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Using the Thermal Work Limit (TWL) as an Environmental Determinant of Heat Stress for Construction Workers

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Abstract

Construction workers are vulnerable to heat stress in summer as evidenced by deaths and injuries caused by heat stroke. Over the past centuries, many heat stress indices have been developed to assist with the management of these problems. To address this pressing need of the industry, an enhanced model based on a multi-dimensional environmental indicator, the Thermal Work Limit (TWL) index, is developed. Field studies were conducted between July and September 2010 in Hong Kong on ten apparently healthy and experienced construction rebar workers. Based upon 281 sets of synchronized meteorological and physiological data collected from four different construction sites, physiological, work–related, environmental and personal parameters were measured to construct the heat stress model. Multiple linear regression showed that a total of ten determining factors are able to predict the workers' subjective Rating of Perceived Exertion (RPE)

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(adjusted R^2 =.79, p<.05). The accuracy of the TWL heat stress model was found to be statistically acceptable (Mean Absolute Percentage Error = 4.3%, Theil's U inequality coefficients = 0.003). Alcohol drinking habit, age and work duration are the three most important predictors to determine the physiological responses of construction workers. The model reported in this paper provides a scientific prediction of the reality which may benefit the construction industry to produce solid guidelines for workers working in hot weather.

Keywords: Heat stress model; Tolerance; Outdoor; Heat stroke; Rebar workers

Introduction

Workers, soldiers, and travelers are often exposed to severe environmental heat stress, which may deteriorate work efficiency and productivity, and may even threaten survival (Kaming et al. 1997; Liu et al. 2003; Nielsen 2006; Rojas and Aramvareekul 2003). It is expected that the physiological heat strain experienced by an individual is affected by the total heat stress exposed to. Many previous research studies have estimated the stress inflicted by a wide range of work conditions and climate, and estimated the corresponding physiological strain and to combine them into a single heat stress index (Epstein and Moran 2006). A heat stress index is a single value that integrates the effects of the basic parameters in any human thermal environment such that its value varies with the thermal strain experienced by the individual (Parsons 2003). Over 60 heat stress indices have been developed (Parsons 2003) since Houghton and Yaglou formulated the Effective Temperature (ET) scale as an index of thermal comfort in 1923 (Houghton and Yaglou 1923).

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This index was originally established to provide a method for determining the combined effects of air temperature and humidity on thermal comfort (Steadman 1979). Many cities in the United States issue excessive heat alerts based on a heat index (HI), which is a metric using two common meteorological values, i.e., temperature and relative humidity (Metzger et al. 2010).

The HI, although simple in terms of understanding and application, has its own limitations. Four basic elements namely, air temperature, mean radiant temperature, absolute humidity, and air movement are common parameters for evaluating the thermal environment. Sunlight is the main component of the environmental heat load (Brotherhood 1987), and adequate air movement is essential for the efficient evaporation of sweat (Brotherhood 2008). By ignoring sunlight and wind, the temperature-humidity indices (i.e., ET and HI) could underestimate or overestimate environmental warmth. Some agencies (American College of Sports Medicine 2007; Grimmer 2006; Sports Medicine Australia 2001) recommended that a more embracing index, Wet Bulb Globe Temperature (WBGT) be used instead. WBGT is the most widely used index in assessing heat stress, and has been adopted by the US Occupational Health authorities and other national and international agencies as the basis of heat-stress standard (ACGIH 2000; ISO 7243 2003; Ramsey and Chai 1983).

Although WBGT responds to all four elements of the thermal environment (Budd 2008), it is relatively insensitive to the cooling effect of air movement (Brake and Bates 2002a). In practice WBGT is difficult to apply as it requires an estimation of the workers' metabolic rates, which will not only vary throughout a shift with different tasks performed, but also be voluntarily altered by self-pacing workers (Brake and Bates 2002a). Because of the above limitations, WBGT is considered as an excessively conservative index of environmental heat stress (Miller and Bates 2007). New generation of heat stress indices that address the inadequacies of WBGT have emerged since the last decade.

The ideal heat stress index is one that is simple to determine, reliable and unambiguous in its output, and does not require specific knowledge for its interpretation. One such enhancement is the Thermal Work Limit (TWL) (Bates and Miller 2002). Thermal Work Limit (TWL), included in the Australian Institute of Occupational Hygienists (AIOH) Heat Stress Standard, is a rational heat stress index (Brake 2004). This index has become the de-facto standard in underground mines in Australia, probably the most adverse occupational setting for heat stress. It has been demonstrated that TWL is a more realistic and reliable index of heat stress than other available indices in a variety of sports and circumstances (Brake 2004; Miller and Bates 2007). TWL is particularly suitable in situations where there is significant cooling related to air movement.TWL uses five environmental parameters (dry bulb, wet bulb and globe temperatures, wind speed and atmospheric pressure) and accommodates for the clothing factors to arrive at a prediction of a safe maximum continuously sustainable metabolic rate (W/m^2) for the conditions (Miller and Bates 2007). TWL has been introduced to several large industrial operations located well inside the tropical zone, resulting in a substantial and sustained fall in the incidence of heat illness (Brake and Bates 2002a). Thus, it may be a suitable index to be applied in the construction industry. The

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TWL algorithm accurately predicts work rates that would be limiting under a given set of environmental conditions. Guidelines for TWL are proposed along with recommended interventions by Brake and Bates (2002b). For example, work status is classified according to the values of TWL. If it is <115 W/m^2: withdrawal; 115-140 W/m^2: buffer; 141-220 W/m^2: acclimatization; and >220 W/m^2: unrestricted (Brake and Bates 2002b).

Rebar work is one of the most labor-intensive and long duration tasks in construction (Balasubramanian and Prasad 2007; Jarkas 2010). Due to global warming and urbanization, many subtropical regions such as Hong Kong suffer from high temperature (ranging from 29 °C to 34 °C), high humidity (ranging from 75% to 90%), and low wind speed in summer from July to September (Hong Kong Observatory 2011). The TWL approximately ranges from 240 W/m^2 to 90 W/m^2 during summer time in Hong Kong (Department of Employment, Economic Development and Innovation 2010; Hong Kong Observatory 2011). It was reported that 10 percent of rebar workers in Hong Kong have suffered heat stroke (Apple Daily 2009) and a rebar worker was reported to fall to death on a construction site because of heat stroke (Apple Daily 2010). However, unlike most developed countries (Moriokal et al. 2006; Townsend et al. 2011), there is no legal recommendation concerning the human work limit under hot weather in Hong Kong (Hu et al. 2012). One major reason may be the lack of empirical study showing the human work limit under heat and humid environment. Therefore, the aim of the current study was to develop a multi-dimensional environmental indicator (i.e., TWL) to predict the maximum work duration under different severity of heat stress.

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Methods and materials

Field studies were conducted during the summer time in Hong Kong (from July to September of 2010). Experimental research is a collection of research activities which use treatment and controlled testing to understand causal processes. In general, one or more variables are manipulated to determine their effect on a dependent variable (Experiment Resources 2008). Experiments are conducted at construction sites to determine relationships between identified variables by holding one, or a few variables constant and investigating the effect on the dependent variable of changing these independent variables. The main stages in experimental research are shown in Fig. 1. Rebar workers aged between 20 and 60 years old were invited to participate in this study. They performed tasks of fixing and bending steel reinforcement bars until voluntary exhaustion. The physiological conditions of participants and environmental parameters of construction sites were measured and monitored. Exploratory factor analysis (EFA) was applied to identify the physiological factors of rebar workers. Multiple linear regression was employed to establish the heat stress model. The accuracy of the model is verified against data which has not been used in developing the model. The Mean Absolute Percentage Error (MAPE) and Theil's U inequality coefficients were used to evaluate the forecasting performance of the model.

(Please insert Figure 1 here)

Target participants

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Ten apparently healthy and experienced construction rebar workers participated in this research study. Exclusion criteria included: flu in the week prior to participation, and a history of diagnosed major health problems including diabetes, hypertension, cardiovascular disease, neurological problem and regular medication intake. The physical characteristics of the participants were as follows (mean ± SE): age 39.0 ± 12.5 years old; height 169.2 ± 6.5 cm; weight 60.3 ± 6.2 kg; percentage of body fat 12.3 ± 4.3%; resting heart rate 78.0 ± 10.5 beats per minute; diastolic blood pressure 80.0 ± 10.0 mmHg; systolic blood pressure 127.8 ± 10.8 mmHg. Participants were clearly informed of the purposes and the procedures of the study before starting any tests. Written consent was obtained from all participants prior to the study. Their participation was on a voluntary basis and participants could withdraw at any time without penalty. Data collected from the study was password-protected and kept centrally in a stand-alone server and was used for this study only. The study was conducted according to the Declaration of Helsinki and the protocol was fully approved by the Research Committee of the authors' host institution.

Experimental procedures

Prior to the experiment, participants were asked to rest at room temperature of approximately 22°C for 15 minutes to stabilize their body temperature and heart rate. The minimum heart rate recorded during this period is considered as the resting heart rate (RHR). During this period, the testing procedures were fully explained to each participant. Whilst taking the rest, participants were requested to complete a pre-experiment individual data collection sheet which includes questions on age, height, smoking and alcohol drinking habits and other personal information.

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Smoking and alcohol drinking habits were recorded in three categories namely "none", "occasionally", and "usually" according to the amount of their weekly alcohol intake and daily cigarette consumption. Before the start of the test, participants were evaluated with measurement of body weight, percentage of body fat (PBF) and heart rate. Blood pressure was measured both before the field study and after the participants cooled down from work for 20 minutes.

Fig. 2 shows various apparatus used for the respective measurements of demographic, physiological data, as well as environmental data on site. Before the commencement of rebar work, heart rate (Heart rate monitor, Polar, Finland), blood pressure (HEM-712C, OMRON, Japan), and percentage of body fat (InBody 230, Biospace Co., Ltd., USA) of the participants were measured. The physiological parameters of the participants were measured by the portable metabolic cart ($K4b^2$, COSMED, Rome, Italy). Moreover, A heat stress monitor (QUESTempº 36, Australia) was deployed to measure the prevailing environmental data such as the dry bulb temperature, wet bulb temperature, globe temperature, relative humidity, and air velocity (wind speed) through an additional detachable air-probe.

(Please insert Figure 2 here)

During the experiment, participants performed steel bar bending and fixing tasks as per their usual daily work routine. Participants were permitted to drink water as they desired and necessary. Without disturbing participants' normal operation, participants were asked to report on a RPE

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value for every 5 minutes, to indicate the amount of strain or level of exhaustion. The RPE, defined as the intensity of subjective effort, stress, or discomfort felt during physical activity, has been discerned to be a simple and valid method for regulating exercise intensity (Coquart et al. 2009; Foster et al. 2001; Zeni et al. 1996). Perceived exertion was assessed with Borg CR10 Scale, a 10-point single-item scale with anchors ranging from 1 'very very easy' to 10 'maximal exertion' (Borg 1990). Oxygen consumption (VO2), minute ventilation (MV), respiratory exchange ratio (RER), metabolic equivalent (MET), energy expenditure (EE), heart rate (HR) and a train of objective physiological parameters were continuously monitored and recorded in every 5 seconds. Alongside with the measurement of physiological data, prevailing environmental parameters: dry bulb temperature, wet bulb temperature, globe temperature, wind speed were monitored and captured simultaneously. A clothing insulation factor of 0.60 clo (Mejet et al. 2008) corresponding to a typical dress code of wearing a T-shirt, light trousers and thick soled shoes was adopted in calculating the TWL. Entering those environmental parameters as well as atmospheric pressure and clothing insulation factor into the TWL calculator (Department of Employment, Economic Development nad Innovation 2010), a heat stress index value that a well hydrated, acclimatized worker can maintain in a specific thermal environment within safe limits of core body temperature and sweat rate can be computed. Values for the computed TWL ranged between 60 and 281 W/m^2. Fig. 3 exhibits the frequency distribution of TWL.

(Please insert Figure 3 here)

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Different stages of construction from foundation works to core structural works were studied to capture a wide spectrum of empirical data. Locations where the participants worked were recorded to ascertain the effects of heat stress under shade or direct sunlight. A total of 281 data sets of environmental and physiological data were captured in four construction sites over ten different working days. 271 sets of data were used to construct the heat stress model, and the remaining 10 sets were used for validation of the model developed.

TWL-heat stress model

Factors in the heat stress model

Heat incurred disorders accompanied with acute symptoms often appear at human physiological limits (Lu and Zhu 2007). The RPE scale can be considered as a practical and cost-effective approach to quantify the physiological responses during exercise such as construction works. It has been reported that RPE is highly correlated with many physiological factors such as heart rate, ventilation, respiratory rate, oxygen uptake, hydration status and fatigue in undertaking the work activity; work-related factors such as type of exercise and time; personal factors such as age, resting heart rate, percentage of body fat, clothing and drinking/smoking habits; as well as environmental factors such as temperature, relative humidity, wind speed and air quality (Dishman et al. 1994; Fogarty et al. 2005; Impellizzeri 2004; Ko et al. 1998; López-Miñarroa and Muyor Rodríguezb 2010; Nakamura et al. 2009; Shanholtzer and Patterson 2003; Spielholz 2006). TWL not only covers those environmental parameters but also accommodates for clothing

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characteristics. Air pollution is another factor that directly induces the metabolic disorders. Air pollution index (API) measured and updated hourly by the Hong Kong Environmental Protection Department is transformed by many complicated air quality data into a single number (Environmental Protection Department 2004). Table 1 summarizes the factors and relevant indicators influencing RPE as identified from earlier research studies (Chan et al. 2012).

(Please insert Table 1 here)

Descriptive statistics of physiological parameters

Objective physiological parameters such as VO2, MV, RER, MET, EE, HR were monitored in every 5 seconds. All analyses examining the six-subtest configuration were conducted using the correlation matrix shown in Table 2.

(Please insert Table 2 here)

Exploratory factor analysis (EFA) on physiological parameters

Exploratory factor analysis is a statistical grouping technique, and is widely used in social sciences (Hon et al. 2012; Hutcheson and Sofroniou 1999). This method combines variables that are collinear into clusters. This reduces the data set to a more manageable size while retaining as much as possible of the original information of the predictor variables (Norusis 2008). In this study, EFA technique was used to identify the physiological factors (underlying cluster of

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physiological variables) in rebar workers. The number of factors to represent the set of data was determined by examining the total percentage of variance explained by each factor. In this investigation, principal components analysis was selected to identify the underlying factors because of the distinctive characteristic of data-reduction capacity for factor extraction (Fox and Skitmore 2007). To obtain principal factors for a clearer image, factor extraction with Varimax Rotation and Kaiser Normalization were also conducted through the SPSS FACTOR program (SPSS V13.0, USA).

The appropriateness of the factor model was evaluated before using factor analysis in this study. The sampling adequacy using the Kaiser-Meyer-Olkin (KMO) value and the Barlett's Test of Sphericity were used to test out the appropriateness (Norusis 1993). The KMO value of .80 (acceptable value is more than .50) and Bartlett's p-value of .00 (allowable value is less than .05) were computed which implied that factor analysis was appropriate for the factor model (Sun et al. 2009). Both the eigenvalue criterion (according to which one drops any factors with an eigenvalue of less than one) and the scree plot criterion indicated the existence of two major latent structures (factors) as the best solution for explaining the variability in the data. Table 3 manifests that 82% of the total variance is attributable to two underlying factors. Therefore, physiological factor with two factors is considered adequate to represent the original data set.

To identify the factors, it is necessary to group the variables that have large loadings for the same factors (Kim and Mueller 1978). In fact, factor analysis does not attach labels to the factors and

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the substantive meaning given to a factor is typically based on the examination of what the high loading variables measure (Black 1997). Energy Consumption (EC) and Respiratory Exchange Rate (RER) were considered as appropriate labels for these two underlying factors, which are described in Table 3. The two underlying physiological factors were found to be in the range of -1 to 5 in this study. Therefore the level of workload is classified into three broad categories: *light* (EC = 0; RER = 0), *moderate* (EC = 2; RER = 2) and *heavy* (EC = 4; RER = 4) as advocated by Yeunga et al. (2005).

(Please insert Table 3 here)

Multiple regression analysis

Multiple regression analysis is used to analyze the relationship between a single dependent variable (RPE) and several independent variables [e.g. Age (A), Duration (T), Thermal Work Limit (TWL), Air Pollution Index (API), Alcohol Drinking Habit (ADH), Smoking Habit (SH), Percentage of Body Fat (PBF), Resting Heart Rate (RHR), Energy Consumption (EC), Respiratory Exchange Rate (RER), and Job Nature (JN)]. Since the rebar workers were allowed to have water intake as they desired and necessary, their hydration level was not included as a variable in this study (Nolte et al. 2011; Wilk et al. 2010). SH, ADH, JN are considered as dummy variables for qualitative facts in this regression model. Dummy variables are widely used as devices to sort data into mutually exclusive categories (Draper and Smith 1997).

It describes the process of constructing a mathematical expression or equation used to represent the behavior of the phenomenon being studied (Belsley et al. 1980; Chan et al. 2004). To compare across regression equations involving different numbers of independent variables or different sample sizes, the adjusted coefficient of determination (adjusted R^2) is calculated to reflect the goodness of fit of the model. Based on 271 sets of synchronized data, multiple regression analysis was conducted to construct the heat stress model.

While dealing with large number of independent variables, it is of significant importance to determine the best combination of these variables to predict the dependent variable. Stepwise regression method serves as a robust tool for the selection of best subset models, i.e. the best combination of independent variables that best fits the dependent variable with considerably less computing than is required for all possible regressions (Rawlings 1998). The variable selection process terminates when all variables in the model meet the criterion to stay and no variables outside the model meet the criterion to enter (SPSS Inc. 2004). It is reasonable to expect stepwise selection to have a greater chance of choosing the best independent variables factors related to physiological, work-related, environmental and personal factors with the application of SPSS. In this study, stepwise selection procedure was used to construct the multiple linear regression prediction model. However, it is inevitable that physical apparatus for taking measurements may have suffered a transient malfunction, which may result in a large negative impact on the accuracy and reliability of the model; therefore outliers at group-level per condition (at standard deviation ≥2.2) were identified and removed by the SPSS box-plot procedures (Chan et al. 2001; Schroeder

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et al. 1986). Twenty-three outliers were deleted after this analysis.

Regression results

Multiple stepwise regression analysis generates a linear equation that predicts a dependent variable as a function of several independent variables. Relationships between RPE and factors of physiological status were established by using the stepwise addition and deletion regression technique. The results of regressions on the single dependent variable RPE and the eleven independent variables were presented in Table 4. A multiple regression equation (RPE) with ten determining factors was finally constructed as shown in Eq. (1). The results from the best-fit run of multiple regression analysis indicated a p-value of less than .05 and adjusted R^2 value of .79, which implied a good-fit and a robust model (Chan et al. 2010).

$$RPE = -1.13-0.01TWL+1.30T+0.10API+0.07A-0.06PBF+2.30ADH+0.44SH+0.15EC+0.16RER-0.02RHR \quad \text{Eq. (1)}$$

where *TWL* is thermal work limit (W/m2); *T* is work duration (hour); *API* is air pollution index; *A* is age; *PBF* is percentage of body fat (%); *RHR* is resting heart rate; *ADH* is alcohol drinking habit ("none"= 0, "occasionally"= 1, "usually"= 2), *SH* is smoking habit ("none"= 0, "occasionally"= 1, "usually"= 2); *EC* is energy consumption; and *RER* is respiratory exchange rate.

(Please insert Table 4 here)

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Model validation

Model validation is an important step when developing a model, especially when dealing with multiple parameters. Validating and analyzing cases that get further from the database created is necessary and provide good answers of the accuracy of the model when it deals with completely different cases than the ones originally studied. The TWL-heat stress model was validated against data collected under the same experimental procedures but was not used in the construction of the model. Table 5 summarizes ten sets of comparisons between the reported values by the individual participants and the predicted values from the regression model equation.

The Mean Absolute Percentage Error (MAPE) and Theil's U inequality coefficients were used to evaluate the forecasting performance of the model. The prediction percentage error of the TWL-heat stress model is consistently within the acceptable limit of 10% (Goh 2000), giving a relatively low MAPE of 4.3%. The Theil's U statistics also reveal that the TWL-heat stress model has a high level of prediction. Hence, the results verify that the TWL-heat stress model is adequately accurate and robust to predict the physiological responses of rebar workers in Hong Kong.

(Please insert Table 5 here)

Discussion of regression results

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An enhanced heat stress model, based on a multi-dimensional environmental parameter, TWL, and other personal characteristics was developed. TWL is a thermal indicator integrating five main environmental variables of dry bulb, wet bulb and globe temperatures, wind speed and atmospheric pressure, and is more comprehensive and embracing than other environmental indicators such as the Heat Index (HI) (temperature plus relative humidity) and WBGT (dry-bulb, wet-bulb and globe temperatures). Additionally, TWL is applicable to situations where work is carried out in thermally stressful environments. With an adjusted R^2 value of .79 and a MAPE of 4.3%, the TWL-heat stress model which incorporates the individual's personal characteristics and other meteorological and physiological parameters, the prediction performance of the enhanced model is considered as reliable and accurate (Havenith 2001). The TWL-heat stress model reveals that RPE increases with age, work duration, air pollution index, alcohol drinking habit, smoking habit, respiratory exchange ratio, and energy consumption, but decreases with percentage of body fat, resting heart rate, and TWL.

The interrelations between morphological components and temperature regulation are complex. Differences in findings are often stemmed from varying combinations of components studied and the magnitude of the differences between the populations (Anderson 1999). Levels of body fat are epidemiologically dependent on gender and age (Jackson et al. 2002). Essential fat is the level below which physical and physiological health would be negatively affected. Controversy exists as to whether a particular body fat percentage is better for one's health (American Council on Exercise 2009). Although a negative correlation with PBF may appear counterintuitive, this

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finding reinforces the findings of Haymes et al. (1974) where they found that in the warmest environment (32.2 °C), lean subjects had higher rectal temperatures and greater changes in rectal temperatures during exercise than those of heavy subjects. In an experiment set up to quantify the relative influence of fitness, acclimatization, gender and anthropometric measures on physiological responses to heat stress, Havenith and Middendorp (1990) found that the PBF and the surface to mass ratio had relatively the largest influence of all the individual parameters for the variance in heat storage.

The relative importance of factors in predicting RPE can be seen in Table 5. Standardization of the coefficients is usually done to answer the question of which of the independent variables have a greater effect on the dependent variable in a multiple regression analysis, when the variables are measured in different units of measurement (Schroeder et al. 1986). Alcohol drinking habit, age, and work duration are the three most important predictors to determine the physiological responses of construction workers. However, it is stressed that these relative rankings should be interpreted with caution as they represent the resultant effect of a multiple regression model. Therefore, these variables should be interpreted collectively rather than individually.

An enhanced model, based on the Thermal Work Limit (TWL) index, is developed. When compared with the WBGT-heat stress model, its main strengths are that: (1) TWL is a thermal indicator integrating five environmental parameters (i.e. dry bulb, wet bulb and globe temperatures, wind speed and atmospheric pressure temperature, humidity, wind speed and solar radiation) as

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well as clothing insulation and vapor permeation, which is more comprehensive than the Wet Bulb Globe Temperature (WBGT) adopted in the previous model; and (2) although the adjusted R^2 (0.79) is the same as the WBGT-heat stress model (0.79), the MAPE (4.3%) is noticeably lower than the previous model (5.6%) and hence implying that the prediction performance of the enhanced model is more reliable and accurate.

Practical application to construction industry

The Hong Kong government and the whole construction industry have expressed profound concerns of working in hot weather and promulgated a series of fundamental practice notes and guidelines on working in hot weather. Preventive measures on work arrangement, work-break cycle and cool-down facilities have been advocated to protect site personnel working in hot weather. Apart from those fundamental practice notes and guidelines on working in hot weather, health and safety measures linked up to heat stress measured by scientific and clinical parameters are urgently needed.

The heat stress model could be further developed to determine the heat tolerance time (HTT) of rebar workers in practice. HTT is defined as the duration for a rebar worker to work continuously until exhaustion. Exhaustion was reached when the worker requested for a break or reported an RPE of 7 as “Very hard”. According to the heat stress model, HTT can be computed when other variables are kept constant. Table 6 illustrates the HTT at different levels of heat exposure by age and workload groups. It can be seen that the HTT for a 45 years old rebar worker, who does not

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smoke or consume alcohol, and work continuously at TWL of 160 W/m^2 and API of 30 with heavy workload, is 73 minutes (Eq.2, Table 6).

$$HTT = [7\ (RPE) + 1.13 + 0.01*160\ (TWL) - 0.10*40\ (API) - 0.07*45\ (A) + 0.06*12.3\ (PBF) - 2.30*1\ (ADH) - 0.44*1\ (SH) - 0.15*2\ (EC) - 0.16*2\ (RER) + 0.02*78\ (RHR)]/1.3*60 \quad \text{Eq. (2)}$$

where *TWL* is thermal work limit (W/m^2); HTT is heat tolerance time (min); *API* is air pollution index; *A* is age; *PBF* is percentage of body fat (%); *RHR* is resting heart rate; *ADH* is alcohol drinking habit ("none"= 0, "occasionally"= 1, "usually"= 2), *SH* is smoking habit ("none"= 0, "occasionally"= 1, "usually"= 2); *EC* is energy consumption ("light"= 0, "moderate"= 2, "heavy"= 4); and *RER* is respiratory exchange rate ("light"= 0, "moderate"= 2, "heavy"= 4).

(Please insert Table 6 here)

Protection of workers in hot environment requires a mechanism of identifying conditions where excessive thermal stress places their health at risk. International Standard ISO: 2004 (ISO 7933 2004) applies the predicted heat strain index, but the complexity of this index discourages its use. The American Conference of Governmental Industrial Hygienists (ACGIH)'s threshold limit value (TLV) (which is based on the WBGT index) provides useful advice to individual exposed to heat stress (ACGIH 2007). The existing shortcomings of WBGT are widely recognized (Brake and

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Bates 2002b; Taylor 2006) and include the need to estimate metabolic rates and its relative insensitivity to the cooling effect of air movement. Furthermore, existing OHS requirements (ACGIH 2000; ISO 7243 2003) on work limits at heat exposure failed to consider the personal characteristics (i.e., age, PBF, smoking and alcohol drinking habits, etc.), which would underestimate or overestimate the personal heat tolerance time. The HTT derived from the TWL-heat stress model refines the proposed guidelines along with recommended interventions by Brake and Bates (2002b), which is better able to safeguard workers' health and safety of site personnel working in hot weather and at the same time to ensure optimal labor productivity.

Strengths and limitations of the study

Construction management research, unlike other well defined and established disciplines, is very often being criticized of having an inappropriate research design and adopting an improper methodology. It is generally acknowledged that there is no best way of data collection (National Academy of Sciences 2008). This study illustrates how experimentation can be designed and applied in construction management research. Although the current study is limited in sample size, further research work with enlarged sample size should be launched to verify the current findings.

Conclusions

Workers in different industries may have different degrees of susceptibility to heat stress. An industry-specific study would better reflect the real situation. Since this study is addressed

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

specifically to the construction industry, more work is needed to further investigate other industries and in other countries to provide a holistic view in future. Environmental indicators such as the heat index and wet bulb globe temperature, although commonly applied to assess the thermal environment for simplicity reason, their shortcomings have been widely reported. A multi-dimensional index, TWL, was adopted to develop an enhanced heat stress model. It was found that personal factors such as age, smoking and alcohol drinking habits, resting heart rate and percentage of body fat; work related factors such as work duration; environmental factor such as TWL and air pollution index, and physiological factors such as energy consumption, and respiratory exchange rate are good predictors in determining rebar workers' physiological responses. Alcohol drinking habit, age and work duration are the three most important predictors to determine the physiological responses of construction workers. The prediction performance of the TWL-heat stress model was demonstrated to be reliable and accurate. With the help of the newly developed TWL-heat stress model, a set of good practices could be developed to ensure the health and safety of site personnel working in hot weather. This would be of tremendous value in better safeguarding workers' health and safety by reducing the occurrence of heat stroke on site.

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Appendix

List of variable descriptions and units

TWL	Thermal work limit (W/m^2)
RPE	Rating of perceived exertion
HI	Hear index (°C)
WBGT	Wet bulb globe temperature (°C)
PBF	Percentage of body fat (%)
RHR	Resting heart rate (bpm)
HR	Heart rate (bpm)
VO2	Oxygen consumption (ml/min/Kg)
MV	Minute ventilation (l/min)

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012; posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

RER	Respiratory exchange rate
MET	Metabolic equivalent
EE	Energy expenditure (Kcal/min)
API	Air pollution index
HTT	Heat tolerance time (min)
JN	Job nature (“bar bending” =1, “bar fixing” = 2)
A	Age (years)
T	Work duration (hour)
SH	Smoking habit (“none”= 0, “occasionally”= 1, “usually”= 2)
ADH	Alcohol drinking habit (“none”= 0, “occasionally”= 1, “usually”= 2)
Clo	Clothing insulation factor

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Figure Caption List

Figure 1

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Figure 1 Main stages in experimental research

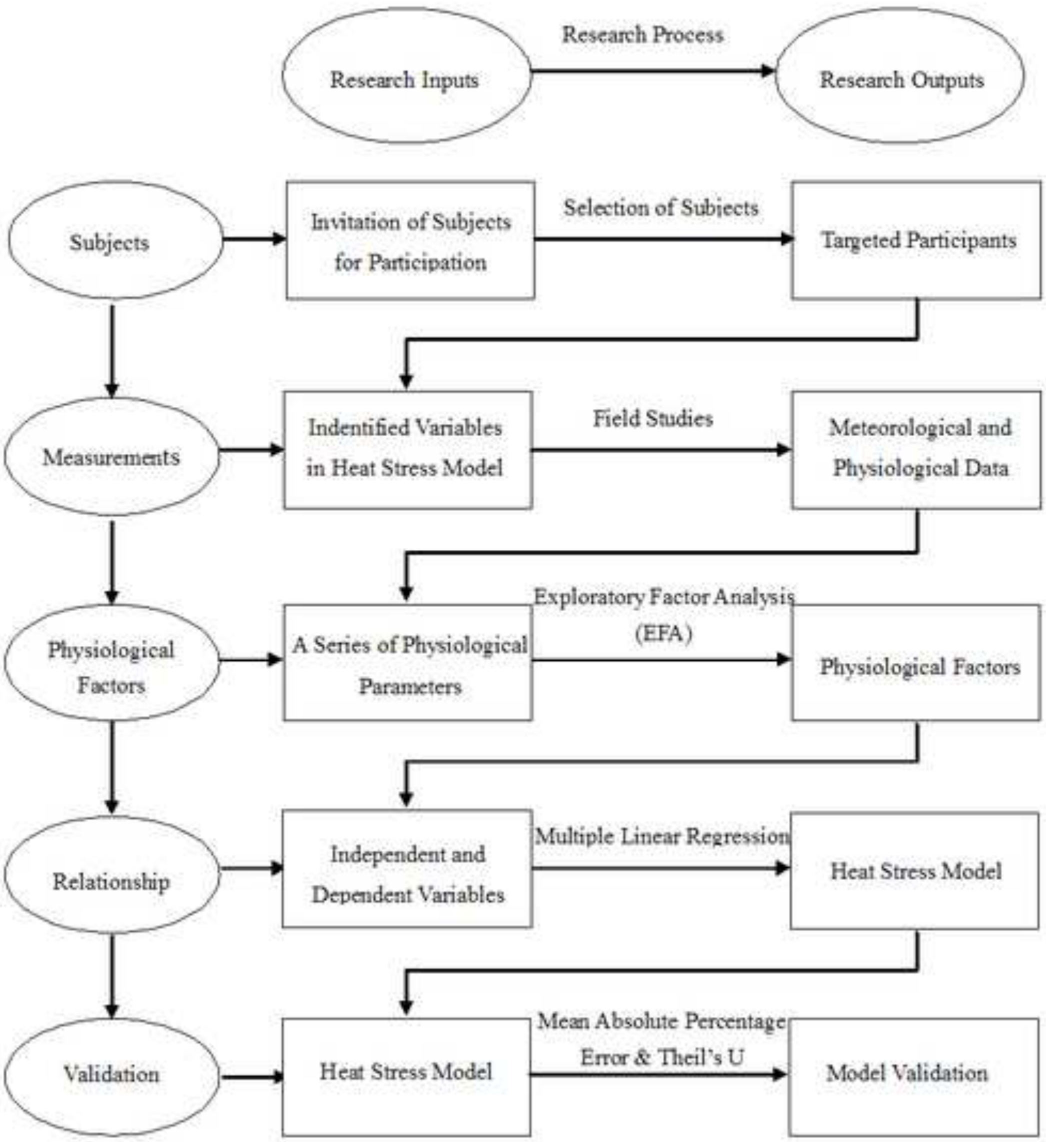


Figure 2

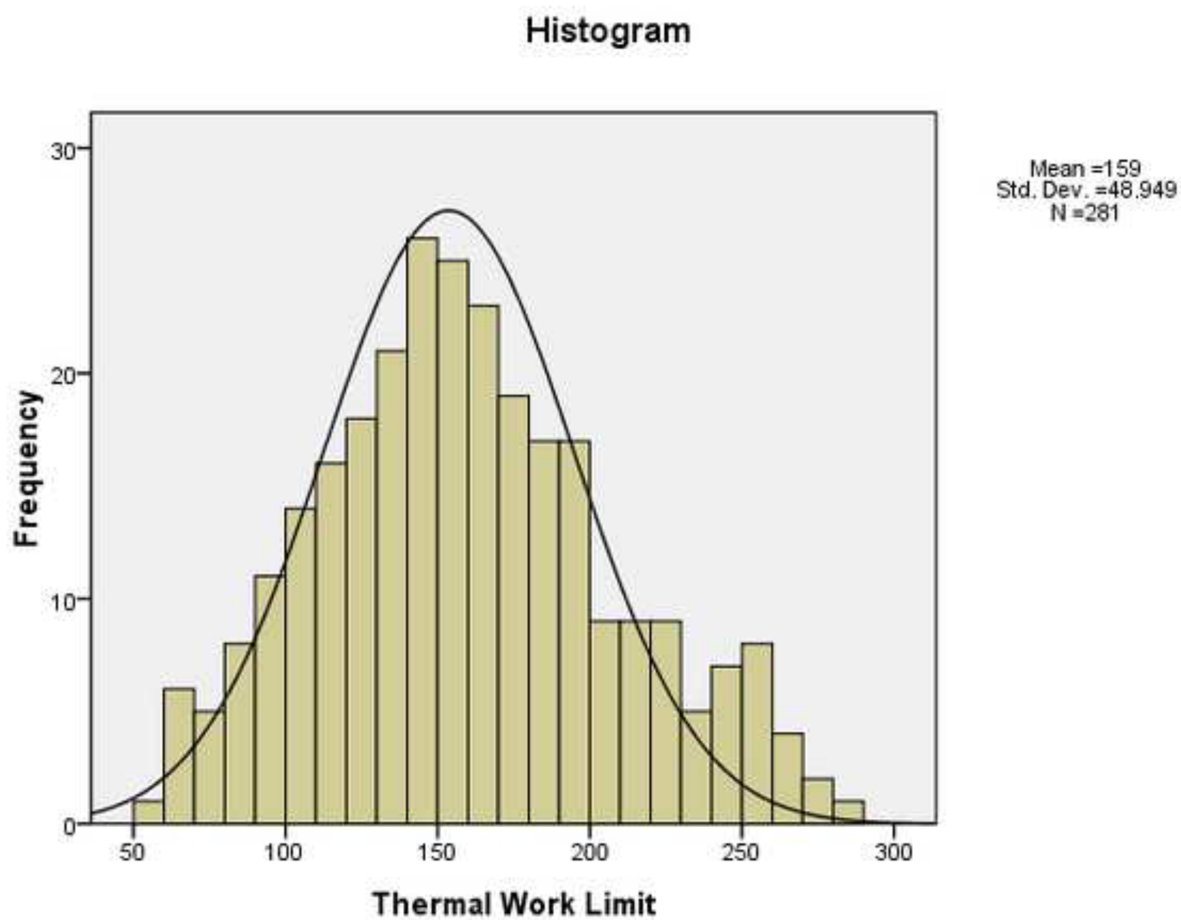
Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Figure 2 Various apparatus used in the field experiment (From left to right: InBody 230, COSMED K4b2, QUESTemp°36 heat stress monitor)

Figure 3

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Figure 3 Frequency distribution diagram of Thermal Work Limit (TWL)



Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
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Table 1 Factors and indicators influencing the Rating of Perceived Exertion (RPE)

	Factor	Indicator to measure the identified factors
Physiological factors	Energy expenditure	)
	Metabolic equivalents	)
	Oxygen consumption	) Energy consumption (EC)
	Minute ventilation	)
	Heart rate	)
	Respiratory exchange ratio	Respiratory exchange rate (RER)
	Hydration	Total body water (TBW)
Work-related factors	Work type	Job nature (JN)
	Time	Work duration (T)
Environmental factors	Temperature	
	Relative humidity	) Thermal work limit (TWL)
	Wind speed	
	Air pollution	Air pollution index (API)
Personal factors	Age	Age (A)
	Physique	) Percentage of body fat (PBF)
		) Resting heart rate (RHR)
	Alcohol/tobacco intake	) Smoking habit (SH)
		) Alcohol drinking habit (ADH)
	Clothing	Clothing insulation factor (Clo)

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Table 2 Correlations between the six physiological subset scores for total sample (N = 281)

	Mean ± SD	VO_2	MV	RER	HR	MET	EE
VO_2 (ml/min/Kg)	13.5 ± 4.9						
MV (l/min)	28.5 ± 8.6	.74					
RER	1.0 ± 0.2	-.31	-.23				
HR (bpm)	115.1 ± 18.1	.46	.41	.21			
MET	3.8 ± 1.4	.97	.74	-.31	.46		
EE (Kcal/min)	4.1 ± 1.4	.95	.82	.-25	.47	.96	

Note: All correlations were statistically significant ($p < .01$).

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Table 3 Factor loadings of physiological factor variables

Physiological factor item	Factor Loading	Percentage of Variance Explained	Cumulative Percentage of Variance Explained
Factor 1:Energy Consumption (EC)			
Energy expenditure	**.98**		
METs	**.97**		
Oxygen consumption	**.97**		
Minute ventilation	.35		
Heart rate	.28		
Respiratory exchange ratio	-.26	64.21	64.21
Factor 2: Respiratory Exchange Rate (RER)			
Energy expenditure	-.00		
METs	-.10		
Oxygen consumption	-.10		
Minute ventilation	**.80**		
Heart rate	**.56**		
Respiratory exchange ratio	**.93**	17.99	**82.19**

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Table 4 Multiple regression analysis for RPE

Model	Unstandardized Coefficients	Standardized Coefficients (Rank)	t	Sig.
(Constant)	-1.13		-2.47	.01
Age (*A*)	0.07	0.56 (2)	13.20	.00
Alcohol drinking habit (*ADH*)	2.30	0.62 (1)	15.53	.00
Duration (*T*)	1.30	0.42 (3)	13.29	.00
TWL	-0.01	-0.20 (7)	-5.39	.00
Air pollution index (*API*)	0.10	0.39 (4)	7.80	.00
Percentage of body fat (*PBF*)	-0.06	-0.26 (5)	-7.16	.00
Smoking habit (*SH*)	0.44	0.22 (6)	6.12	.00
Energy consumption (*EC*)	0.15	0.10 (9)	3.35	.00
Respiratory exchange rate (*RER*)	0.16	0.10 (10)	3.02	.00
Resting heart rate (*RHR*)	-0.02	-0.13 (8)	-4.07	.00

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
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Table 5 Evaluation of accuracy of the heat stress model by MAPE

Sample	RPE												
	TWL	T	API	AGE	PBF	ADH	SM	EC	RER	RHR	Actual value by workers	Forecast value from model	Percentage error (%)
1	162	0.43	32	42	13.4	1	0	1.27	-0.72	71.4	4	4.67	16.75
2	126	0.50	32	42	13.4	1	0	-0.94	-0.18	71.4	5	5.00	0.00
3	115	0.54	32	42	13.4	1	0	-0.90	-0.03	71.4	5	5.09	1.80
4	185	0.48	32	42	13.4	1	0	-0.82	-1.55	71.4	5	4.80	4.00
5	135	0.52	32	42	13.4	1	0	-0.18	-0.77	71.4	5	5.05	1.00
6	178	0.50	32	42	13.4	1	0	-0.80	0.42	71.4	5	5.09	1.80
7	115	0.54	32	42	13.4	1	0	0.04	0.41	71.4	5	5.27	5.40
8	147	0.5	32	42	13.4	1	0	2.17	0.13	71.4	5	5.28	5.60
9	143	0.47	32	42	13.4	1	0	0.50	1.32	71.4	5	5.32	6.40
10	143	0.47	32	42	13.4	1	0	0.25	-0.91	71.4	5	5.03	0.60
													MAPE = 4.33%
													U = 0.001

Note: MAPE is mean average percentage error; U is Theil's U statistics.

where *TWL* is thermal work limit (W/m^2); *T* is work duration (hour); *API* is air pollution index; *A* is age; *PBF* is percentage of body fat (%); *RHR* is resting heart rate; *ADH* is alcohol drinking habit ("none"= 0, "occasionally"= 1, "usually"= 2), *SH* is smoking habit ("none"= 0, "occasionally"= 1, "usually"= 2); *EC* is energy consumption ("light"= 0, "moderate"= 2, "heavy"= 4); and *RER* is respiratory exchange rate ("light"= 0, "moderate"= 2, "heavy"= 4).

Journal of Management in Engineering. Submitted February 1, 2012; accepted October 19, 2012;
posted ahead of print October 20, 2012. doi:10.1061/(ASCE)ME.1943-5479.0000162

Table 6 Heat tolerance times at different levels of heat exposure and by different age and workload groups

TWL(W/m^2)	25			35			45			55			Interventions (Brake and Bates 2002)
	Light	*Moderate*	*Heavy*	*Light*	*Moderate*	*Heavy*	*Light*	*Moderate*	*Heavy*	*Light*	*Moderate*	*Heavy*	
220	222	194	165	190	162	134	158	129	101	126	97	68	Acclimatization
210	218	189	161	186	157	132	153	125	96	121	92	64	
200	213	185	156	181	152	130	149	120	91	116	88	59	
190	209	180	151	176	148	128	144	115	87	112	83	54	
180	204	175	147	172	143	126	139	111	82	107	78	50	
170	199	171	142	167	138	123	135	106	78	102	74	45	
160	195	166	138	162	134	121	130	102	73	98	69	41	
150	190	162	133	158	129	119	126	97	68	93	65	36	
140	186	157	128	153	125	117	121	92	64	89	60	31	Buffer
130	181	152	124	149	120	115	116	88	59	84	55	27	
120	176	148	119	144	115	113	112	83	54	79	51	22	
110	172	143	114	139	111	111	107	78	50	75	46	18	Withdrawal
100	167	138	110	135	106	108	102	74	45	70	42	13	
90	162	134	105	130	102	106	98	69	41	66	37	8	

Note: *API* is 30; *PBF* is 12.3 (%); *RHR* is 78; *ADH* is 0 (None); *SH* is 0 (None); Workload is *Light* (EC = 0 ; RER = 0), Workload is *Moderate* (EC = 2 ; RER = 2), Workload is *Heavy* (EC = 4 ; RER =4).