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Application of thermoregulatory modeling to predict core and skin temperatures in firefighters

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ABSTRACT

The purpose of the study was to compare body temperature responses from subjects who exercised while wearing firefighter clothing to predictive data from a real-time thermoregulatory model that had been initially developed and validated for use in the military. Data from two firefighter studies, firefighter study 1 (FFS1: 7 males and 3 females, continuous treadmill exercise at 50% VO_{2max}, 25 °C, 50% RH) and firefighter study 2 (FFS2: 6 males, intermittent treadmill exercise at 75% VO_{2max}, 35 °C, 50% RH), were utilized for the thermoregulatory modeling and comparison. The results showed that prediction error (RMSD) of the model for core and skin temperatures was 0.33 and 0.65 °C in FFS1 and 0.39 and 0.86 °C in FFS2, respectively. While the real-time thermoregulatory model tested in the present study showed the potential for providing a means for reasonably accurate prediction of body temperature responses in firefighters, further development on the model's metabolism algorithms to include adjustments for protective clothing, options to facilitate external work, inclusions of cooling effects are suggested.

Relevance to industry: Firefighters exposed to thermal extremes experience physiological strain, but direct monitoring of physiological variables is not always practical. Thermoregulatory models can simulate the thermal responses reasonably accurately by applying known thermo-physiological mechanisms together with heat loss mechanisms related to clothing and environment in an effort to improve firefighter safety.

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1. Introduction

Firefighting is one of the most physically demanding occupations with a high risk of exposure to environmental and chemical hazards which require firefighters to wear personal protective equipment (PPE) and self-contained breathing apparatus (SCBA). The physical demands of firefighter activities in various tasks resulting from intrinsic metabolic demands and extrinsic clothing factors force firefighters to work at near and/or maximal heart rate (HR) (Barr et al., 2010; Bilzon et al., 2001; von Heimburg et al., 2006). In particular, the combined weight of both the PPE and SCBA as well as the clothing insulation characteristics (e.g., increased thermal resistance and decreased vapor permeability) play a significant role in determining the physical demands experienced by firefighters performing various tasks (Bruce-Low et al., 2007; White et al., 1989). Previous investigations (Bilzon et al., 2001; Bishop et al., 1995; Cloutier and Champoux, 2000; Rossi, 2003; Smith et al., 2001; von Heimburg et al., 2006) have well documented profiles of physiological and thermoregulatory strain resulting from performing various firefighter activities which highlight the compromised physical capability, an early onset of volitional fatigue, impaired cognitive function, reduced work tolerance, and coupled with an increased risk of physical injuries and illness (e.g., heat stroke).

Over the past several decades, laboratory and field-based human heat stress studies, including simulated firefighter activities, have provided valuable information that has helped to identify the thermo-physiological responses to firefighter activities and provide practical safety information for firefighters. These numerous human studies have also contributed to the development of a number of heat stress indices (HSI) applicable to individuals in occupational settings (Barr et al., 2010). Yet, no single HSI is universally accepted in the field (Brake and Bates, 2002), and certain HSI are of limited value for firefighters. For example, Wet Bulb Globe Temperature (WBGT), commonly used in military training and athletic settings, may not be an adequate heat stress index for firefighters engaging in active structural firefighting in which thermal extremes of 1–4 kW m^2 radiant heat and

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100–160 °C ambient temperature are achieved (Barr et al., 2010). Although monitoring physiological variables, such as the metabolic rate and body temperature of a firefighter working in these thermal extremes, may be the best approach in assessing the firefighters' thermo-physiological strain and determining their work limit, direct acquisition of such physiological data may not be practical in the field. Thermoregulatory mathematical models, on the other hand, can simulate the physiological stress responses reasonably accurately by rationally applying known thermo-physiological mechanisms of metabolism, respiration, skin blood flow, and sweating, together with heat loss mechanisms related to clothing and environment.

The purpose of the present study was to demonstrate the utility of a thermoregulatory model in predicting body temperature responses of firefighters and comparing this prediction to the observed responses to simulated firefighter activities. The thermoregulatory model utilized in this study was Initial Capability Decision Aid (ICDA) model originally developed primarily for military personnel and validated at the United States Army Research Institute of Environmental Medicine (Yokota et al., 2008, 2012). Thus, the present study examined the potential applicability of the model as a means of real-time prediction of the core body and skin temperatures of firefighters in the field.

2. Methods

2.1. Human subjects

Data ($n = 16$) from two firefighter studies that were conducted previously at the National Personal Protective Technology Laboratory (NPPTL) were used to compare core body (T_c) and skin (T_{sk}) temperatures observed from human subjects to those predicted by the thermoregulatory model. Although firefighter activities are often extremely strenuous, they are also often characterized by the combination of low intensity work for a prolonged period and moderate to high intensity work for shorter intermittent periods (Barr et al., 2010). Thus, we selected data set from the studies consisting of two different working intensities, duration, and environmental conditions. The duration of work in both studies was limited to 45 min to mimic a maximal allowable duration of firefighter activities under a standard 45 min rated SCBA. Both studies were originally approved by the National Institute for Occupational Safety and Health (NIOSH) Human Subjects Review Board (HSRB) and written informed consent was obtained from all subjects who participated in each of the studies. The subjects' characteristics and the study protocols are summarized in Table 1.

Table 1
Descriptive summary of the subjects' characteristics and study protocols.

Study	FFS1	FFS2
Subjects	10 (7 males, 3 females)	6 (all males)
Age (years)	25.3 (5.9)	30.5 (6.8)
Height (m)	1.7 (0.1)	1.8 (0.1)
Weight (kg)	73.1 (13.5)*	90.6 (12.2)*
VO_{2max} (ml kg^{-1} min^{-1})	45.2 (7.5)	46.3 (6.6)
A_D (m^2)[a]	1.9 (0.2)*	2.11 (0.1)*
Study protocol	Continuous	Intermittent
Exercise	Treadmill, 50% VO_{2max}	Treadmill, 75% VO_{2max}
Clothing	Structural firefighter clothing (1.6 clo)[b]	+SCBA
Total weight carriage (clothing + SCBA; kg)	20.0 (0.4)	20.2 (0.2)
T_a (°C)	22	35
RH (%)	50	50
Radiant heat	No	No

Values are mean (standard deviation).
*Significantly different between FFS1 and FFS2 ($p < 0.05$).
[a] Dubois body surface area ($0.202 \times \text{weight}^{0.425} \times \text{height}^{0.725}$).
[b] Thermal insulation of clothing (1 clo = 0.155 m^2 °C W^{-1}).

2.1.1. Firefighter study 1 (FFS1)

Ten subjects (7 males, 3 females) performed a continuous treadmill exercise in moderate ambient conditions (22 °C, 50% RH, 0.15 m s^{-1} wind speed) while wearing a standard set of structural firefighter clothing consisting of helmet, turnout jacket/pants, gloves, boots (intrinsic clothing insulation = 1.6 clo or 0.248 m^2 °C W^{-1}, Morning Pride/Total Fire Group, Dayton, OH), and SCBA (NXG2 Airpak, Scott Health & Safety, Monroe, NC). The subjects exercised at 50% of their maximal aerobic capacity (VO_{2max}) on an inclined treadmill until volitional fatigue or at the end of 45 min of exercise. Treadmill speed and incline yielding the target intensity was individually calculated from the subjects' initial VO_{2max} test results. Upon the termination of exercise, the subjects were seated on a chair for a 5 min recovery period while remaining fully clothed during which the physiological variables continued to be measured. Average exercise duration completed was 30.8 (8.1) min [mean (standard deviation)].

2.1.2. Firefighter study 2 (FFS2)

Six male subjects performed an intermittent treadmill exercise in hot ambient conditions (35 °C, 50% RH, 0.15 m s^{-1} wind speed) wearing the same firefighter clothing and SCBA combination as in FFS1. The exercise protocol consisted of three exercise–rest cycles with exercise at 75% VO_{2max} for 15 min separated by a 10 min rest period while seated on a chair exposed to the same environmental conditions (total protocol time of 75 min). However, exercise was stopped and shifted to rest if they reached volitional fatigue or any of the test termination criteria (e.g., 90% $HR_{max} > 1$ min, $T_c > 38.5$ °C). During this study, the subjects' turnout jacket was opened half way through during the first and second stages of rest and removed completely during the final stage of rest as a safety feature to promote heat dissipation in the hot environment. During these rest periods, we modified simulation values for heat dissipation from the clothing to 35% and 50% increase for the partial opening and the complete removal of the jacket, respectively. Average exercise duration completed for the three exercise stages was 24.8 (2.7) min.

In both studies, the subjects were hydrated by administering a controlled amount of water (5 ml kg^{-1} body mass) during an initial stabilization period which consisted of a 2 min warm-up stage (walking at 3.2 km h^{-1}, 0% grade) prior to the beginning of the main exercise stage. T_c was measured by a rectal thermistor (4600 precision rectal thermometer, YSI Temperature, Dayton, OH) and T_{sk} values were measured by skin thermistors (Grant probe high precision thermistors, Grant Instruments Ltd, Cambridgeshire, England) attached to the upper chest, front shoulder, anterior thigh, and shin in order to calculate a weighted mean T_{sk} (Ramanathan, 1964). The body temperature data were collected each second and presented as one-minute averages throughout the entire trial. HR was also continuously monitored by a HR monitor (Polar Heart Rate Monitor Series 610, Polar, Lake Success, NY) throughout the testing. HR input for the model was calculated from 1 min averages of measured HR from each individual subjects performing both the FFS1 and FFS2.

2.2. Initial Capability Decision Aid (ICDA) model

The ICDA model was chosen to predict core and skin temperature responses of firefighters in the present study as the model has been validated under both the controlled laboratory (Yokota et al., 2008) and field (Yokota et al., 2012) studies in military and civilian work scenarios. Thus, it is adequate to test the model applicability to an occupational setting at which the present study emphasizes on firefighter activities. The model consists of two main compartments (core and skin) surrounded by a passive clothing layer. This model utilizes non-invasive measures as baseline inputs including HR, environmental conditions (operative or ambient temperature, relative humidity, wind speed, and mean radiant temperature), clothing (insulation and permeability) in addition to a subject's anthropometric values (height, weight). These inputs characterize individuals and are used by the model to determine energy flows between and within the compartments, the body temperatures and thermo-physiological responses. All of the metabolic heat production (M) is assumed to be generated in the core compartment. The core transfers heat to the environment by several means including respiration (Q_{res}), conduction (Q_k) through the tissue to the skin, by convection through blood flow (Q_{bf}) between core and skin, and any external work (W_{ext}, e.g., climbing a hill, lifting weights etc). W_{ext} in real-life conditions, which may be difficult to quantify and measure in real-time, is rarely continuous for a long period of time and can often be neglected (Yokota et al., 2012). If the energy produced and lost by the core does not balance, the difference is stored (S_c) resulting in an increase in body temperature:

$$S_c = M - Q_{res} - Q_k - Q_{bf} - W_{ext} \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{1}$$

Metabolic heat production (M) of the model is calculated using the ratio of current measured experimental HR to the baseline HR, environmental operative temperature, and body surface area (Berglund, 1977):

$$M = [0.68 + 4.69(\mathrm{HR_{ratio}} - 1) - 0.052(\mathrm{HR_{ratio}} - 1)\,(T_a - 20)]58.1A_D \quad [\mathrm{W}] \tag{2}$$

where $\mathrm{HR_{ratio}}$: observed HR given at the time divided by baseline HR at a comfortable resting state immediately prior to initial work, A_D: Dubois body surface area (m^2). Operative temperature (T_o, in °C) is equivalent to the average of the mean radiant temperature (MRT) and ambient temperature (T_a) weighted by the relevant heat transfer coefficients. In the present study, T_o was equal to T_a (when MRT was equal to T_a) in the uniform climate chamber environment. Prediction of M using equation (2) was tested for various laboratory conditions (T_a: 20–40 °C, $\mathrm{HR_{ratio}}$: 1.2–2.1, wind speed: 1.25 m s^{-1}, dew point temperature: ≤20 °C, clothing: 0.7 intrinsic clo) (Berglund, 1977). HR input for equation (2) was calculated from 1 min average of measured HR from each individual subject at the beginning of treadmill exercise in the FFS1 and FFS2.

The respiratory heat loss via convection and evaporation during inhalation and exhalation were determined by (Fanger, 1972; Kraning and Gonzalez, 1991):

$$Q_{res} = [0.0014M(34 - T_a) + 0.0023M(44 - P_a)]A_D^{-1} \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{3}$$

where T_a is the ambient temperature (°C) and P_a is the ambient water vapor pressure (Torr). Thus, T_a and P_a for studies 1 and 2 were 22 °C, 9.9 Torr and 35 °C, 21.1 Torr, respectively.

The passive heat conduction from core to skin based on the conductance of the tissue and temperatures between compartments was determined from (Gagge et al., 1986):

$$Q_k = k(T_c - T_{sk}) \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{4}$$

where k is the conductance of tissue between core and skin, 5.28 W/(°C*m^2). T_c is the core temperature and T_{sk} is the skin temperature.

The heat transported (Q_{bf}) by blood flow between core and skin is:

$$Q_{bf} = \mathrm{skbf} * \mathrm{cpb}(T_c - T_{sk}) \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{5}$$

where cpb is specific heat of blood (1.163 W h/(L °C) and skbf is the skin blood flow determined by the differences between temperatures of compartments and their set points, vasodilation, and vasoconstriction coefficients.

In a similar fashion, heat storage of skin (S_{sk}) and its rate of temperature change can be determined from an energy balance on the skin:

$$S_{sk} = \left(Q_{bf} + Q_k\right) - Q_{dry} - Q_{evap} \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{6}$$

where the heat flow by skin blood flow (Q_{bf}) and conduction (Q_k) are the same as determined for T_c in the equations (4) and (5). Q_{dry} represents dry heat loss from the skin and Q_{evap} is the evaporative heat loss. Q_{dry} was determined using a method described by (Kraning and Gonzalez, 1991):

$$Q_{dry} = (T_{sk} - T_o)\,R_{clt}^{-1} \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{7}$$

where T_{sk} is mean skin temperature, T_o is the operative temperature, and R_{clt} is the total thermal resistance (°C m^2 W^{-1}) of clothing and boundary layer from skin to the environment. The intrinsic value (clothing layer) of 1.6 clo (0.248 m^2 °C W^{-1}) for firefighter clothing was used to estimate R_{clt} in the model by adding the boundary layer resistance between the clothing and the local environment (Berglund, 1985).

The evaporative heat loss from the skin is from water diffusion through evaporation of sweat on the skin (Fanger, 1972):

$$Q_{evap} = (1 - \omega)0.06E_{max} + \omega E_{max} \quad \left[\mathrm{W \cdot m^{-2}}\right] \tag{8}$$

where ω is skin wettedness determined by the ratio of sweat evaporation to the rate of maximum evaporation (E_{max}) at completely wet skin. E_{max} is the maximum evaporative rate from skin completely covered with sweat, calculated from saturated vapor pressure (Torr) of water on the skin at the skin temperature and in the air at its dew point temperature (Gagge and Gonzalez, 1996).

2.3. Statistical analysis

The observed and predicted T_c were paired for each individual subject and analyzed using root mean square deviation (RMSD) analysis to evaluate the precision of the model as previously described (Haslam and Parsons, 1998). RMSD measures a difference between measured and predicted values across time and provide an average residual in the same unit of the measurement values. Typically, RMSD from the model prediction is directly compared with the average standard deviation of observed data from human testing. In the present study, accuracy of model prediction was considered acceptable when RMSD ≤ one standard deviation of the observed T_c and/or T_{sk}.

3. Results

Observed and predicted T_c and T_{sk} at the end of each stage in FFS1 are summarized in Table 2 and the overall T_c response across the time is depicted in Fig. 1(a). T_c response between observation and prediction was found to be similar during the first 5 min of exercise. Thereafter, both observed and predicted T_c, increased

Table 2
Descriptive summary of observed and predicted heart rate, core and skin temperature in FFS1.

Stage	Variables				
	Observed			Predicted	
	HR	T_c	T_{sk}	T_c	T_{sk}
Baseline	89.6 (16.6)	36.99 (0.36)	32.59 (0.74)	36.99 (0.36)	32.59 (0.74)
Warm-up	103.0 (16.9)	36.99 (0.34)	32.96 (0.96)	36.96 (0.32)	32.89 (0.80)
Exercise	179.0 (9.3)	37.71 (0.24)	35.99 (0.46)	38.27 (0.55)	35.88 (0.88)
Rest	135.4 (8.8)	37.89 (0.25)	35.81 (0.53)	38.36 (0.61)	35.03 (0.57)

Values are mean (standard deviation) ($n = 10$).

continuously, but the average rate of increase during exercise was greater in the predicted (0.040 °C min^{-1}) compared to the observed T_c (0.023 °C min^{-1}) thus resulting in the higher final T_c. This pattern accounted for approximately 0.56 °C and 0.47 °C at the end of exercise and at the 5 min rest period, respectively. T_{sk} responses between the observation and prediction did not differ initially while the observed T_{sk} kept rising at a greater rate than the predicted T_{sk} after 10 min of exercise. During rest, predicted T_{sk} recovery was more rapid following the cessation of exercise compared to the observed T_{sk}. Overall, T_c and T_{sk} predicted by the model showed RMSD of 0.33 °C and 0.65 °C, respectively, while the standard deviation from the observed T_c and T_{sk} across the time was 0.36 °C and 0.57 °C, respectively. Thus, for the FFS1 trial, the model prediction slightly overestimated the final T_c and T_{sk}, but reasonably agreed with the observed responses overall as defined as being one standard deviation of the observed data.

Observed and predicted T_c and T_{sk} at the end of each stage in FFS2 are summarized in Table 3 and the overall T_c response across the time is depicted in Fig. 1(b). The initial T_c observed in FFS2 was very similar to those in FFS1. However, the average rate of T_c increase at 75% VO_{2max} in a 35 °C environment of FFS2 was much greater in both observed (0.037 °C min^{-1}) and predicted (0.051 °C min^{-1}) values than found in FF1 at an exercise level of 50% VO_{2max} in a cooler (22 °C) environment. The predicted T_c was consistently higher over time and 0.60 °C greater at the peak value than was the observed T_c. The initial T_{sk} responses significantly differed between the observation and prediction although both observed and predicted T_{sk} reached a similar level at the end of 2nd exercise bout and paralleled thereafter. During the rest, T_{sk} recovery was greater in the observation than prediction in contrast to those in FFS1 in which the subjects remained fully clothed compared to those with a jacket removal during rest in FFS2. The model prediction of T_c and T_{sk} in FFS2 showed RMSD of 0.39 °C and 0.86 °C, respectively. These prediction errors are significantly greater than one and two standard deviations of observed T_c (0.24 °C) and T_{sk} (0.39 °C).

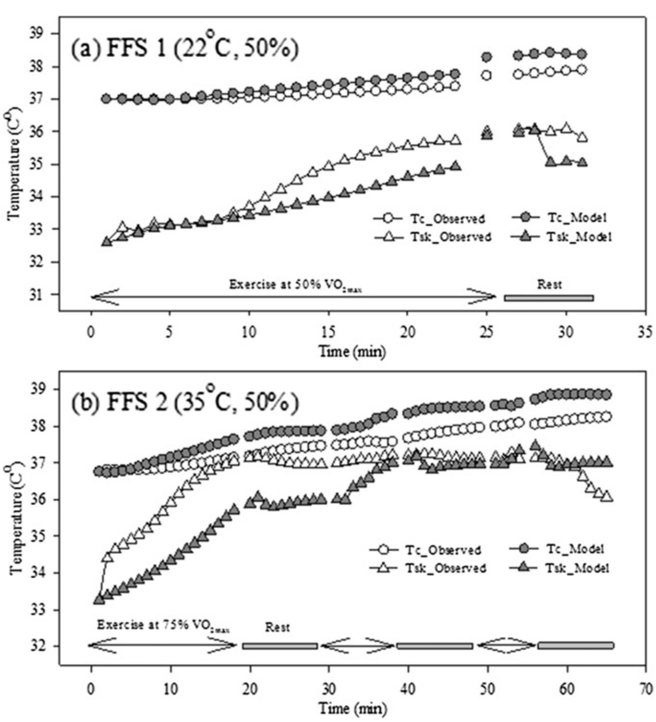

Fig. 1. Observed and predicted core and skin temperature responses from FFS1 (a) and FFS2 (b). Values are presented as mean (FFS1, $n = 10$; FFS2, $n = 6$).

4. Discussion

The present study was aimed at comparing the core body and skin temperature responses of firefighters observed from experimental trials and the real-time thermoregulatory model. To address this, T_c and T_{sk} responses in individuals performing two experimental firefighter protocols were compared with modeled outputs of T_c and T_{sk} predicted from HR-based metabolic calculation and the rational heat exchange mechanisms described previously. The model prediction of T_c and T_{sk} in FFS1 protocol (50% VO_{2max}, 22 °C, 50% RH) was similar to the observed T_c responses with prediction errors within an acceptable range. On the other hand, the prediction error of T_c and T_{sk} in the FFS2 protocol (75% VO_{2max}, 35 °C, 50% RH) was greater than one and two standard deviations of the observed T_c and T_{sk}, respectively. These ranges of prediction errors could only explain about 5–30% of the observed data. Thus, the model prediction in FFS2 was not as accurate as the prediction in FFS1.

The discrepancy between the observed and predicted thermoregulatory responses during exercise (specifically in FFS2) was indicated by the greater rise of T_c in the model prediction beginning after the initial 5–7 min of exercise. This was due to a greater HR_{ratio} resulting in the overestimation of M (equation (2)) compared to M actually achieved at any given time of exercise. The metabolic estimation in the proposed model was empirically derived taking into account the impact of various environmental temperatures on the HR of individuals who wore light clothing without any load carriages. Under these conditions, the model assumes that HR and M are linearly related (Berglund, 1977; Yokota et al., 2008). While the HR response to the heat exposure during rest and exercise has been well documented (Rowell et al., 1969), assumptions regarding the linear relationship between HR and M are limited when above the FLEX HR (defined as "the mean of the highest HR during rest and the lowest HR during lightly imposed exercise") and may require an individual calibration for a precise estimation (Ceesay et al., 1989; Williams et al., 1962). Additionally, from the onset of exercise to achieving steady-state exercise, oxygen consumption does not initially match exercise intensity resulting in what is known as oxygen deficit (Whipp, 1971; Whipp and Wasserman, 1972); thus a lag period exists until the body achieves a steady-state oxygen consumption (Kay et al., 1995). Therefore, taking into account the initial increase in HR as entirely a function of changes in M, especially in the heat, may require adjusting factors to realistically predict M.

Another component of prediction error noted was a predicted T_c pattern that deviated from that observed during recovery. The prediction line appeared to decrease and/or plateau immediately after the cessation of each exercise bout. This situation represents negative and/or zero instantaneous heat storage whereas the observed T_c increased continuously at an attenuated rate of rise compared to exercise. This abrupt transition to the thermal balance

Table 3
Descriptive summary of observed and predicted heart rate, core and skin temperature in FFS2.

Stage	Variables				
	Observed			Predicted	
	HR	T_c	T_{sk}	T_c	T_{sk}
Baseline	77.3 (7.6)	36.75 (0.15)	33.26 (0.87)	36.75 (0.15)	33.26 (0.87)
Warm-up	97.7 (9.1)	36.80 (0.15)	34.63 (0.76)	36.74 (0.15)	33.48 (0.82)
Exercise 1	157.4 (23.5)	37.13 (0.17)	37.04 (0.33)	37.64 (0.17)	35.71 (0.21)
Rest 1	129.7 (14.7)	37.46 (0.21)	36.95 (0.29)	37.86 (0.21)	35.99 (0.30)
Exercise 2	175.8 (6.8)	37.63 (0.27)	37.17 (0.37)	38.25 (0.27)	36.93 (0.38)
Rest 2	136.2 (9.1)	37.96 (0.28)	37.13 (0.24)	38.53 (0.28)	36.96 (0.41)
Exercise 3	178.9 (8.5)	38.02 (0.29)	37.08 (0.49)	38.64 (0.29)	37.38 (0.46)
Rest 3	122.3 (11.3)	38.25 (0.29)	36.06 (0.93)	38.85 (0.29)	37.01 (0.43)

Values are mean (standard deviation) ($n = 6$).

between metabolic heat production and heat loss seems unlikely especially given the fact that the environmental conditions remained constant without active cooling provided to the subject. Lastly, the model prediction showed consistently lower T_{sk} than observation which showed a more abrupt rise during the first few minutes of exercise, especially in the hot ambient condition. However, increased insulation and evaporative resistance of highly insulating clothing like firefighter PPE impede both dry heat loss and sweat evaporation. The trapped heat and humidity elevates the microclimate thermal stress inside PPE which further leads to an increase of skin temperature, especially during work under non-compensable thermal conditions. Thus, adjustments in heat exchange as a function of PPE insulation and breathability characteristics need to be reassessed.

It has been demonstrated that other thermoregulatory models predicted greater than the mean of two standard deviations from the observed data over time (Cadarette et al., 1999; Haslam and Parsons, 1998) thus accounting for only about 5% of the observed responses. A recent study (Wang et al., 2011) that validated the accuracy of the Predicted Heat Strain model (PHS) under different clothing ensembles reported a prediction error (RMSD) of 2–3.2 times greater than that observed for T_{sk} in various types of clothing tested and 3.7 times greater than that observed for T_c in firefighter PPE. Compared to previous studies, prediction error for T_c in the present study showed an acceptable and/or moderate level of error presenting RMSD of 0.33 °C (0.91 SD) for FFS1 and 0.39 °C (1.63 SD) for FFS2 under firefighter ensemble with SCBA. The advantage of the present model is its potential for real-time prediction for the core body and skin temperature responses of firefighters in the field. During actual firefighting activities, the implementation of an additional physiological monitoring system (e.g., portable indirect calorimetry) could cause a secondary hazard (Barr et al., 2010) and may not be feasible for a timely response to an emergency. However, HR can be attained relatively conveniently with a minimum of interference with other firefighting equipment. In fact, some previous studies have shown the possibility of monitoring HR during an extended shift and incidents (Bos et al., 2004; Kuorinka and Korhonen, 1981; Sothmann et al., 1992). Thus, the thermal strain of firefighters can be estimated from the model using monitored HR which may then be useful in assessing the safety of firefighters. The model may also be useful in guiding the implementation of additional fireground strategies such as task shifts, rehabilitation, and so forth.

The limitations of the present study include whether the human trials adequately represent the level of work encountered by firefighters on the fireground such that the measured thermal strain parameters were sufficiently realistic to compare with the predictive model. While this limitation exists, prolonged work at a low intensity and intermittent work at a high intensity are plausible work scenarios in the field (Barr et al., 2010). Moreover, the overall response and final outcomes of the thermoregulatory parameters agreed well with previous data used to simulate firefighter activities (Barr et al., 2010). It also must be acknowledged that no radiant heat source was present during the present human trials. Although many firefighter activities do not involve exposure to radiant heat, the lack of a radiant heat source prevents modeling of the physiological stress experienced by firefighters in structural fires; the model seems adequate for firefighter activities that do not involve radiant heat. While the current ICDA model algorisms exclusively take into account for anthropometric variables of subjects in the prediction, further studies regarding gender related differences such as sweat rate, physical fitness and/or metabolic heat production (Ashley et al., 2008; Mehnert et al., 2002) are warranted to better apply the model results into heat stress indices and/or exposure limits in diverse occupational populations.

5. Conclusion

The present study has shown an initial effort to apply the ICDA thermoregulatory model (Yokota et al., 2008), which was initially developed to predict the physiological status in military personnel during mission operation scenarios, to predict the body temperature responses in firefighters. The results showed that the model applicability to a specific occupational population wearing protective clothing seems promising with empirical follow-on modifications of the model algorithms.

Disclaimer

The opinions or assertions contained herein are solely the views of the authors and are not to be construed as either official policy or position of the NPPTL/NIOSH/CDC, the Army, or the Department of Defense. Mention of commercial products or trade names does not constitute endorsement by NPPTL/NIOSH/CDC, the Army, or the Department of Defense.

Conflict of interest

The authors do not identify any conflict of interest with regard to this study.

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