Prediction of Core Body Temperature from Multiple Variables

Victoria L. Richmond¹, ²*, Sarah Davey¹, Katy Griggs¹ and George Havenith¹

¹.Environmental Ergonomics Research Centre, Loughborough University, Loughborough, UK;
².Loughborough University, Loughborough, UK

*Author to whom correspondence should be addressed. The High Performance Centre, English Institute of Sport, Bisham Abbey National Sports Centre, Bucks SL7 1RB, UK; Tel: 07747 797052; e-mail: victoria.downie@eis2win.co.uk

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ABSTRACT

This paper aims to improve the prediction of rectal temperature (\(T_{re}\)) from insulated skin temperature (\(T_{is}\)) and micro-climate temperature (\(T_{mc}\)) previously reported (Richmond et al., Insulated skin temperature as a measure of core body temperature for individuals wearing CBRN protective clothing. Physiol Meas 2013; 34:1531–43.) using additional physiological and/or environmental variables, under several clothing and climatic conditions. Twelve male (25.8 ± 5.1 years; 73.6 ± 11.5 kg; 178 ± 6 cm) and nine female (24.2 ± 5.1 years; 62.4 ± 11.5 kg; 169 ± 3 cm) volunteers completed six trials, each consisting of two 40-min periods of treadmill walking separated by a 20-min rest, wearing permeable or impermeable clothing, under neutral (25°C, 50%), moderate (35°C, 35%), and hot (40°C, 25%) conditions, with and without solar radiation (600 \(W \text{ m}^{-2}\)). Participants were measured for heart rate (HR) (Polar, Finland), skin temperature (\(T_s\)) at 11 sites, \(T_{is}\) (Grant, Cambridge, UK), and breathing rate (f) (Hidalgo, Cambridge, UK). \(T_{mc}\) and relative humidity were measured within the clothing. \(T_{re}\) was monitored as the ‘gold standard’ measure of \(T_c\) for industrial or military applications using a 10 cm flexible probe (Grant, Cambridge, UK). A stepwise multiple regression analysis was run to determine which of 30 variables (\(T_{is}\), \(T_s\) at 11 sites, HR, f, \(T_{mc}\), temperature, and humidity inside the clothing front and back, body mass, age, body fat, sex, clothing, Thermal comfort, sensation and perception, and sweat rate) were the strongest on which to base the model. Using a bootstrap methodology to develop the equation, the best model in terms of practicality and validity included \(T_{is}\), \(T_{mc}\), HR, and ‘work’ (0 = rest; 1 = exercise), predicting \(T_{re}\) with a standard error of the estimate of 0.27°C and adjusted \(r^2\) of 0.86. The sensitivity and specificity for predicting individuals who reached 39°C was 97 and 85%, respectively. Insulated skin temperature was the most important individual parameter for the prediction of \(T_{re}\). This paper provides novel information about the viability of predicting \(T_c\) under a wide range of conditions, using predictors which can practically be measured in a field environment.

KEYWORDS: extreme environments; heat stress; heat stress indices

INTRODUCTION

High core body temperature (\(T\)) is the single most reliable predictor of exhaustion during exercise in the heat (Montain et al., 1994) and the ability to monitor thermal responses could help reduce the risk of heat exhaustion for individuals working or exercising...
in hyperthermic conditions (Malchaire et al., 2001). However, the invasive monitoring of $T_c$ is often not practical for a host of reasons (acceptance, hygiene, comfort etc.), and to avoid the necessity to monitor the individual, many heat strain indices have been developed to predict human responses under certain conditions. These indices can be broken down into two main types; ‘empirical indices’ derived using samples of human subjects whose responses to a range of thermal environments are used to form an equation or nomogram; and ‘rational indices’ that utilize several measurements (e.g. environmental and clothing) and use heat transfer calculations to predict human responses to thermal environments, usually by means of a computer programme.

Of the two index types, rational indices are the most comprehensive as they are designed to integrate all environmental and behavioural variables, but as there is no practical way to measure all of these directly, they are often assumed or regarded as constants (Epstein and Moran, 2006). Additionally, these indices do not account for any variation in the responses between individuals, which would either place more people at risk or necessitate a conservative limit for withdrawal from exercise (Havenith, 1997, 2001; Havenith and Fiala, 2015). Physiological monitoring of individuals in thermally challenging environments to assess their heat strain could help mitigate these limitations. Moran et al. (1998b) attempted to do this with the physiological strain index (PSI), to produce a simple model, valid across any conditions. The PSI is based on heart rate (HR) and rectal temperature ($T_{re}$) and describes the combined cardiovascular and thermal strain on a scale of 0–10. Although there are several studies that support the validity of the PSI in its ability to distinguish between different levels of hydration and exercise intensity (Moran et al., 1998a), between genders (Moran et al., 1999) and different levels of physiological strain for firefighters in personal protective equipment (PPE) (Petruzello et al., 2009), the inclusion of an invasive measure of $T_c$ does not provide an acceptable heat strain index for use in the occupational setting. As an alternative, other surrogate, non-invasive measurements that estimate $T_c$ can be used that are suitable for field deployment such as tympanic, aural, forehead, or axilla temperature. These however tend to show less reliable associations with $T_{re}$ and oesophageal temperature (Ganio et al., 2009), and a viable alternative remains to be identified. A recent study showed that a prediction equation including insulated skin temperature ($T_s$) and microclimate temperature ($T_{mc}$) can predict $T_{re}$ with a standard error of the estimate (SEE) of 0.2°C in emergency service (ES) personnel wearing chemical biological, radiological, and nuclear (CBRN) protective clothing (Richmond et al., 2013). However, these findings were only valid under the specific conditions used in these exposures and the study did not include other variables that may further improve the prediction of $T_{re}$.

Similarly, Buller et al. (2011) proposed a model to estimate $T_s$ heat production, and heat loss from the body using real-time physiological measurements of HR, accelerometry, and skin heat flux using a dynamic Baysian Network model and a Kalman filter to enable forward predictions, but results may not be reliable enough to protect individuals in high heat stress conditions. Yokota et al. (2008) presented a model for predicting $T_c$ based on measured HR and environmental conditions, observing SEEs up to 0.31°C for the various datasets, and finally in 2013, Buller et al. (2013) used a Kalman filter approach in the estimation of human $T_c$ from sequential HR observations as a single parameter with 95% of predictions falling within ±0.63°C. Though all these methods may be acceptable for prediction of group responses, for individual’s protection the discrepancies were too large. Further, the datasets used had only a limited amount of data at very high $T_s$ and thus most of these statistics are based on the lower $T_c$ values, where the deviation is not relevant in any case (Havenith and Fiala, 2015).

As indicated by the studies mentioned above, there are known physiological responses that occur in association with exercise and climate induced hyperthermia which could be included in the model to help explain more of the variance in $T_s$ than can be attributed to $T_{is}$ and $T_{mc}$ only. HR increases during passive heat stress as a result of the changes in skin blood flow (SkBF). As $T_c$ increases, cutaneous vasodilation occurs to allow increased volumes of blood to flow to the skin to aid dry heat loss. Elevated skin temperature ($T_s$) is associated with reduced cardiac filling and stroke volume; therefore, the way to maintain cardiac output is by increasing HR. However, identifying the cardiovascular response to hyperthermia during exercise is complex because HR increases not only to assist cooling, but also to meet the additional oxygen...
requirement by the working muscles. The inclusion of a variable in the model which changes only in response to the increase in metabolic rate due to ‘work’ may improve the predictive power of HR. One such possibility is to investigate changes in breathing frequency \((f)\) as another physiological response that may reflect an increase in \(T_c\). Around 100 years ago it was first established by Haldane (1905) that hyperthermia increases ventilation \((V_e)\) \([\text{Tidal volume}, (V_e) \times f]\) in humans. The study showed that HR increased by about 36 b min\(^{-1}\) for every 1°C rise in \(T_c\) and that as \(T_c\) rises, the alveolar \(CO_2\) decreases (suggesting hyperpnea has occurred). While some studies suggest that the change in \(V_e\) during passive heat stress is due to an increase in \(f\) (Petersen and Vejby-Christensen, 1977; Fan et al., 2008), others show that the change in \(V_e\) is due to an increase in \(V_T\) (Gaudio and Abramson, 1968; Cabanac and White, 1995). During exercise, identifying the thermal component of the increase in \(V_e\) is complicated due to the added impact of exercise on breathing; however, the relationship between \(V_e\) and thermoregulation may result in \(f\) explaining some of the variance in \(T_{re}\).

The aim of this study was to investigate the potential of using a combination of simple non-invasive measures associated with \(T_c\) to improve the prediction of \(T_{re}\) over several, substantially different heat stress scenarios. Variations in the environment were introduced (work/rest cycles; clothing; environmental conditions; solar radiation) to ensure a more general applicability and validation of any prediction model developed. In order to assess the accuracy of \(T_{re}\) prediction, a pre-defined ‘acceptable’ limit should be set; however, opinion in the literature is divided on this point. While some authors have agreed that the standard deviation of a measurement site should not be greater than 0.1°C (Moran and Mendal, 2002), others are less stringent, accepting an SEE of 0.3°C (Gant et al., 2006) and ±0.5°C (Gunga et al., 2009) between a ‘gold standard’ and a surrogate measure of \(T_c\). However, accepting such large prediction errors would require work to stop at quite low predicted \(T_c\)’s to avoid placing workers at the extremes of the \(T_c\) distribution at risk. Based on evidence from the literature, and the SEE achieved using non-invasive measures in previous work (Richmond et al., 2013), this study aimed to achieve an SEE of ≤ 0.2°C.

**METHODS**

Twenty-one participants volunteered to take part in the trial. All participants were verbally briefed, issued with a participant information sheet, and gave written informed consent. Ethics approval for the procedures was secured from the Loughborough University ethics committee. All participants completed a health screening questionnaire prior to taking part in the study.

**Experimental protocol**

The study took place in the environmental chamber at Loughborough University. Prior to the trial, all participants carried out a sub-maximal and maximal intensity fitness test on a treadmill to determine maximum HR and maximum oxygen uptake (\(\dot{VO}_2_{\text{max}}\)). Participants were measured for height and body mass, as well as estimated body fat (%) (Durmin and Womersley, 1974). All participants completed between two and six trials under different environmental and clothing conditions (Table 1). Though temperatures were very different in conditions C1–C5, vapour pressures/concentrations were kept almost identical, and moisture load was instead induced by wearing PPE with different permeability. The experimental protocol involved sitting in the chamber for 10 min, followed by 2 × 40 min walking on a treadmill at a set speed and gradient (depending on the fitness and capability of the participant). The exercise intensity was ~40% \(\dot{VO}_2_{\text{max}}\) which was set using the corresponding HR identified from the fitness test. This was regarded as a reasonable work rate that could be sustained over the duration of a work shift. The 40min periods of exercise were separated by seated rest outside the chamber. The rest was included because a heat strain monitor needs to be valid during rest as well as exercise, not only so that \(T_c\) can continue to be monitored once exercise has ceased, but because heat exhaustion can still occur at rest. The length of the rest was determined by the \(T_c\) of the individual, with participants returning to the chamber once \(T_c\) had dropped by 0.4°C. In C6, the work period was increased to 60 min in order to elicit a greater hyperthermic response.

Two different PPE ensembles were worn: one permeable (PERM) and one impermeable (IMP). The PERM ensemble was a cotton coverall (Arco Ltd, Hull, UK) and the IMP ensemble was a coated nylon coverall (FRS Countryware Limited, Bridgnorth, UK). The same clothing was worn underneath the coveralls by all...
Table 1. Experimental conditions, including the ‘real-life’ conditions replicated.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T_{\text{amb}}, RH, P_a,$ and PPE</th>
<th>Real-life conditions</th>
</tr>
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<tbody>
<tr>
<td>C1</td>
<td>25°C, 50%, 11.5 g m$^{-3}$, IMP</td>
<td>Indoors, cool conditions, protective clothing</td>
</tr>
<tr>
<td>C2</td>
<td>40°C, 25%, 10.2 g m$^{-3}$, PERM</td>
<td>Indoors, hot factory conditions, basic level PPE</td>
</tr>
<tr>
<td>C3</td>
<td>40°C, 25%, 10.2 g m$^{-3}$, IMP</td>
<td>Indoors, hot factory, protective clothing</td>
</tr>
<tr>
<td>C4</td>
<td>30°C, 35%, 10.7 g m$^{-3}$, PERM, solar</td>
<td>Outdoors, hot sunny day, basic level PPE</td>
</tr>
<tr>
<td>C5</td>
<td>40°C, 25%, 10.2 g m$^{-3}$, PERM solar</td>
<td>Desert environment, basic level PPE</td>
</tr>
<tr>
<td>C6</td>
<td>40°C, 35%, 17.9 g m$^{-3}$, PERM</td>
<td>Indoors, hot factory, basic level PPE</td>
</tr>
</tbody>
</table>

Participants which consisted of black Lycra shorts and a long-sleeved cotton t-shirt. The clothing ensembles had the same total local thermal resistance (0.166 m$^2$ K W$^{-1}$), but the total local evaporative resistance was considerably higher for IMP (213 m$^2$ P$^{-1}$ a W$^{-1}$) than PERM (42.4 m$^2$ P$^{-1}$ a W$^{-1}$). The thermal and evaporative resistance of the clothing was measured using thermal manikin by EMPA, Switzerland. In the two solar conditions, two 1000 watt metal halide Compact Source Iodide lamps (GE Lighting) were used to simulate solar radiation, directed to the back of the participant. The amount of direct radiation was measured with a Pyranometer (CM11, Kipp & Zonen, the Netherlands) and kept at a fixed level of ~530 W·m$^{-2}$.

There were five termination criteria:

- $T_e$ of 39.5°C
- $T_s$ of 45°C
- HR >95 %max
- Voluntary withdrawal
- Withdrawal by experimenter

Measurements

On arrival, ~1h prior to the start of a trial commencing, participants were issued with, and inserted a rectal probe (Edale Instruments, Cambridge, UK) to a depth of 10cm. Rectal temperature was chosen as the ‘gold standard’ measure of $T_e$ for the purposes of this study. Participants were then asked to change into their standardized t-shirt and Lycra shorts, and return to the prep room for nude weight and clothed weight to be recorded (Sartorius IS 150 I GG-H scale, Sartorius, Goettingen, DE). Skin temperature was measured (iButton DS1192L, Homechip, Milton Keynes, UK) at 11 sites (forehead, chest, upper back, upper arm, lower arm, hand, lower back, abdomen, thigh, calf, and foot), and secured using a soft cloth hypoallergenic tape (3M Medipore, 3M Healthcare, UK). Insulated skin temperature was measured at the lower part of the neck between C7 and T2 (spinoous process) using skin probes (Grant Instruments, Cambridge, UK) connected to a Squirrel SQ800 data logger (Grant Instruments, Cambridge, UK) which recorded data every 20 s. The probe was covered by a 5 cm × 5 cm × 1 cm block of closed-cell cross linked polyethylene foam (Rubber Astic International, Birmingham, UK), which was secured around the probe head and onto the skin surface by use of a double-sided adhesive patch (3M Health Care, UK). A further layer of 11 cm × 11 cm single-sided adhesive patch (woven spun lace tape 1776, 3M Health Care, UK) was used to cover the polyethylene block and provide additional skin adhesion. Micro-climate temperature was measured on the outer side of the insulation foam, also using a Grant thermistor. HR, $f$, and electrocardiogram (ECG) were measured using the Equivital monitor (Hidalgo, Cambridge, UK). HR was also measured using a polar HR monitor and watch (RS 800, Polar, Finland). Rectal temperature and HR were monitored ‘live’ throughout the trials for safety, and were recorded at 5-min intervals so changes in the rate of rise could be observed. At the end of each trial, participants were re-weighed, both nude and with their clothing, to enable sweat rate and evaporative heat loss to be estimated. Participants were asked for their subjective rating of thermal comfort (TC), thermal sensation (TS), and thermal preference (TP) at the start and end of each exercise bout.

Statistical analysis

All values are presented as mean ± SD and statistical significance was accepted at the $P < 0.05$ level.
linear regression and univariate analysis of variance (ANOVA) were used to develop the prediction equation for $T_{re}$. The data from each condition for every participant taken at 10-min intervals were entered into SPSS in order to run an exploratory linear multiple regression analysis. Thirty potentially relevant variables ($T_{is}$, $T_{mc}$ at 11 sites, HR, $f$, $T_{mc}$, temperature, and humidity inside the clothing front and back, body mass, age, body fat, height, sex, clothing, $VO_2$, TC, TS, TP, and sweat rate) were entered into the model and a stepwise regression was performed. Using the results of that analysis, variables were added one by one to the model using the ‘enter’ method. In cases where the relationship between $T_{is}$ and the primary variable in the equation was better described as a curvilinear model, the covariates were centred to reduce collinearity (Bland, 2000). Once the best equation was determined using this model, fixed factors were added to the model using univariate ANOVA. In determining the most significant and practical covariates to include in the model, the improvement in the SEE and adjusted (adj) $r^2$ were examined as variables were added and removed.

Adherence to the assumptions of multiple regression was assessed (Havenith and Fiala, 2015). Independence of data points was determined using the Durbin–Watson statistic (Durbin and Watson, 1951), which tests a regression model for serial correlation. A value near 2 indicates non-autocorrelation, a value near 0 indicates positive autocorrelation, and a value near 4 indicates negative autocorrelation. Although there are some specific tables for determining upper and lower bounds of acceptability depending on the number of variables in the model and the number of data points, a value of between 1 and 3 is often regarded as ‘acceptable’ and is a useful rule of thumb for assessing the autocorrelation in a model. Data were also checked for outliers and heteroscedasticity.

Once the model structure in terms of included variables had been determined, it was validated using the same dataset, with a ‘leave-one-out’ bootstrapping approach. Twenty-one different equations (same variables, different coefficients) were developed, using 20 participants for each equation, leaving one out each time. Rectal temperature was then predicted for each participant using the equation from which they were excluded. The mean of the 20 coefficients was then taken to produce a more ‘robust’ equation based on an independent sample.

The validity of the model was assessed by (i) the SEE and (ii) by calculating the sensitivity (number of individuals over 39°C correctly identified) and specificity (number of individuals under 39°C correctly identified) of the model. Determining the sensitivity and specificity of the model was chosen as an additional assessment as it shows how many individuals are correctly or incorrectly identified as ‘safe’ or ‘at risk’ and therefore provides a tangible way of describing the validity of a measure.

RESULTS

The physical characteristics of the 21 participants are shown in Table 2.

Prediction of $T_{re}$

Figure 1 shows $T_{re}$ and HR for all conditions, with data points coded by work or rest. The HR associated with a given $T_{re}$ is lower during rest.

The exploratory stepwise regression analysis produced an equation that explained 82% of the variance with an SEE of 0.25°C, and included 13 variables (with most significant first; $T_{mc}$, $T_{is}$, HR, $VO_2$, chest temperature, lower arm temperature, upper arm temperature, age, sweat rate, hand temperature, mean $T_s$, and TC). The next step was to determine the most appropriate model using all the data. Due to the outcome of the stepwise prediction, $T_{is}$ and $T_{mc}$ were chosen as the first physiological measure on which to base the prediction model. The $T_{re}$ and $T_{is}$ at 10-min intervals from all participants ($n = 1091$) are shown in Fig. 2. This figure shows that the relationship between $T_{is}$ and $T_{re}$ is better described as a curvilinear model ($r^2 = 0.54$) than a linear model ($r^2 = 0.46$), therefore a curvilinear model was applied. All input variables were centred in order to reduce the problem of multicollinearity, which can occur when a single variable is used twice in a model ($x$ and $x^2$) (Bland, 2000).

The first model included centred $T_{is}$ ($cT_{is}$) and $cT_{is}^2$ and both variables were significant ($P < 0.05$, adj $r^2 = 0.54$, SEE = 0.38°C). The addition of centred $T_{mc}$ ($cT_{mc}$) improved adj $r^2$ to 0.76 and the SEE to 0.28°C ($P < 0.05$). In an attempt to improve this prediction, factors that might help distinguish between periods of work and rest were added to the model separately. Breathing rate and $VO_2$ were significant, but only marginally reduced the error ($P < 0.05$, adj $r^2 = 0.76,$
HR provided the greatest increase in \( \text{adj } r^2 \) (0.80) and decrease in the SEE (0.25°C). When ‘participants’ was added into the model as a fixed factor, there was an interaction effect between participant and \( T_{re} \), which resulted in an increase in \( \text{adj } r^2 \) to 0.83 and a decrease in the SEE to 0.23°C. This shows that the model provides a closer prediction of \( T_{re} \) when each participant has a different equation, but as this is impractical, this option was not followed up. Finally, PPE, sex, work, and training status (individuals were classed as ‘trained’ or ‘untrained’ based on their \( \dot{V}O_2 \max \)) were added to the model as fixed factors. Only sex and work had an interaction effect with \( T_{re} \) (adj \( r^2 \) = 0.80,

### Table 2. Descriptive characteristics of the participants (mean ± SD) (range).

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Male ((n = 12))</th>
<th>Female ((n = 9))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>25.8 ± 5.1 (19–36)</td>
<td>24.2 ± 5.7 (19–36)</td>
</tr>
<tr>
<td>Body mass (kg)</td>
<td>73.6 ± 11.5</td>
<td>62.4 ± 6.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>177.9 ± 5.6</td>
<td>168.7 ± 3.4</td>
</tr>
<tr>
<td>( \dot{V}O_2 \max ) (ml kg min(^{-1}))</td>
<td>52.3 ± 11.4</td>
<td>52.5 ± 11.6</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>13.3 ± 4.6</td>
<td>19.3 ± 8.1</td>
</tr>
</tbody>
</table>

**Figure 1** Rectal temperature \((T_{re})\) and heart rate during work and rest for all conditions.

**Figure 2** Measured rectal temperature \((T_{re})\) against measured insulated skin temperature \((T_{is})\) (°C) for all conditions.
SEE = 0.25°C and adj $r^2 = 0.81$, SEE = 0.24°C respectively, $P < 0.01$).

Using all the data, and taking into consideration practicality (limiting the number of predictors and considering the ease of obtaining them) and accuracy of the prediction, the following equation provides the optimal prediction of $T_{re}$:

$$T_{re} = 37.06 + (0.520 \times [T_{is} - 37.1])$$

$$- (0.061 \times [T_{mc} - 35.5]) +$$

$$+ (0.089 \times T_{is}^2 - 1378) +$$

$$+ (0.007 \times HR) - (0.294 \times work)$$

rest = 0; exercise = 1 adj $r^2 = 0.82$, SEE = 0.24°C.

In an attempt to improve the SEE, the next stage of the analysis involved developing prediction equations for a subset of data (accurate prediction of low $T_c$ was deemed irrelevant, and the focus was put on the higher values: $T_c \geq 36.5°C, n = 886$). For this subset of data, there was little difference in the relationship between $T_{re}$ and $T_{is} (\geq 36.5°C)$ when described as a linear ($r^2 = 0.43$, SEE = 0.40°C) or quadratic ($r^2 = 0.44$, SEE = 0.39°C) equation, so a linear equation was developed.

In order to remove the impact of any possible dependency between development and validation of the equation, 21 regression equations were developed, leaving one participant out from each analysis and using that person to validate the equation (bootstrap method). Rectal temperature was then predicted for each participant using the equation they were left out of in the development process. Figure 3 shows the regression line for predicted against measured $T_{re}$. The equations were developed using only $T_{is}$ data points above 36.5°C, so with the exclusion of these data points the adj $r^2 = 0.86$ ($P < 0.05$) and SEE = 0.27°C. The following equation was developed by averaging the coefficients from the 21 equations:

$$T_{re} = 15.35 + (0.648 \times T_{is}) - (0.064 \times T_{mc})$$

$$+ (0.008 \times HR) - (0.381 \times work)$$

rest = 0; exercise = 1.

Figure 3 also shows the sensitivity and specificity of predicted $T_{re}$ with a theoretical upper threshold of 39°C. The vertical dashed line takes into account the 0.27°C error. To protect 97.5% of individuals from exceeding a $T_{re}$ of 39°C, they need to stop at a predicted $T_{re}$ of 38.46°C $[39 - (2 \times SEE)]$. The sensitivity is increased to 97% (27 of 28 data points correctly identified as $>39°C$), but the specificity is reduced to 85%. In protecting most individuals from possible heat illness, many individuals would be stopped at an actual $T_c$ of below the designated $T_{re}$ limit (bottom right quadrant of the graph). The solid horizontal line indicates the current safe recommendation by the World Health Organisation of 38°C (WHO, 1996).

**DISCUSSION**

This study aimed to determine whether $T_{re}$ changes during exercise can be modelled using non-invasive physiological, physical, and/or environmental measures. To avoid the criticisms on earlier studies, rather than focussing on a single condition, the experimental trials included as many conditions and measurements as were feasible, with an exercise protocol developed to elicit physiological responses indicating high strain levels. This project covered four different, low humidity external climates, and by using impermeable garments too also produced skin microclimates with very high humidity, whereby a very wide range of skin micro-climate conditions were achieved.

Insulated skin temperature was the most important physiological parameter for the prediction of $T_{re}$ followed by $T_{mc}$. During heat stress, blood flow to the skin increases to dissipate the heat generated in the muscle (Bernard and Kenney, 1994). Through conduction, convection, radiation, and mostly evaporation, the blood loses heat through the skin before it is returned to the working muscle. The purpose of the insulation material at the surface of the skin is to impede this heat loss, therefore causing the temperature of the skin to become close or equal to $T_c$. The origin of the concept for using $T_{re}$ to predict $T_{re}$ comes from the convergence of $T_{is}$ and $T_c$ in conditions of uncompensable heat stress. As the temperature gradient between the core and environment reduces, the capacity for heat dissipation from core to skin is removed. Therefore, $T_c$ will converge with $T_{re}$ and the temperature of the skin will eventually reflect changes in $T_{re}$ (Pandolf and Goldman, 1978). Covering the skin thermistor with an insulation material should mimic this condition and provide an estimate of $T_{re}$.

In addition to $T_{is}$ and $T_{mc}$, several other potentially relevant physiological measures were added to the equation to see whether they could improve the prediction. When added to the equation in combination with ‘work’, HR explained a significant amount of the
variance in $T_{re}$; thus improving the predictive capacity of the equation. During passive heat stress, SkBF increases in response to rises in $T_r$ and $T_c$. This elevation in SkBF occurs through an increase in cutaneous vascular conductance and cardiac output (Crandall et al., 1999). Rowell et al. (1969) showed an increase in HR of 82 b·min$^{-1}$ following 30 min of passive heating from a $T_{re}$ of 37.12 to 38.23°C. Similarly, Crandall et al. (1999) reported an increase in HR of 23 b·min$^{-1}$ when $T_{es}$ increased from 36.5 to 37.2°C during passive heating, showing a cardiovascular response to hyperthermia. During exercise, this relationship becomes more complex. The onset of exercise is accompanied by an initial increase in cutaneous vasoconstriction as blood is directed away from the skin and towards the working muscles (Hunold et al., 1992). Therefore, any increase in HR at the onset of exercise is due to the increased requirement of blood to the working muscles. As exercise continues and metabolic heat production causes internal temperature to rise, a threshold is reached at which thermoregulatory reflexes are evoked (Johnson and Park, 1982). Above this threshold, cutaneous vasodilation occurs to allow an increase in SkBF, which enables dry heat loss from the skin. This redistribution of fluids from the blood plasma to the skin tissue, as well as the increased demand for SkBF, causes a decrease in stroke volume, which results in an increase in HR to maintain cardiac output. This is known as cardiovascular drift and although it is influenced by an increase in body temperature, it is also affected by the increased oxygen cost of exercise. It was hypothesized that by identifying the proportion of the rise in HR during exercise which is due only to the thermoregulatory response, HR may provide an even stronger prediction of $T_{re}$. Figure 1 shows a comparison of the regression lines for HR against $T_{re}$ during ‘work’ and ‘rest’. This shows two things; firstly the increase in HR that occurs with increasing $T_{re}$ during rest; and secondly, the increase in HR between rest and work (for a given $T_{re}$) that occurs due to exercise. By including ‘work’ in the equation, the different intercepts of the two regression lines are accounted for, going some way to distinguishing between the cardiovascular response due to ‘work’ and due to the thermoregulatory response.

Breathing rate was included as a measurement due to the relationship that exists between $V_E$ and changes in $T_c$ (Haldane, 1905; Fujii et al., 2012). However, there were issues in this experiment with the measurement of $f$. Firstly, analysis of the data was difficult due to the many factors that affect $f$ including talking, drinking, or sporadic deep intakes of breath. Secondly, measurement of $f$ using the Equivital monitor was deemed unreliable: the monitor detects $f$ in two ways; one via impedance of the chest strap; and, one using the ECG signal. The values reported by these two methods were different, and it was not possible to determine which was more reliable. Despite these problems with the measurement of $f$, it was found to be significant in the model, albeit not powerful enough to warrant inclusion in the model. However, the effect of changes in $T_c$ on $V_E$ is well established, and this is a measure worthy
of further investigation if the problems associated with its measurement can be overcome.

The prediction of $T_{re}$ from $T_{es}$, $T_{mc}$, HR, and ‘work’ using the bootstrap method of validating the equation has a lower SEE (0.27°C) and explained more of the variance in $T_{re}$ (86%) than previous work that has used similar non-invasive measures to monitor heat strain. Xu et al. (2013) reported that $T_s$ and heat flux measured at the sternum explained ~75% of the variance in observed $T_s$ in hot environments for participants wearing army combat uniform and body armour. Niedermann et al. (2013) developed a model for participants exercising in hot (30°C) and ambient (10°C) conditions, and included three $T_s$ two skin heat fluxes and HR. The root mean square deviation ranged from 0.28 to 0.33°C in the various conditions, and the variables in the model explained a maximum of 73% of the variance in observed $T_{re}$. Taylor et al. (1998) compared four $T_{es}$ sites with $T_{es}$ while cycling at different intensities under five thermal loads. Oesophageal temperature was regressed against $T_{es}$ and the best prediction under all conditions was using $T_{es}$ on the spine ($r^2 = 0.86$). Although no values for error were given, the report states that temperatures were offset by as much as 2°C during the temperate conditions, whereas they converged in the heat, particularly when $T_{es}$ approached 39°C. Bernard and Kenney (1994) reported lower errors in the prediction of $T_{re}$ from non-invasive measures. Three thin copper disks each containing a thermocouple were placed on the skin with a thermal insulator between each disk. Under hot conditions in impermeable ($T_{amb}$ 55°C) and cotton ($T_{amb}$ 45°C) coveralls there was a high correlation of disk temperature with $T_{es}$ (0.93) and an SEE of 0.2°C.

Despite the positive findings from the current study in relation to much of the published literature, the model developed, using many more predictors, did not predict $T_{re}$ with a lower SEE than the previous work by our group (Richmond et al., 2013) in which $T_{es}$ and $T_{mc}$ only were used to model $T_{re}$ with an SEE of 0.2°C and an adj $r^2$ of 0.85 in ES personnel wearing CBRN protective clothing. One reason is the inclusion of several different climate and clothing conditions to develop a more universal equation. When the adj $r^2$ and SEE were calculated for each individual condition, the equations for three of the six conditions gave an SEE of 0.21°C; closer to the value deemed as ‘acceptable’ prior to the start of the study. However, when all the data were combined in order to develop a universal model, the additional variation added by the other conditions increased the error. Another possible reason is the different clothing that was used in this trial compared with previously. The PPE worn by ES personnel in our earlier study was fully encapsulated which reduces the exchange of heat between the surface of the skin and the environment. The impermeable clothing worn in the current study did not cover the head and neck of the participant, leaving the sensor patch and surrounding skin exposed to the environment. While the insulating material over the skin thermistor should minimize evaporative heat loss from the skin, it is possible that cooling of surrounding tissue caused a reduction in $T_{es}$ when exposed to open air conditions.

Although the SEE of 0.27°C fell outside the predefined acceptable error of 0.20°C, the impact of the error of the model developed on drop-out rate is still worthy of consideration. The sensitivity and specificity plot showed that to prevent 97.5% of the population from exceeding 39°C, they would need to be stopped at a predicted $T_{re}$ of 38.4°C. This would result in 50% of the population being withdrawn from work at a true $T_{re}$ of 38.65°C; considerably lower than many people can tolerate in compensable conditions. This would have a negative impact on work productivity and efficiency. Despite the SEE being lower than hoped, it is clear from Fig. 3 that using equation (2) to predict $T_{re}$ would improve considerably on the WHO standards (withdrawal at 38°C), with fewer individuals being stopped before reaching potentially critical temperatures, and therefore improving work productivity.

**CONCLUSION**

For the current study, which included six environmental conditions, two clothing ensembles, and a wide variety of physiological and environmental measurements, it was not possible to predict $T_{re}$ within the SEE of 0.2°C. However, the inclusion of ‘work’ and HR into the equation provided a better estimation of $T_{re}$ than $T_{es}$ and $T_{mc}$ alone, with ‘work’ helping to distinguish between the different regression lines observed for HR at work and at rest. It was hoped that $f$ might improve the prediction due to the relationship between $V_f$ and increasing $T_s$, but this was not possible due to problems with the measurement of $f$. Nevertheless, the relationship between $f$ and hyperthermia may be worth further
investigation under other conditions (e.g. when the individuals are not drinking or talking), and using different monitoring equipment. The findings from this work could be used to implement a practical, valid prediction of body temperature under certain conditions in the workplace (i.e. for selected conditions), thereby improving health, safety, and productivity. As these findings are specific only to the conditions trialled here, future work might also include repeating this study under additional conditions, and using fully encapsulated PPE to establish whether the addition of ‘work’ and HR improved further the errors reported previously (Richmond et al. 2013). However, given that in this study prediction models were investigated with the largest possible number of predictors, but in the end not achieving the required predictive power to work over the whole range of conditions tested here (which was extensive compared to other studies but not exhaustive), the idea that it is possible to create a universally usable non-invasive heat stress monitor may be unachievable.

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DECLARATION

The authors declare no conflict of interest relating to the material presented in this article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors.

REFERENCES

work in hot conditions. *Int Archives of Occ Env Health*; 75: 153–62.


