.

**Instantaneous Metabolic Rate.** The instantaneous metabolic rate, \( q_m \), in the Pennes’ equation (Eq. (A1) in the Appendix) is given by [34]

\[
q_m = \left( \frac{\sum q_i V_i + (HR - HR_0) \text{BSA}}{RM} \right) \left( \frac{1}{V_{\text{body}}} \right) \tag{5}
\]

where \( q_i \) and \( V_i \) are the resting volumetric metabolic rate and volume of individual domain, respectively; \( HR \) is the current heart rate; \( HR_0 \) is the experimentally recorded initial heart rate; \( RM \) is the increase in heart rate per unit metabolic rate; and \( \text{BSA} \) is the body surface area. \( RM \) and \( \text{BSA} \) are defined as

\[
RM = \frac{HR_{\text{max}} - HR_0}{MWC - \left( \frac{\sum q_i V_i}{\text{BSA}} \right)} \tag{6}
\]

\[
\text{BSA} = 0.202 \times W^{0.425} H^{0.725} \tag{7}
\]

**Table 1** Thermal conductivity, density, and specific heat for the whole body model

<table>
<thead>
<tr>
<th>Domain</th>
<th>Thermal conductivity, ( \kappa ) (W/m( ^\circ )C) [2,4,5]</th>
<th>Density, ( \rho ) (kg/m(^3)) [2,4,12–15]</th>
<th>Specific heat, ( c ) (J/kg(^\circ )C) [2,4,5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.43 ± 6.3%</td>
<td>1055 ± 4.3%</td>
<td>3089.4 ± 6.6%</td>
</tr>
<tr>
<td>Muscle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gut</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2 (a) A schematic of the 3D whole body model and (b) a typical mesh used for the computational simulations.
Table 2  Actual metabolic rate, scaled-down metabolic rate, and perfusion for the whole body model

<table>
<thead>
<tr>
<th>Domain</th>
<th>Actual metabolic rate, $q'$ (W/m$^3$) [23,16,17]</th>
<th>Scaled-down metabolic rate, $q$ (W/m$^3$)</th>
<th>Blood perfusion, $\phi$ (1/s) [2,5]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>9865.5 ± 18.4%</td>
<td>6191.0 ± 18.4%</td>
<td>0.0045</td>
</tr>
<tr>
<td>Muscle</td>
<td>597.5 ± 18.4%</td>
<td>375.0 ± 18.4%</td>
<td>0.0004</td>
</tr>
<tr>
<td>Organ</td>
<td>4326.9 ± 18.4%</td>
<td>2715.3 ± 18.4%</td>
<td>0.0030</td>
</tr>
<tr>
<td>Gut</td>
<td>6994.0 ± 18.4%</td>
<td>4389.0 ± 18.4%</td>
<td>0.0082</td>
</tr>
</tbody>
</table>

Table 3  Properties of the blood and firefighting suit

<table>
<thead>
<tr>
<th>Entity</th>
<th>Thermal conductivity, $k$ (W/m·C)</th>
<th>Density, $\rho$ (kg/m$^3$)</th>
<th>Specific heat, $c$ (J/kg·C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firefighting suit [32,33]</td>
<td>0.0345</td>
<td>135.96</td>
<td>1335.4</td>
</tr>
<tr>
<td>Blood [2]</td>
<td>0.510</td>
<td>1046.00</td>
<td>3651.0</td>
</tr>
</tbody>
</table>

where $HR_{\text{max}}$ is the maximum heart rate and MWC is the maximum working capacity defined as

$$HR_{\text{max}} = 205 - (0.624A)$$  \hspace{0.5cm} (8)

$$\text{MWC} = (41.7 - (0.224A))W^{0.666}$$  \hspace{0.5cm} (9)

where A is the age and W is the weight of the firefighter. In the model, 92% of the increase in metabolic rate was transferred to the muscle domain while the remaining was assigned to the organ domain [35]. The perfusion values for muscle and organ were allowed to vary with their respective metabolic rate values. However, perfusion values were limited between 0.0005 and 0.0115 s$^{-1}$ based on the physiologic variation in cardiac output (5–40 L/min).

**Cardiac Output and Stroke Volume.** Cardiac output was defined as the volume of blood being pumped by the heart per unit time. This, in the context of the current study, was the volumetric summation of perfusion in the body. Thus, the cardiac output is given by

$$\text{Cardiac Output} = (\omega_{\text{he}} \times V_{\text{he}}) + (\omega_{\text{mu}} \times V_{\text{mu}}) + (\omega_{\text{at}} \times V_{\text{at}}) + (\omega_{\text{gu}} \times V_{\text{gu}})$$  \hspace{0.5cm} (10)

where the subscripts “he,” “mu,” “or,” and “gu” refer to the domains, head, muscle, organ, and gut. The stroke volume was calculated by dividing the cardiac output by the heart rate.

**Boundary Conditions.** When the increase in perfusion was inadequate to regulate the body temperature, sweating was triggered to increase the removal of excess heat from the muscles [23,26]. This can be expressed as

$$-k_i \frac{\partial T_i}{\partial n} \bigg|_{\text{at surface}} = h(T_i - T_{\text{air}}) \bigg|_{\text{at surface}} + E$$  \hspace{0.5cm} (11)

where $n$ is the normal direction of the skin surface, $h$ is the heat transfer coefficient, and $T_{\text{air}}$ is the ambient air temperature. $E$ represents the heat loss due to sweating, which was calculated as a function of the evaporative heat transfer rate, $h_s$, and the difference between the vapor pressure of water at the skin temperature, $p_{\text{sk}}$, and the partial pressure of water vapor in the ambient air, $p_{\text{air}}$. Additional details about $p_{\text{sk}}$ and $p_{\text{air}}$ can be found in our previous study [23]. The expression for $E$ [30] is given as

$$E = 0.1333 \left[ \frac{\text{kPa}}{\text{mm Hg}} \right] w_f \phi (p_{\text{sk}} - p_{\text{air}})$$  \hspace{0.5cm} (12)

The skin wettedness factor, $w_f$, indicated the amount of skin layer that was covered with sweat and it varies between 0 and 1 [26,30]. The estimation of $w_f$ is challenging, particularly in events like firefighting as it is dependent on factors such as amount of skin exposure, time, clothing, ambient temperature, removal of sweat using absorbent, and humidity [36]. Therefore, in the present study, the $w$ was calculated based on the slope of $T_{\text{sk},\text{air}}$ and the duration of the rest periods. The optimized $w$ value of 0 for rest period R1 and 0.3 for rest period R2 was used for the computations [26,27]. The value of the intrinsic clothing thermal efficiency, $f_{\text{cl}}$, [30] was kept at 0.36 [26] for the torso and head regions during the rest periods.

The $h$ and $T_{\text{air}}$ values were provided as the boundary conditions to the model. At ambient conditions ($T_{\text{air}} = 25$ °C), the $h$ value of 4.7 W/m$^2$·C was iteratively determined by satisfying the steady-state condition [23], wherein, the tissue temperature is equal to initial $T_{\text{blood}}$ value of 37 °C.

**Uncertainty Analysis.** The whole body model was used to quantify the uncertainty in numerical core body temperatures ($T_{\text{c1}}$ and $T_{\text{c2}}$) due to variability in the tissue parameters (input parameters). The sensitivity coefficient method, which is a local approach, was used for conducting the uncertainty analysis [37]. The overall uncertainty in each numerical core body temperature can be calculated by

$$\sigma^2 = \sum_{i=1}^{n} \left( \frac{\partial S}{\partial X_i} u_i \right)^2$$  \hspace{0.5cm} (13)

where $n$ is the simulation uncertainty, $S$ is the simulation result ($T_{\text{c1}}$ or $T_{\text{c2}}$), $X_i$ represents the ith input parameter, $\partial S/\partial X_i$ is the sensitivity coefficient, $u_i$ is the experimental uncertainty in the ith input parameter, and $n$ is the number of input parameters. The expression for the sensitivity coefficient, obtained using Taylor series expansion, is given as

$$\frac{\partial S}{\partial X_i} = \frac{S(X_1, \ldots, X_i + \Delta X_i, \ldots, X_n) - S(X_1, \ldots, X_i - \Delta X_i, \ldots, X_n)}{2\Delta X_i} + O(\Delta X_i^2)$$  \hspace{0.5cm} (14)

where terms of second-order and higher are truncated, thus resulting in a second-order accurate central difference solution. Each input parameter was perturbed above and below its mean (baseline) value by a relative perturbation size, $\Delta X/X$, of 0.1.
This relative perturbation size was selected based on the recommended values in the ASME V&V 20, 2009 [37] for minimizing the truncation and round-off errors. Subsequently, the \( T_{\text{c,n}} \) values, computed using the perturbed input parameters, were used to obtain the sensitivity coefficient (Eq. (14)). The uncertainty, \( u \), in \( T_{\text{c,n}} \) was then calculated using Eq. (13). Thus, the total uncertainty, \( u \), accounts for the perturbation (\%T) of input parameter and the variability (\%u) in human subjects.

To determine the uncertainty in \( T_{\text{c,n}} \), \( 2n + 1 \) computations were performed where \( n \) is the number of input parameters. Although four tissue parameters (\( k, \rho, c, q \)) were chosen as input parameters for the uncertainty analysis, a different \( q \) value was assigned to each of the four domains \( \{ q_{\text{loc}}, q_{\text{max}}, q_{\text{min}}, q_{\text{eu}} \} \) for the computations. Considering each \( q \) to be a separate input parameter resulted in a total of seven input parameters. The uncertainty in \( T_{\text{c,n}} \) due to variability in \( k, \rho, c, \) and \( q \) was determined by adopting the same methodology.

The Pennes equation (Eq. (A1) in the Appendix) was solved by utilizing a first-order implicit transient scheme which is inherently stable and a second-order spatial discretization scheme. Further, an implicit formulation was employed to solve the energy balance equation (Eq. (A2) in the Appendix) [23]. A fixed time-step size of 20 s was used for a total time of 95 min (285 time-steps) to solve the transient thermal response. This size of the time-step was selected based on the acquisition of heart rate data [29]. Further, the energy residuals were converged to \( 10^{-10} \) at each time-step. For each time-step, approximately eight iterations were required for achieving convergence.

In addition, a mesh independence study was conducted on the whole body model. The mesh was refined until the change in steady-state temperature was less than 1% at ambient conditions (Fig. 2(b)). A total of 340,000 tetrahedral elements were used to discretize the human whole body computational domain. For all the computations, a finite volume solver (FLUENT, ANSYS, Inc., Canonsburg, PA) was used. User-defined functions, written in C programming language, were used to assess the effects of perfusion (Eq. (A1) in the Appendix), solve the energy balance equation (Eq. (A2) in the Appendix), and to compute the instantaneous metabolic rate (Eq. (5)) and heat loss due to sweating (Eq. (12)). Further details regarding the numerical schemes used for solving the governing equations are given in our previous study [23]. The individual uncertainty in \( T_{\text{c,n}} \) and \( T^{*}_{\text{c,n}} \) was initially evaluated by perturbing each tissue property at a time while keeping other input parameters at baseline values. Subsequently, the overall uncertainty at \( T_{\text{c,n}} \) and \( T^{*}_{\text{c,n}} \) was obtained by combining the individual uncertainties using Eq. (13).

**Results**

The transient variations in the core body temperature of the firefighter were determined using a whole body computational model. The \( T_{\text{c,n}} \) was quantified by accounting for individual and combined effects of variability in tissue parameters: specific heat, \( c \), density, \( \rho \), and conductivity, \( k \), as well as metabolic rate, \( q \). Additionally, the cardiac output and the stroke volume were also determined.

**Temperature Distribution.** The temperature contours at steady-state (prefirefighting scenario) and during a firefighting scenario (\( t = 60 \) min) are provided in Figs. 3(a) and 3(b), respectively. The firefighting training drill of 95 min consisted of alternating firefighting scenarios, Sc, and rest periods, \( R \). The computed steady-state temperature varied between 27.6 \( ^\circ \)C in the suit layer to 38.2 \( ^\circ \)C in the internal organs and gut (Fig. 3(a)). Lower temperatures were observed at the surface region of the whole body domain. Nearly uniform temperatures were observed in the inner regions, such as the torso and legs. The \( T_{\text{c,n}} \), defined as the average tissue temperature of the gut domain, was observed to be 37.4 \( ^\circ \)C. As a representative case, Fig. 3(b) shows the temperature distribution at the end of the second firefighting scenario (Sc2). The temperature field was found to be somewhat uniform in the inner regions. This is similar to that observed for the steady-state case (Fig. 3(a)). However, the temperature increased during the firefighting scenario and varied from 28.0 \( ^\circ \)C in the suit layer to 38.2 \( ^\circ \)C in the internal organs and gut.

![Temperature Distribution](image)

**Fig. 3 Contour plot of the whole body temperature at (a) steady-state and (b) at the end of work scenario 2 (Sc2)**

The corresponding \( T_{\text{c,n}} \) was calculated to be 38.2 \( ^\circ \)C and was around 2% higher than the steady-state \( T_{\text{c,n}} \).

**Temporal Variations in the Core Body Temperatures.** The \( T_{\text{c,n}} \) was compared with the numerical core body temperature, \( T^*_{\text{c,n}} \), as shown in Fig. 4(a). The \( T^*_{\text{c,n}} \) was computed using rest metabolic rate values, \( q^* \), obtained from previous studies [2,3,16,17]. The variations between \( T^*_{\text{c,n}} \) and \( T_{\text{c,n}} \) were observed to increase at higher temperatures (Fig. 4(a)). At Sc5 (\( t = 95 \) min), \( T^*_{\text{c,n}} \) was 40.0 \( ^\circ \)C while \( T_{\text{c,n}} \) was 38.6 \( ^\circ \)C resulting in a maximum difference of 1.4 \( ^\circ \)C or 3.6\% \( =\{40.0 - 38.6\}/38.6 \times 100\% \). A comparison of the numerical core body temperature, \( T_{\text{c,n}} \), based on scaled-down metabolic rate, \( q^* \), with \( T_{\text{c,n}} \) is shown in Fig. 4(b). A maximum deviation of 0.3 \( ^\circ \)C or 0.8\% \( =\{38.3 - 38.0\}/38.3 \times 100\% \) was observed at Sc2 (\( t = 54 \) min) between \( T_{\text{c,n}} \) (38.3 \( ^\circ \)C) and \( T_{\text{c,n}} \) (38.0 \( ^\circ \)C). This difference was comparatively better than the difference noted between \( T^*_{\text{c,n}} \) and \( T_{\text{c,n}} \) (Fig. 4(a)). Consequently, hereafter in the Results section, the individual uncertainty due to variability in each tissue parameter is reported...
for $T_{c,N}$ and not for $T_{c,c}$. However, the overall uncertainty is reported for both $T_{c,N}$ and $T_{c,c}$.

**Effect of Specific Heat, $c$, Density, $\rho$, and Conductivity, $k$.** The uncertainty in transient $T_{c,N}$ due to variability in $c$ is represented in Fig. 5(a). The uncertainty in $c$ was reported to be 6.6% (Table 1). Accounting for this uncertainty, a maximum uncertainty of $\pm 0.10 \, ^{\circ}C$ in $T_{c,N}$ was observed (Sc3, $t = 95 \, \text{min}$). Figure 5(b) illustrates the influence of variability in $\rho$ on the transient $T_{c,N}$. A 4.3% uncertainty in $\rho$ resulted in a maximum uncertainty of $\pm 0.07 \, ^{\circ}C$ (Sc3, $t = 95 \, \text{min}$) in $T_{c,N}$. Figure 5(c) illustrates the effect of variation in $k$ on the transient $T_{c,N}$. A maximum uncertainty of $\pm 0.01 \, ^{\circ}C$ in $T_{c,N}$ (Sc3, $t = 95 \, \text{min}$) was observed due to an uncertainty of 6.3% in $k$. It was observed that the $c$ had more influence on $T_{c,N}$ compared to $\rho$ and $k$. Furthermore, in the above three cases, the uncertainty in $T_{c,N}$ increased with the increase in $T_{c,N}$ value. For example, when the $T_{c,N}$ was $38.3 \, ^{\circ}C$, the uncertainty associated with it due to variability in $c$ was observed to be $\pm 0.06 \, ^{\circ}C$ (Fig. 5(a)). When the value increased to $38.8 \, ^{\circ}C$, the corresponding uncertainty was $\pm 0.10 \, ^{\circ}C$.

**Effect of Rest Metabolic Rate, $\dot{q}$.** Figure 6 illustrates the uncertainty in transient $T_{c,N}$ due to variability in $\dot{q}$. As a result of an 18.4% variability in $\dot{q}$, a maximum uncertainty of $\pm 0.20 \, ^{\circ}C$ was observed in $T_{c,N}$ ($t = 95 \, \text{min}$). Uncertainty in $T_{c,N}$ increased when the $T_{c,N}$ value got elevated. For example, the uncertainties in $T_{c,N}$ at the end of Sc1, Sc2, and Sc3 were observed to be $\pm 0.06 \, ^{\circ}C$, $\pm 0.13 \, ^{\circ}C$, and $\pm 0.20 \, ^{\circ}C$, respectively. These values corresponded to $T_{c,N}$ values of $37.7 \, ^{\circ}C$, $38.2 \, ^{\circ}C$, and $38.8 \, ^{\circ}C$, respectively. As observed from Figs. 5 and 6, $\dot{q}$ had a greater effect on $T_{c,N}$ in comparison to $c$, $\rho$, and $k$. 

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**Fig. 4** (a) Comparison of numerical core body temperature ($T_{c,N}$) with experimental core temperature ($T_{c,E}$) and (b) comparison of $T_{c,E}$ with core body temperature based on scaled-down metabolic rate ($T_{c,N}$)

**Fig. 5** Uncertainty in $T_{c,N}$ due to variability in (a) specific heat, $c$; (b) density, $\rho$; and (c) thermal conductivity, $k$.

**Fig. 6** Uncertainty in $T_{c,N}$ due variability in metabolic rate, $\dot{q}$.
The overall uncertainties in the sensitivity coefficient method for parameter uncertainty propagation were observed in the two numerical core body temperatures, $T_{c,E}$ and $T_{c,N}$. Higher uncertainty was observed in $T_{c,N}$ compared to $T_{c,E}$. Maximum uncertainty of $0.40\, ^\circ C$ was observed in $T_{c,N}$ compared to $0.23\, ^\circ C$ for $T_{c,E}$. Baseline $T_{c,N}$ showed a maximum deviation of 1.4$ ^\circ C$ or 3.6$ ^\circ C$ from $T_{c,E}$.

Core Body Temperatures. In our previous study [23], the average core body temperature was defined as the average tissue temperatures in the numerical core body temperatures, $T_{c,E}$ and $T_{c,N}$, was the same. The methodology adopted for the quantification of uncertainties in $T_{c,E}$ and $T_{c,N}$ was different. The overall uncertainties in $T_{c,E}$ and $T_{c,N}$ at a higher mean values. For example, uncertainty values in $T_{c,E}$ at the end of Sc1, Sc2, and Sc3 were observed to be $0.08\, ^\circ C$, $0.14\, ^\circ C$, and $0.23\, ^\circ C$, respectively. These values corresponded to $T_{c,N}$ values of $37.7\, ^\circ C$, $38.2\, ^\circ C$, and $38.8\, ^\circ C$. A maximum overall uncertainty of $0.23\, ^\circ C$ was observed in $T_{c,N}$ value of $38.8\, ^\circ C$. The $T_{c,N}$ values predicted by the computational model over the entire range of tissue parameters were observed to fall mostly within the range of $T_{c,E}$ values.

Comparing Overall Uncertainty in $T_{c,E}$ and $T_{c,N}$. The overall uncertainties in the two numerical core body temperatures, $T_{c,E}$ and $T_{c,N}$, based on the error in temperature measurement system, with that in $T_{c,L}$, is determined based on combined uncertainties due to variability in $\rho$, $q$, $c$, and $k$. Higher uncertainty was observed in $T_{c,N}$, at the end of Sc3.

**Discussion**

The variability in tissue parameters is observed to have an effect on the core body temperature of firefighters during firefighting. This effect can be quantified using a whole body computational model as demonstrated in the results above. Using the sensitivity coefficient method for uncertainty analysis, we could assess the influence of individual and combined variability in tissue parameters on $T_{c,N}$.

Temperature Distribution. From the results (Fig. 3(a)), the metabolic rate is observed to influence the steady-state temperature distribution in the human body. Elevated temperatures were observed in the inner zones (organ and gut) due to the higher metabolic rate in these domains. Similarly, higher temperature values were observed in the head due to the increased metabolic rate in the brain. However, the muscle and the suit layer exhibited reduced temperatures due to a lower metabolic rate and the ambient boundary condition, respectively.

**Core Body Temperatures.** In our previous study [23], the numerical core body temperature was defined as the average tissue temperature ($T_c$) of the “organ” domain. However, in the current study, the whole body model was subdivided to include an exclusive “gut” domain which was enclosed within the organ domain.

The average temperature in this domain was computed as the core body temperature. We assume that this modification could not affect the comparison between the numerical and experimental core body temperatures due to an improved localized averaging of the numerical core body temperature.

Variations in Core Body Temperatures. An increase in $T_{c,N}$ was observed at all scenarios. This can be attributed to the
continuous heat generation in the tissues, and ineffective heat dissipation from the body due to the presence of the suit layer (Figs. 4(a) and 4(b)). The suit layer, comprising of a “jacket” and “pants,” was worn throughout the firefighting scenarios (Sc1, Sc2, and Sc3). However, the jacket was removed by the firefighter during the rest periods (R1 and R2). This could be one of the reasons for the observed reduction in temperature rise during R1 and R2 (Figs. 4(a) and 4(b)). Further, variations were observed between the trends of \( T_{c,E} \) and \( T_{c,N} \). Specifically, there was a delay in time rate of change of \( T_{c,N} \) compared to that in \( T_{c,E} \). One of the reasons for the delay could be a lower thermal diffusivity adopted in the numerical analysis.

**Effect of Variability in Input Parameters on \( T_{c,N} \).** The variability in \( \dot{q} \) contributed highest toward the overall uncertainty in \( T_{c,N} \). One of the reasons for this effect is the higher variability in \( \dot{q} \) (18.4%) compared to the variability in \( c \) (6.6%), \( p \) (4.3%), and \( k \) (6.3%). Furthermore, the uncertainty in \( \dot{q} \) had an effect on the instantaneous metabolic rate, \( \dot{q}_m \), which, in turn, influenced the \( T_{c,N} \) [26,27]. This could be another reason for the higher effect of variability in \( \dot{q} \) on the uncertainty in \( T_{c,N} \).

**Cardiac Output and Stroke Volume.** The cardiac output and the stroke volume obtained in the current study were mostly within the physiological range [26]. It may be noted that a decrease in both cardiac output and stroke volume was observed at the end of firefighting scenarios 2 and 3 (Sc2 and Sc3). The stroke volume was determined from the cardiac output and the heart rate. While the cardiac output was associated with the overall perfusion in the body, the perfusion in the organ and muscle varied with their respective metabolic rates. Therefore, a better correlation between the perfusion and the metabolic rate could help in improving the determination of cardiac output and stroke volume.

**Limitations.** The following limitations have been identified which may change the outcomes reported above.

The whole body model assumed a constant value of ambient temperature \( (T_{a,w} = 25 \degree C) \) and heat transfer coefficient \( (h = 4.7 \text{ W/m}^2 \text{C}) \). However, these parameters can vary in realistic conditions [30].

The range of parameter values of several tissues was based on studies [2,3] conducted using limited number of subjects \((n < 10)\). Evaluating the data of a larger group of human subjects may lead to a more accurate estimation of the range of tissue parameters. The accuracy of the tissue parameters can be improved by conducting a more comprehensive analysis of individual tissues in the human body. The weighted average and overall ranges of values of tissue parameters were calculated based on a fixed mass of tissues [5], while the percentage content of different types of tissues in the human body (for example, fat/muscle content) and the weight of tissues may vary from person to person. In other words, knowledge of firefighter-specific tissue parameters is expected to improve the prediction of \( T_{c,N} \). Further, the variation of \( c, \rho, \) and \( k \) with temperature has not been accounted for in the present study.

The average \( \dot{q} \) of 3200 kcal/day (unscaled) calculated based on individual tissue values [2,3,16] was higher (~60%) than the reported average value of 2000 kcal/day (scaled) for a resting human being [23,30,31]. The resting \( \dot{q} \) for the firefighter could be higher, and it may influence the transient variation in \( \dot{q} \) with respect to the heart rate, which has been accounted for in this formulation. Therefore, incorporation of improved resting \( \dot{q} \) specific to individual firefighter could lead to a better comparison between the \( T_{c,E} \) and \( T_{c,N} \).

In the future, evaluating the effect of the variations in ambient conditions, properties of the firefighting suit, and the variation of tissue parameters with temperature can further enhance the applicability of the whole body model. Further, data-driven models have been reported to be effective for short-term prediction of the \( T_{c,N} \) of individual firefighters [38,39]. Therefore, individualized prediction of the \( T_{c,N} \) for a firefighter could be improved by developing hybrid models which combines the strength of the whole body model and the utility of data-driven predictive models.

**Conclusion**

The current study evaluated the effect of variability in tissue parameters on \( T_{c,N} \) of a firefighter using the whole body computational model. The uncertainty quantification facilitated in predicting a realistic range of \( T_{c,N} \) during firefighting by accounting for the natural variability in tissue parameters among the human population. Based on the results, variability in \( \dot{q} \) had the maximum contribution toward the overall uncertainty in \( T_{c,N} \) while variability in \( k \) was found to have the least effect on it. The applicability of the whole body computational model can be further extended to determine the \( T_{c,N} \) under different environmental factors and physiological conditions of individuals. Based on the model results, firefighters, athletes, and other personnel could be informed of when they should stop exercising to prevent health problems that arise due to higher thermal stress. This can be achieved using minimal real time data from the subject.

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**Nomenclature**

- \( A = \) age (yr)
- \( BSA = \) body surface area (m\(^2\))
- \( c = \) specific heat capacity (J/kg °C)
- \( E = \) heat loss due to sweating (W/m\(^2\))
- \( f = \) intrinsic thermal efficiency (dimensionless)
- \( h = \) overall heat transfer coefficient (W/m\(^2\) °C)
- \( HR = \) heart rate (beats/min)
- \( k = \) thermal conductivity (W/m °C)
- \( m = \) mass (kg)
- \( MWC = \) maximum working capacity (W/m\(^2\))
- \( p = \) vapor pressure of water (mm Hg)
- \( \dot{q} = \) scaled-down resting metabolic rate (W/m\(^3\))
- \( \dot{q}_m = \) instantaneous metabolic rate (W/m\(^3\))
- \( \dot{q}_r = \) resting metabolic rate obtained from literature (W/m\(^3\))
- \( R = \) rest period
- \( RM = \) increase in metabolic rate per unit heart rate (beats \( m^2/W \) min)
- \( S = \) simulation result
- \( Sc = \) firefighting scenario
- \( t = \) time (s)
- \( T = \) temperature (°C)
- \( T_c = \) core body temperature
- \( T_{c,E} = \) experimental core body temperature
- \( T_{c,N} = \) numerical core body temperature based on \( \dot{q}_r \)
- \( u = \) simulation uncertainty
- \( u_{is} = \) experimental uncertainty of a tissue property

- \( W = \) weight (kg)
- \( W/B = \) weight per body mass (kg/m\(^2\))
- \( W/BSA = \) weight per body surface area (kg/m\(^2\))
The volumetric average blood perfusion rate per unit volume of tissue, \( \dot{q}_w \), and the perfusion weighted average tissue temperature, \( T_w \), are defined as

\[
\dot{q}_w = \frac{1}{V_{\text{body}}} \iiint_{V_{\text{body}}} \rho \dot{q} \, dV_{\text{body}}
\]

\[
T_w = \frac{1}{\rho \dot{q}_w} \iiint_{V_{\text{body}}} \rho \dot{q} \, dV_{\text{body}}
\]


