A method to identify individually physiological response differences to heat exposure using Comprehensive Deviation Coefficient (CDC)

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Yongqiang Li, Chenqiu Du, Runming Yao, Guoqing Li, Baizhan Li

Abstract

With increasing global warming, a method to identify individual heat exposure risk and conduct interventions is essential, in order to mitigate impacts of extreme climates on people's health. This paper aims to examine the differences of individual's physiological response in hot environments and consequently proposes a personal-based method to identify potentially vulnerable populations with high risk. A heat exposure experiment was carried out in a climate chamber to build datasets, with nine conditions combining air temperature (35°C/38°C/40°C) and relative humidity (25%/40% /60%). The rectal temperature (Tre), skin temperature (Tsk) and heart rate (HR) of 10 subjects were monitored. Data were analyzed using multiple-dimensional metrics of average deviation(AD), coefficient of variation(CV) and skewness(SKEW). The study introduced the Moment of Inertia (MI) and the Simulated Mass System (MS) in a multidimensional coordinate system and developed a *Comprehensive Deviation Coefficient (CDC)* method. Using various combinations of AD/CV/SKEW, the values of CDC_{Tre}, CDC_{Tsk}, CDC_{HR} were calculated; the high-risk thermal environment (40°C/60%) and subject were thus identified. The proposed CDC method enables to distinguish the individual's physiological response differences, under different hot environments and personal characteristics. The equations in this method can be programed in computer and integrated with smart sensor technology, contributing to identify the high-risk environments and provide precautions for susceptible populations, to mitigate the heat exposure hazards on people' health and safety.

Keywords

Hot environment; Physiological response; Individual difference; Multidimensional metrics; Comprehensive Deviation Coefficient(CDC) method; Heat stress risk.

Nomenclature

AD	average deviation	**HR_t**	total heart rate (beat/minute)
ADu	DuBois body surface area (m^2)	**HR_S**	static exertion heart rate (beat/minute)
$AD_{Tre,in,i}$ **$AD_{Tsk,in,i}$** **$AD_{HR,in,i}$**	AD of Tre/ Tsk/ HR under the influence of internal personal difference	**HR_T**	thermal strain heart rate (beat/minute)
$AD_{Tre,out,i}$ **$AD_{Tsk,out,i}$** **$AD_{HR,out,i}$**	AD of Tre/ Tsk/ HR under the influence of external hot environments	**MI**	moment of inertia (kg•m^2)
AV	average value	**MS_i**	simulated mass system
$AV_{Tre,in,i}$ **$AV_{Tsk,in,i}$** **$AV_{HR,in,i}$**	AV of Tre/ Tsk/ HR under the influence of internal personal difference	**n**	size of the sample
$AV_{Tre,out,i}$ **$AV_{Tsk,out,i}$** **$AV_{HR,out,i}$**	AV of Tre/ Tsk/ HR under the influence of external environment difference	**Nor**	normalization process
C_{mj}	characteristic parameter of “Vj” under the influence of “fi” (i=m)	**SD**	standard deviation
C_k	characteristic parameter of “Vj” (AV/ AD/ CV/ SKEW, k≥1)	**SKEW**	skewness
$C_{s,fi}$	characteristic parameter C under the influence of “fi”	**$SKEW_{Tre,in,i}$** **$SKEW_{Tsk,in,i}$** **$SKEW_{HR,in,i}$**	SKEW of Tre/ Tsk/ HR under the influence of internal personal difference
CV	coefficient of variation (dimensionless)	**$SKEW_{Tre,out,i}$** **$SKEW_{Tsk,out,i}$** **$SKEW_{HR,out,i}$**	SKEW of Tre/ Tsk/ HR under the influence of external environment difference
$CV_{Tre,in,i}$ **$CV_{Tsk,in,i}$** **$CV_{HR,in,i}$**	CV of Tre/ Tsk/ HR under the influence of internal personal difference	**Sum**	summation
$CV_{Tre,out,i}$ **$CV_{Tsk,out,i}$** **$CV_{HR,out,i}$**	CV of Tre/ Tsk/ HR under the influence of external environment difference	**Tre**	rectal temperature (°C)
fi	variable factors affecting W (dimensionless, i=1,2,3…m)	**Tsk**	skin temperature (°C)
HR	heart rate (beat/minute)	**Vj**	variation of W caused by “fi” (dimensionless, j=1,2,3…n)
HR_0	thermal neutrality heart rate (beat/minute)	**W**	target parameter (as Tre/ Tsk/ HR)
HR_e	residual heart rate (beat/ minute)	**W_{fi}**	target parameter W under the influence of “fi” (as Tre/ Tsk/ HR)
HR_M	metabolic heart rate (beat/ minute)	**x**	each sample of the target parameter
HR_N	emotion heart rate (beat/minute)	**Δ**	the comprehensive MI (dimensionless)

PHS	predicted heat strain model	**SWreq**	Required sweat rate, W/m^2
HSI	heat stress index (dimensionless)	**WBGT**	wet bulb globe temperature (°C)

1. Introduction

According to the newly issued report on the State of the Global Climate by World Meteorological Organization (WMO), the average global temperature for 2013-2017 was the highest compared to the recorded five-year averages before[1]. For example, in 2017, there was a *Level 2* heatwave alert issued by the Public Health England(PHE) in England in June, with some areas reaching their highest temperatures since June 1976 [2]. Just over the past summer in 2019, Europe boiled in soaring temperatures and 40°C heatwave swept from south to north, especially in France[3]. The climate change and globe warming [4] further accompanied with the increased frequency and intensity of extreme heatwave events in many regions [5-6]. Exposures to such extreme heat conditions has led to heat stroke, heat exhaustion, heat cramps, and heat rashes [7]. Evidence from a large number of epidemiological studies[8-10] have revealed that the hot environments and extreme heatwaves aggravated the heat-related mortality and morbidity of populations, especially for cardiovascular and respiratory diseases, resulting in a more severe and widespread health risk impact[11-13]. A report in *Lancet* analyzed 74,225,200 deaths in various periods between 1985 and 2012 and concluded that extreme cold and hot temperatures were responsible for 0.86% (0.84%-0.87%) of total mortality[14]. In particular, excess mortalities of nearly 19,000 occurred during the 2003 European extreme heat event[15], especially in France inside of households (appropriately 50%) [16]. After implementing the heat health action plans, for example, in Frankfurt, the excess mortality for the overall population in the heatwaves was decreased, comparing 2003 (77.8%) to the following years (2006: 12%, 2010: 22.7%, 2015: 38.1%)[17]. In fact, many at-risk populations are exposed to warm temperatures inside buildings. For example, in New York, almost 85% classified hyperthermia cases succumbed to heat in their own home [18]. In another tropic region, Huang[19] analyzed the heatwave events in 60 provinces in Thailand and also found that mild heatwaves were associated with greater cumulative effects on total and cause-specific mortality, partly due to the protection awareness in extreme heatwave events.

In recent years, combined with the “The Belt and Road Initiative” development, China is experiencing a rapid urbanization and increased urban population. However, in the context of on-going climate change, the magnitude of heatwave impacts increased by intensities and durations of the heatwaves, according to a study in 31 Chinese capital cities during 2007–2013[20]. In such cases, occupational heat exposure and injury risk for people, like workers in construction sites, has been increasingly a focused question so that how to mitigate the impacts due to heat exposure is among the most urgent of people’ needs. According to the US Census of Fatal Occupational Injuries[21], workers account for 36% of the heated-related mortalities from 2003 to 2008. In China, quite a number of occupational workers are involved in physically demanding tasks under hot environments both indoors and outdoors. In such contexts, a concerted effort must be made to promote the health and safety for people, develop targeted protection policies and managements, and minimize the productivity/performance loss.

Exposing to high temperature would cause various physiological strains (e.g. increase body and skin temperatures, metabolic rates, sweating, heart rates), deteriorate performance and productivity, increase the incident rates of health-related illness[22, 23]. To prevent body heat strain, a series of practice guidelines/strategies, including permitted work, recover time, work shelters[24], improving thermal environments and ventilation [25] have been studied; more than 100 heat stress indices and models have been developed [26]. Some more complex models, like the required sweat rate (SW_{req}) and predicted heat strain (PHS) model, were subsequently proposed and adopted in ISO7933 standard[27], based on the human heat production and dissipation mechanism[28]. However, they were built by an averaging method [29] and were representative for an average European people [30]. The prediction performance has been challenged with various deviations in applications [31, 32]. It is known that human heat stress results from a combination of factors, including environmental conditions, work demands, and individual characteristics[33, 34]. The differences significantly exist among individuals that make the rational models less valid in practical prediction. Therefore, a method to evaluate the individual differences is of importance, in order to identify the individuals who are vulnerable with increasing health risks in hot environments and to provide early interventions for people, as well as management for supervisors.

However, the inter-individual variability is evident, due to the characteristics of different physiological indices[35]. Heat causing mild stimulus in one person may induce heat-related risk in another [36]. Study from Racinais et al. [37] found a high inter-individual variation in the adaptive responses to a 6-day heat acclimatization experiment (e.g. change in plasma volume from -10% to +20%) with apparent "responders" and "non-responders"; the individual differences were also reported by the authors in another experiment with two-week acclimatization interventions [38]. Recently, Yi et al. [39] established an artificial neural networks method to predict the perception rating of perceived exertion for construction workers and developed an early-warning system against hot and humid climates, based on a database containing 550 sets of synchronized work-related, environmental, and personal data. Chan et al. [40, 41] conducted a multiple regression to relate human physiological responses to environmental, worked-related and personal factors in hot environments. However, in most cases, human heat stress is not linear to these influencing factors; knowledge with respect to risk identification at individual levels remains incompletely understood [30].

To sum up, it poses challenge to use readily-available measurements of individuals to predict different thermal responses accurately [30] and promote protections more effectively[42]. To this end, this study aims to propose a new method to evaluate the individual differences during heat exposures. This is achieved through introducing a multidimensional model, and a Comprehensive Deviation Coefficient(CDC). The method enables to evaluate the degrees of physiological responses of different individuals regarding to environmental and personal parameters, which is expected to fill the knowledge gap of identifying the harsh environments and vulnerable populations during heat exposure, and benefit for targeted protection policies and interventions for people' health and thermal safety.

2. Method of Comprehensive Deviation Coefficient (CDC) evaluation

2.1 Evaluation indices in multiple dimensions

The human physiological strain in hot environments depends on both individual factors (e.g. health status, heat tolerance, sweat rate, regulation degree) and environmental factors (e.g. physical parameters, exposure time). The triggered variability in typical physiological indices (e.g., rectal temperature(Tre), skin temperature(Tsk), heart rate(HR)[30, 43, 44]) contain both absolute changes in the original dimension, like maximum, minimum, mean, standard deviation, and the relative changes in multiple dimensions, like variability, skewness.

① Absolute Variation (AD)

From the measurement point of view, both the system errors and random errors affect the average value(AV) and standard deviation(SD). In contrast, the AD takes AV as reference system and is less susceptibly affected by random errors compared to the SD. The SD is based on the variance by squaring while AD does the logic judgment for data fluctuation[45]. Therefore, the AD is introduced, as shown in Equation (1).

$$AD=\frac{\sum|x-AV|}{n} \quad (1)$$

② Coefficient of Variation (CV)

The CV is a dimensionless statistical index to measure the data dispersion correlating to the AV [46, 47]. Although some other statistics such as the quartiles and SD are commonly used to measure data variability, the CV takes advantage of cross-dimension analysis, which has been widely applied in biomedicine, environmental analysis, manufacturing, dynamics studies, etc.[48, 49]. The CV can be calculated in Equation (2).

$$CV=\frac{SD}{AV} \quad (2)$$

③Skewness (SKEW)

The SKEW is adopted to measure the degree of data skewing. The SKEW measures the asymmetry distribution of data, reflecting the third order central moment of variables. The SKEW for a normal distribution is zero; when the SKEW is negative, the data distribution is partial to left, otherwise to right. The definition of SKEW is shown in Equation (3).

$$SKEW=\frac{n}{(n-1)(n-2)}\sum\left(\frac{x_i-AV}{SD}\right) \quad (3)$$

2.2 Development of CDC method

Given the human physiological regulations are affected by environmental and individual factors, a single mathematics metrics, like AV, SD, AD, CV, SKEW, or a parameter combination of some of these metrics, cannot describe the fluctuation characteristics well. As these metrics reflect information for a target variable in multiple dimensions, a multidimensional coordinate system is necessary, to evaluate the regulations of human physiological parameters and identify the differences systematically. Therefore, with the above mentioned AD/ CV/ SKEW as three dimensions in the coordinate system, this study develops a CDC method through introducing the Moment of Inertia (MI) in the Simulated Mass System (MS). Details are introduced in the following section.

2.2.1 Multidimensional coordinate system

This method is based on a multidimensional decoupling and reorganizing process, which has been widely used in multi-target assessment [50, 51]. The method provides quantitative descriptions of the inner-balance, compliance and deviation for a specific system. The CDC method is originally used to analyze the certain changes under the coupled impacts of multiple variables, and provide quantitative evaluation of these factors. A variable W is assumed with a variety of influencing factors fi (i = 1, 2, 3…m), and shows different variations Vj (j =1, 2, 3…n). The characteristic feature Ck (k≥1) is proposed as the corresponding parameter under each Vj so there is one-to-one relation between the Cj and Vj (k = 1 in this study). After that, factor fi (i = 1, 2, 3…m) is transferred to a group of characteristic parameters Cj (j = 1, 2, 3…n). The relationship between both forms the subjective mapping through the intermediate function Vj. In this case, each Cj value represents a combined effect of fi, but this makes it difficult to reflect the comprehensive effect of Vj (j =1, 2, 3…n), through a single value of C, or a group values of Ci. Therefore, a multidimensional coordinate system is adopted using Vj (j = 1,2,3…n) as variable in each dimension, to describe the factor fi and the effect on W.

2.2.2 Simulated Mass System(MS)

In the coordinate system, the W is reflected by the characteristic parameter Cj (j =1, 2, 3…n, k = 1), using the specific locations (C1, C2, C3 ... Cn). When studying the single impact of factor fm, the other factors of 1, 2, 3…m-1, are fixed. That is, the Cj responding to other factors in the range of 1 to m-1 is averaged. Then the unique Cmj (j = 1-n) can be obtained and a fixed value Wm under factor fm is drawn. In summary, the MS is built with the specific values of W1, W2, W3 ... Wm and their corresponding coordinate positions at Cm1, Cm2 ... Cmj ... Cmn. The mass distribution, location and size of MSm are all under the control of factor fm, to reflect the effect of fm on W. The remaining MS1, MS2, MS3… MSm-1 can be obtained from the individual influence of each variable. In addition, when comparing the impact of different fi on W1, W2, W3 ... Wm, to avoid the influence caused by the uncertainty of the number "m", normalization process is carried out among W1, W2, W3 ... Wm to build the final Simulated Mass System.

2.2.3 Moment of Inertia(MI)

The origin in the coordinate system means that the variable shows absolute stabilization in the coordinate system with the AD, CV and SKEW at value of 0. A distance from the origin, or a greater abstractive mass point indicates a remarkable fluctuation. The MI is then introduced to describe the deviation between MS and the origin, which demonstrates the comprehensive volatility of each parameter. The MI, as a concept from the physical point of view, can express both the quality and distance deviation of a particle, a rigid object or a mass system responding to a fixed point in two-dimensional space, or a fixed shaft in three-dimensional space. The values are only determined by the size and position. The MI has been used in various areas of scientific experiments, engineering, aerospace, biological research and other industrial and social practices [48, 49]. The definition of MI is shown in Equation (4).

$$\mathrm{MI}=\sum_{i}^{n} \mathrm{MR}^2 \tag{4}$$

Where M represents the mass; R^2 represents the distance to certain shaft or point.

The MIi of a specific particle in mass system MSc is then achieved in Equation (5).

$$\mathrm{MIi}=(\mathrm{Wi})\times[\sum \mathrm{Cj}(j=1,2,3\ldots n)]^2 \tag{5}$$

In order to ensure comparability between different individuals, taking the individual Wi divided by AV (Wi) as each mass point, the two parts of MIi, i.e., M and R^2 are expressed using dimensionless DML (Mi)(Equation (6)) and DML (R^2) (Equation(7)).

$$\mathrm{DML(Mi)}=\frac{m\times W_i}{\sum_{i=1}^{m}(W_i)} \tag{6}$$

$$\mathrm{DML}\left(R^2\right)=\sum[\mathrm{Nor}(\mathrm{Cj}(j=1,2,3\ldots n))]^2 \tag{7}$$

Then the influence of factor fi on MI is expressed in Equation (8).

$$\mathrm{MI}_{fi}=\sum_{i=1}^{m}\left\{\frac{m\times W_i}{\sum_{i=1}^{m}(W_i)}\times\sum[\mathrm{Nor}(\mathrm{Cj}(j=1,2,3\ldots n))]^2\right\} \tag{8}$$

From Equations (6)(7), the average maximum values of DLM (MIi)and DLM (R^2) are 1 and n respectively. Therefore, the theoretical range of MI_{fi} is from 0 to n. Then the CDC method can be defined by dividing MI_{fi} by the dimension number "n", as shown in Equation (9).

$$CDC=\frac{\Delta}{n}=\frac{1}{n}\sum_{i=1}^{m}\left\{\frac{m\times W_i}{\sum_{i=1}^{m}(W_i)}\times\sum[Nor(Cj(j=1,2,3\ldots n))]^2\right\} \quad (9)$$

The calculation process of the CDC values is demonstrated in Figure 1. In this study, three typical physiological parameters of Tre, Tsk and HR of 10 subjects are adopted. Changes of these parameters under nine experimental conditions are analyzed, by calculating AD/ CV/ SKEW in three dimensions. Under such cases, k = 1, n = q = 3, p = 9, m = 10. The f(in) represents the individual difference factors and f(out) represents the environmental factors. The W reflects the fluctuation characteristics of Tre, Tsk and HR with the influence of individual and environmental factors. Finally, the CDC values for different physiological parameters can be calculated.

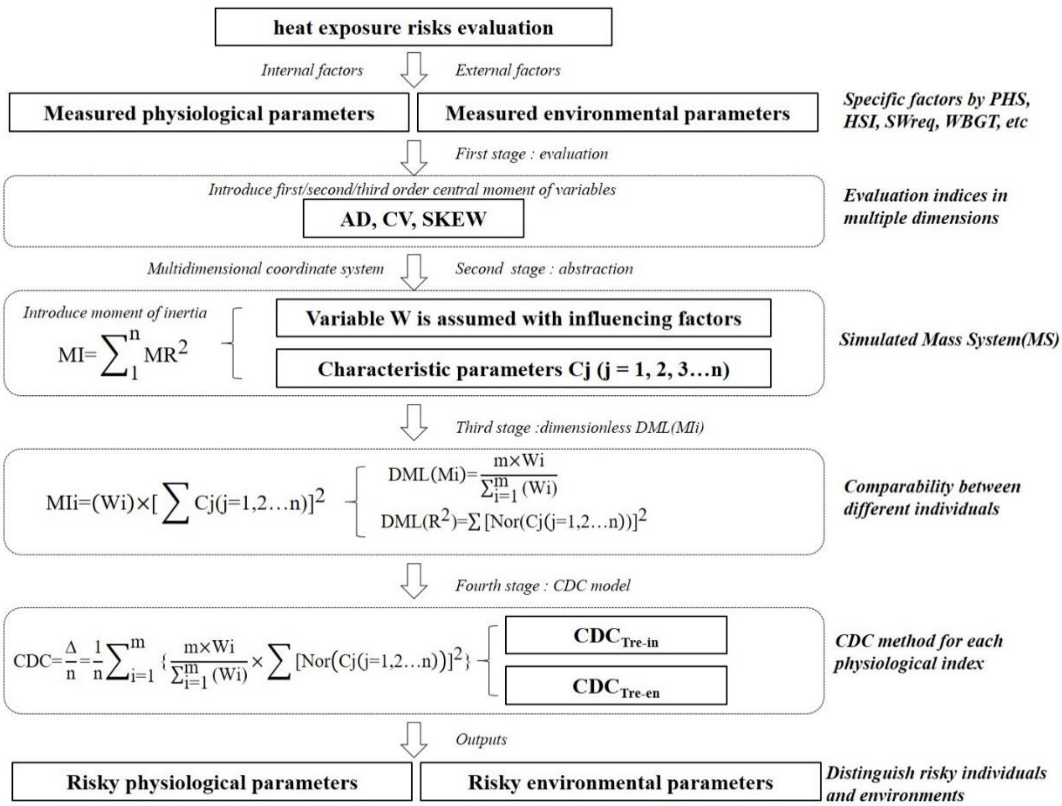

Figure 1 Calculation flow chart for CDC method

Here, taking the physiological parameter of Tre as an example, the mass system of MS(in) for Tre can be built according to Figure 1, and the CDC method to evaluate the individual differences for Tre, namely $CDC_{Tre_{in}}$ can be expressed in Equation (10).

$$CDC_{Tre_{in}}=\frac{1}{n}\sum_{i=1}^{m}\left\{\frac{m\times Tre_{in,i}}{\sum_{i=1}^{m}(Tre_{in,i})}\times\left[Nor(AD_{Tre_{in,i}})^2+Nor(CV_{Tre_{in,i}})^2+Nor(SKEW_{Tre_{in,i}})^2\right]\right\} \quad (10)$$

Meantime, the physiological response differences of Tre caused by environmental factors can be evaluated and the $CDC_{Tre_{en}}$ is defined in Equation (11)

$$CDC_{Tre_{en}}=\frac{1}{n}\sum_{i=1}^{m}\left\{\frac{m\times Tre_{en,i}}{\sum_{i=1}^{m}(Tre_{en,i})}\times\left[Nor(AD_{Tre_{en,i}})^2+Nor(CV_{Tre_{en,i}})^2+Nor(SKEW_{Tre_{en,i}})^2\right]\right\} \quad (11)$$

Similarly, for physiological parameters of Tsk, HR in this study, the $CDC_{Tsk_{in}}$, $CDC_{Tsk_{en}}$, $CDC_{HR_{in}}$, $CDC_{HR_{en}}$ can also be defined through replacing the corresponding parameters in Equations (10)(11).

Taken together, Section 2.2 adopts three typical physiological indices, i.e. Tre, Tsk, HR, and elaborates the calculation process in a multidimensional system. Based on these multidimensional parameters, the CDC method for each physiological index is built and the values can be judged and compared responding to environmental and individual factors.

3. Data collection

To verify the proposed CDC method, a heat exposure experiment was conducted in a simulated climate chamber. We collected data from 10 Chinese labor workers, who were exposed to hot environments, with combinations of three temperature levels and three relative humidity levels (nine conditions). The details for experimental designs have been described in Ref. [52].

3.1 Experimental conditions

The experimental design was referred to Ref. [53, 54], regarding environmental parameters, activity level, resting time and measuring intervals. Totally 9 typical conditions were designed, as shown in Table 1. Table 1 meantime shows the measured parameters during experiments. The measured temperature and RH values in Table 1 were close to the designed conditions, suggesting the thermal environments in climate chamber met the experimental demands. Besides, due to the inner enclosure structure in the climate chamber, the measured black-bulb temperatures were close to the dry-bulb temperatures in the chambers, the differences between both being less than 0.5°C. In the following study, the radiant temperature was thus hypothesized being equal to air temperature.

Table 1 Condition designs and measured parameters in experiments

Conditions	Designs (T/RH)	Measured dry-bulb temperature(°C)	Measured black-bulb temperature(°C)	RH (%)
C1	35°C/25%	35.1±0.2	34.5±0.2	25.9±3.1
C2	35°C/40%	34.8±0.3	34.4±0.3	41.1±2.2
C3	35°C/60%	35.0±0.2	34.6±0.2	58.9±3.6
C4	38°C/25%	37.7±0.1	37.5±0.2	25.4±2.7
C5	38°C/40%	37.8±0.2	37.4±0.3	39.6±2.3
C6	38°C/60%	38.3±0.2	37.6±0.2	59.1±1.7
C7	40°C/25%	39.9±0.2	39.3±0.2	25.3±2.4
C8	40°C/40%	40.1±0.1	39.1±0.3	39.4±2.8
C9	40°C/60%	39.9±0.1	39.3±0.2	57.9±2.9

3.2 Subjects selection

Considering the labor workers were one of the populations who may be in high risk to heat exposure, a group of 25 healthy male candidates were randomly selected from a local construction industry in Chongqing. Then they were asked to participate in a pre-experiment of walking on the treadmill at 0.5m/s for 60min under 38°C/40%. Their Tre, Tsk and HR were continuously measured during exposures. After tests, candidates whose Tre, Tsk and HR exceeded the mean±3SD were excluded[55], to minimize the individual differences. The screening principles and standards for subjects were elaborated in Ref. [52] and finally 10 subjects were selected for the formal experiments. Their basic information is shown in Table 2. Subjects were required to be in accordance with normal resting habits and ensure good sleep 24 hours before tests; no heavy physical work, or drink were allowed.

Table 2 Basic information for the 10 selected subjects

Items	Mean ± SD	Range
Age	39.4±3.6	35-48
Height/m	168±2.3	164-173
Weight/kg	59.8±2.3	55.4-65.6
BMI index/kg.m^{-2}	21.2±0.7	20.1-22.5
Resting HR/bpm	68.3±5.7	59-76

3.3 Experiment procedure

The experiment was performed in accordance with the 1964 Helsinki declaration and its later amendments and comparable ethical standards [58]. Participants were allowed to terminate the tests at any time if they felt uncomfortable during experiments. In addition, according to the recommendations by WHO[59], when a subject' s HR exceeded 180bpm for more than 3 min, or Tre was higher than 39°C under continuous monitoring, the test was terminated.

Subjects were asked to arrive at the preparation room 30min in advance and change the uniform experimental clothes (T-shirt, shorts, shoes and socks). Then they were asked to attach the thermocouples (TMCx-HD, accuracy: ±0.2°C) on local four body parts (i.e. chest, left upper arm, left thigh, left calf). Data of local skin temperatures were continuously recorded every 10s and the mean skin temperature for each subject was calculated by the area-weighed four-point method [56]. The rectal temperature was measured by putting sterilized thermocouple probe into subject's rectum at a depth of 10cm above the anal sphincter, according to the standard method in ISO 9886 [57]. A heart rate sensor (Polar RS800, Finland, accuracy: ±1bpm) was placed at the left of chest with skin contact, to monitor subjects' heart rate, in the time interval of 1min. After preparations, they were sedentary for 30min in the preparation room to eliminate the effects of outdoor environments and metabolic rates. Note that during this period subjects whose measured Tre were higher than 37.4 °C were excluded for attending tests.

The formal experiment commenced when subjects entered the chamber. Then they were asked to walk on the treadmill at a speed of 0.5m/s at a 10% grade. According to the guideline of ISO 8996 [60], the estimated metabolic rate was ~160W/m^2. The test lasted 120min and Tre, Tsk and HR of subjects were monitored and recorded continuously. They were free to drink water but the amount was recorded to correct the sweat produced during heat exposure. The instruments and onsite test are shown in Figure 2.

Figure 2 Instruments and onsite experiment in climate chamber

4. Results

Experimental termination was conducted seriously based on the aforementioned situations. To sum up, subjects exhibited different heat tolerance abilities under the same heat exposure condition. Totally 64.7% of the 90 cases were finished (55 out of 90) in 120min exposure; for the remaining conditions, subjects terminated at different stages within the time length of 120min. About 85.7% (30 out of 35) terminated the test when their rectal temperature exceeded the threshold.

The mean values of Tre, Tsk and HR of each subject in the whole test (≤120min) were averaged. The indices of AD, CV and SKEW of the 10 subjects for the mean Tre, Tsk and HR values were calculated. The following analyzed the comprehensive controllability of these physiological indices and compared the differences among 10 10 subjects) and for the 9 experimental conditions in Section 4.1. The heat risk was evaluated in Section 4.2 through calculating the CDC values for Tre, Tsk and HR.

4.1Evaluaiton of subjects' physiological responses

4.1.1 Tre variation

Figure 3 shows the comprehensive changes of Tre of 10 subjects in the 9 conditions (see Table 1), which are displayed in AD, CV, and SKEW. From Figure 3, the values of AD and CV of subjects' Tre increased with temperature under the same RH level. The volatility of Tre also increased with increasing RH under each temperature level. That is, the AD and CV increased gradually with RH from 25% to 40%, and to 60%. In addition, there were obvious coupling effect of temperature and RH under 35°C/38°C/40°C, where the RH was high (60%). This indicated that the Tre of subjects was significantly affected by high temperature, especially coupled with high relative humidity.

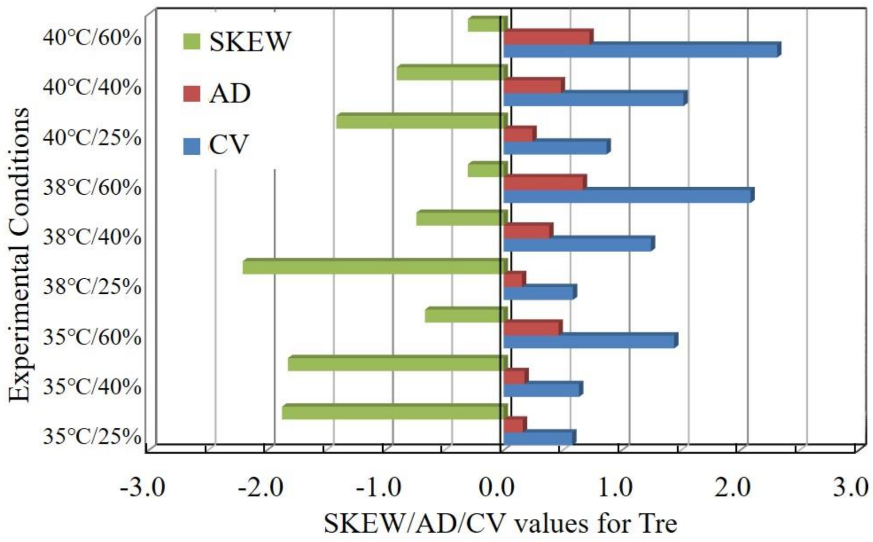

Figure 3 AD, CV and SKEW values of Tre in 9 conditions

The SKEW of Tre indeed reflects the curvature and the second derivative in its change trend. In Figure 3, compared to AD and CV, a larger SKEW was found at RH=25%, and decreased conversely with increasing temperature and RH, indicating an increased control of body to retain the increase of rectal temperature caused by heat stimulus. In particular, the SKEW values were relatively much smaller under conditions of 35°C/60%, 38°C/60%, 40°C/60%. The SKEW was close to zero, comparing -0.30 at 40°C/60% to -0.67 at 35°C/60%. Overall, the values of SKEW were negative in all 9 conditions, indicating the body physiological regulation for Tre was gradually restrained. The control degree was enhanced with increased temperature and humidity, manifesting a determinant protection for body internal heat balance.

4.1.2 Tsk variation

Figure 4 shows the results of the AD/CV/SKEW variations of Tsk of 10 subjects, which shares a similar trend to Tre in Figure 3. According to experimental results, the measured mean Tsk of subjects fluctuated in a narrow range of 34.4 ‐ 36.8°C, regardless of a wide temperature range from 35°C to 40°C. As a result, the AD and CV values of Tsk were small. Moreover, the SKEW distributions of Tsk and Tre were similar to each other but the average value of SKEW for Tsk in 9 conditions was bigger than that for Tre (1.51>1.14). This was inferred that the heat transfer on skin surface by convection and evaporation was more significant compared to the heat exchange in inner body, leading to stronger regulation response on Tsk to alleviate heat strain.

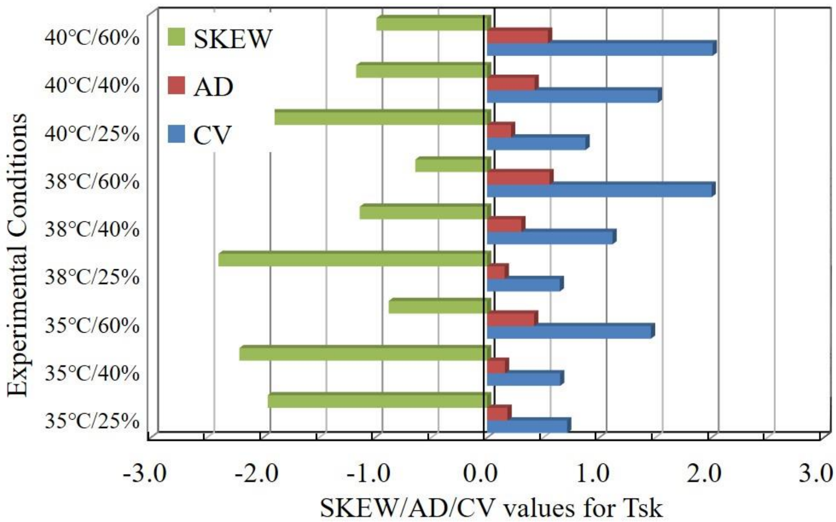

Figure 4 AD, CV and SKEW values of Tsk in 9 conditions

Further comparing the changes of SKEW of Tre and Tsk, the mean values of SKEW of Tre decreased by 0.21 between 38°C-25%/40%/60% and 40°C-25%/40%/60%; while the SKEW for Tsk was less affected by environmental temperature and RH and the value was only 0.08. Besides, the increased RH had negative effects on SKEW(Tsk), comparing 25% to 60% respectively. This was attributed to that the higher RH inhibited the body sweat regulation and evaporative heat loss, especially when the air temperature was higher than the skin temperature. An interesting finding was that the maximum SKEW for both Tre and Tsk occurred at 38°C/25% rather than under high temperature and humidity conditions. We inferred that the 38°C/25% condition provided a stronger heat stimulus on body compared to 35°C-25%/40%/60%, which enhanced the convective heat transfer between skin surface and ambient environment. On the other hand, compared to much stronger heat stimulus, the water vapor pressure differences between skin surface and surroundings was bigger at 38°C/25%, leading to stronger sweating regulation in body.

4.1.3 HR variation

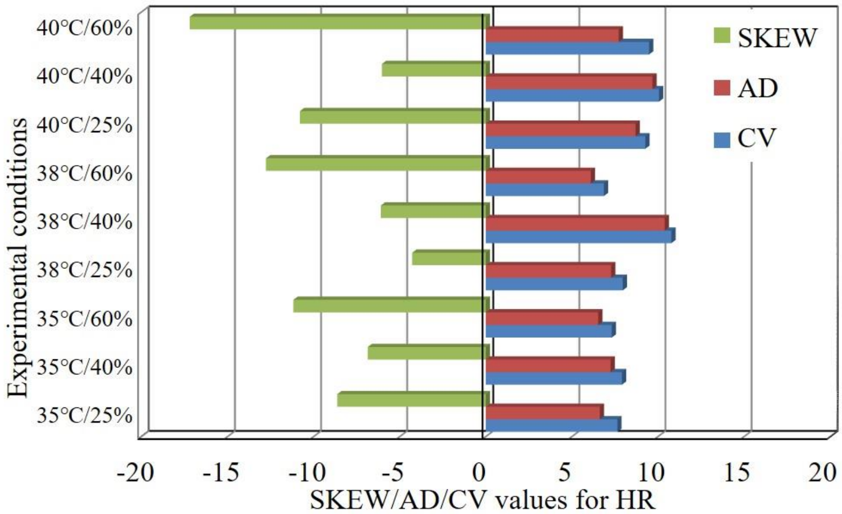

Figure 5 AD, CV and SKEW distribution of HR in 9 conditions

Figure 5 shows the changes of SKEW/AD/CV, demonstrating a comprehensive controllability of HR of subjects. In general, the AD, CV and SKEW of HR fluctuated among different conditions but did not show significant increasing/decreasing trends with temperature and RH, compared to the Tre and Tsk. This was reflected by the small ratios of max/min of AD and CV, about 1.70 and 1.57 respectively; while the values were 4.68 and 3.99 for Tre, and 3.54 and 3.10 for Tsk. The SKEW variation of HR showed an opposite change compared to Tre and Tsk: when the temperature and RH gradually increased, the values of SKEW increased. This indicated that the human body presented effective controls on body heart rates, to respond to temperature and humidity increasing.

4.2. Comparisons between external and internal effects

Figures 3-5 shows the Tre, Tsk and HR variations of subjects in response to environmental temperature and RH, from a multidimensional point of view. Our initial assumption was: when there were no individual differences among 10 subjects, theoretically there would be no differences for Tre, Tsk, and HR regulations after they were exposure to the same heat stimuli. Figure 6 shows the actual values of AD/CV/SKEW of Tre/Tsk/HR among the 10 subjects. The 10 kinds of colors in Figure 6 represent the 10 subjects; the 9 inside-to-outside rings represent 9 indices among 10 subjects, i.e. AD(Tre), AD(Tsk), AD(HR), SKEW(Tre), SKEW(Tsk), SKEW(HR), CV(Tre), CV(Tsk) and CV(HR), according to Equations (1-3). In theory, for each metric, the proportion of AD/CV/SKEW among the 10 subjects should be distributed evenly, namely 10% for each ring in Figure 6. However, there were significant variations of subjects' physiological regulations. For SKEW, the negative values suggested the skew was left and the median for measured Tre, Tsk and HR were distributed on the right of means, which was consistent with Figures 3-5. The absolute values of AD/CV/SKEW of Tre/Tsk/HR among the 10 subjects varied between 7% and 14%, rather than being equal to 10%. In fact, despite the strict control in experiments for age, gender, weight, height and fat ratio [28] of subjects, some unpredictable factors still existed, resulting in the different thermal responses to heat stimuli. However, in most studies for heat stress, the average values are usually adopted and such individual differences are largely simplified or neglected, which lead to a deviation when predicating health risks for personal individual[31, 32].

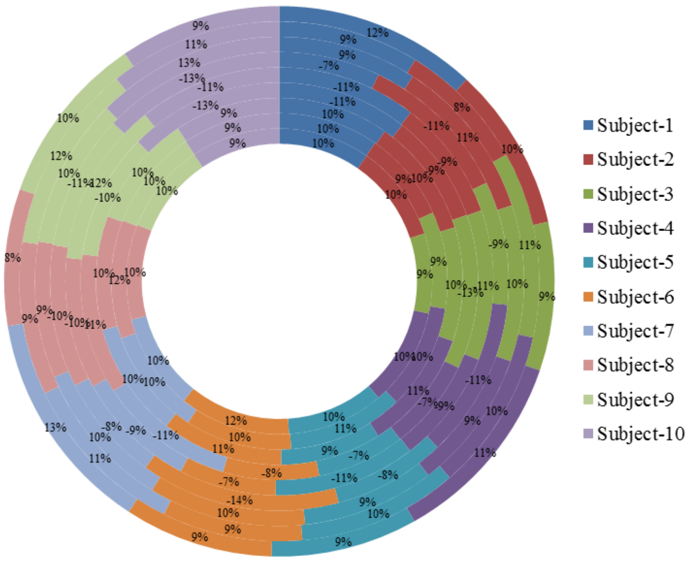

Figure 6 Distribution of AD/ SKEW/CV of Tre/Tsk/HR among 10 subjects

Figure 6 provides an intuitive description of physiological differences among 10 subjects. To evaluate the integrated impacts of both individual factors and environmental factors, we recalculated the CV values of AD/CV/SKEW variations for Tre/Tsk/HR, expressed as CV[AD(Tre/Tsk/HR), CV (Tre/Tsk/HR), SKEW (Tre/Tsk/HR)] and made a comparison between environment and individual, as shown in Figure 7. From Figure 7, whatever the dimensions were, the values of CV-environment were greater than that of CV-individual, revealing the dominant role of environmental factors on human heat strain during heat exposure. In addition, the HR showed the smallest variability in CV[AD/CV/SKEW], which was followed by Tsk. While the values of CV[AD/CV/SKEW] for Tre were the biggest, showing the largest variability of human rectal temperatures influenced by both individual and environmental factors.

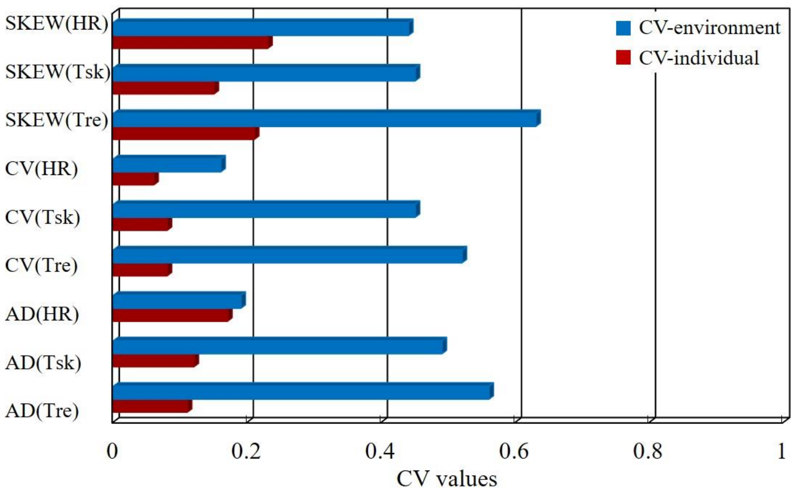

Figure 7 CV[AD/CV/SKEW (Tre/Tsk/HR)] with individual and environmental factors

4.3 Evaluation for CDC values

Based on the method presented in Section 2.2, the CDC values for Tre/Tsk/HR under 9 experimental conditions and within 10 subjects were calculated. The values indeed reflected the variation degrees of human physiological indices responding to environmental stimuli and individual differences: the bigger the values were, the stronger physiological responses the body had, the higher risk for heat strain there would be.

4.3.1 CDC differences caused by individual factors

Given individual differences, the CDC values for 10 subjects are shown in Table 3. Considering the variations of rectal temperature and heart rates were more vital indices for human health and safety, the CDC values for Tre and HR were discussed. From Table 3, the CDC values for subject No. 6 were the highest, 1.14% for Tre and 1.39% for HR respectively (bold in Table 3). In contrast, subject No. 5 had the smallest CDC value of 0.88% for Tre and 0.74% for HR respectively. Table 5 meantime presents the basic information of the 10 subjects. Compared to subject No.6, subject No. 5 was younger, and had the relatively bigger body surface area, which was beneficial for heat loss at skin surface. As a result, looking the 10 subjects as a whole, we could infer that subject No. 6 was with the higher risk and subject No. 5 was relatively safe when they were exposed to the same hot environments.

Table 3 CDC analysis for the internal differences of the Tre/Tsk/HR among subjects

Subjects	Age /yr	Height /m	Weight /kg	Adu /m^2	HR_0 /bpm	CDC_{Tre} (100%)	CDC_{Tsk} (100%)	CDC_{HR} (100%)
No. 1	48	1.72	67.5	1.79	57	1.00	0.97	0.84
No. 2	43	1.65	63.2	1.69	59	0. 97	0.76	1.12
No. 3	35	1.63	58.9	1.63	65	0. 99	1.01	0.91
No. 4	37	1.69	58.9	1.67	69	0. 92	0.96	1.13
No. 5	37	1.75	69.2	1.83	71	0. 88	1.21	0.74
No. 6	**42**	**1.69**	**59.7**	**1.68**	**65**	**1.14**	**0. 91**	**1.39**
No. 7	41	1.63	59.4	1.63	68	1.10	1.00	0.93
No. 8	45	1.71	57.7	1.67	69	1.11	1.22	1.04
No. 9	38	1.61	56.9	1.59	76	0.95	1.11	0.94
No. 10	39	1.7	59.7	1.69	73	1.11	0.97	1.14

To make the comparisons much clearer, Figure 8 demonstrates the distributions of CDC values for Tre/Tsk/HR among the 10 subjects, using the data in Table 3 of the last three columns. As expected, subject No. 5 showed smaller CDC values for Tre and HR, indicating the lower heat strain in inner body, meanwhile the higher CDC value for Tsk indicated a stronger ability of heat loss from skin surface. From this point of view, subject No. 6 was vulnerable to hot exposure, who had higher CDC values for Tre and HR. This indicated that subject No. 6 had a higher risk for physiological strain and should be protected to reduce the potential heat-related accidents.

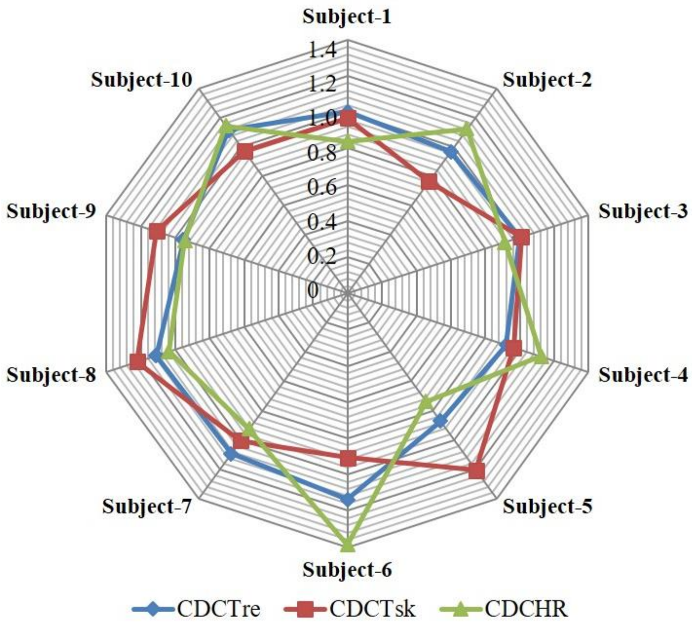

Figure 8 Individual CDC volatility among the 10 subjects

4.3.2 CDC differences caused by environmental factors

In a similar vein, Table 4 shows the fluctuations of physiological indices caused by various temperature and RH. From Table 4, the CDC values of Tre, Tsk, and HR were higher under 60% at each temperature level, and reached the peak values of 2.69%, 2.37%, 2.38% respectively at 40°C/60%. This indicated that the thermal environment of 40°C/60% would cause the strongest physiological strain on human body, meaning it was riskier at such condition, compared to other conditions.

Table 4 The CDC analysis on the impact of environment on Tre, Tsk and HR

Conditions	T(°C)/RH(%)	CDC_{Tre} (100%)	CDC_{Tsk} (100%)	CDC_{HR} (100%)
C1	35°C/25%	1.27	0. 95	0. 94
C2	35°C/40%	1.25	1.09	0. 92
C3	35°C/60%	1.34	1.39	1.18
C4	38°C/25%	1.70	1.24	0. 77
C5	38°C/40%	1.03	0. 96	1.60
C6	38°C/60%	2.29	2.22	1.28
C7	40°C/25%	1.02	1.32	1.63
C8	40°C/40%	1.60	1.60	1.28
C9	**40°C/60%**	**2.69**	**2.37**	**2.38**

Figure 9 intuitively exhibits the CDC distributions of subjects' Tre, Tsk and HR under 9 conditions according to Table 4. The remarkably higher values of CDC_{Tre}, CDC_{Tsk}, CDC_{HR} were found under 40°C/60%RH. This would benefit for managers to avoid such environments, or take measurements, like creating urban green-blue spaces to achieve cooling effects in practical working place**Error! Reference source not found.**, to minimize the risks of over-heating for workers.

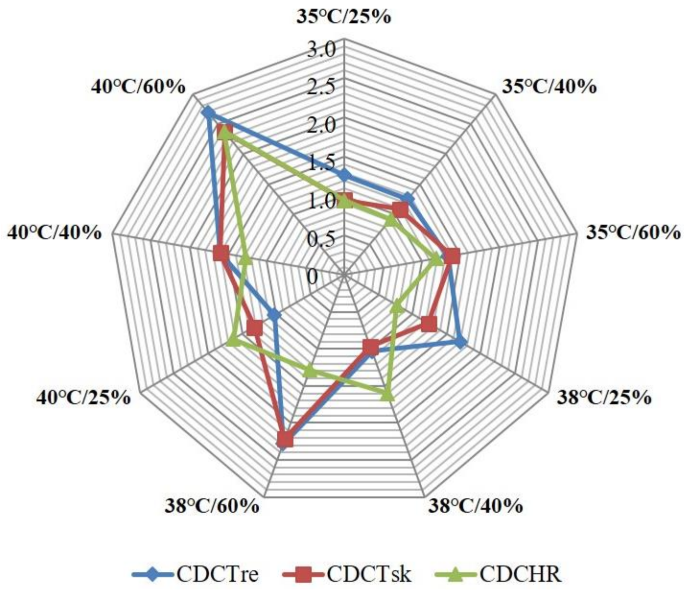

Figure 9 CDC volatility under 9 conditions

5. Discussions

Yao et al.**Error! Reference source not found.** conducted a heat exposure experiment in chamber and found that the mean skin temperature and mean heart rate of subjects increased with increasing environmental temperature and relative humidity. In contrast, the calculated CDC values in Table 4 for Tre, Tsk and HR increased with increasing temperature; while such change trends were not found for increasing relative humidity. This was similar to one study by Du et al **Error! Reference source not found.**: though the temperature and relative humidity were increased during heat exposure, the number of subjects who were terminated at each condition was not linearly increased and the number of subjects who finished the heat exposure was conversely higher under hot-dry condition (40°C /25%) than that under slightly hot-humid condition (38°C/60%). This was attributed to the coupled effects of temperature and relative humidity in hot environment that the human thermal physiological responses caused by humidity stimuli were slight with a certain temperature range. Therefore, in Table 4, the values of CDC_{Tre} and CDC_{Tsk} were slightly smaller at 38°C/40% than that at 38°C/25%. Moreover, the individual differences existed that different subjects responded to different extent when they were exposed to the same thermal stimuli. This could be found in Table 3 and Figure 6 that the regulations of Tre, Tsk and HR differed under different conditions. However, when the environmental temperature and relative humidity were the highest, the effect caused by environmental stimuli was higher that of individual differences. In that case, all the CDC values for Tre, Tsk, and HR were the highest under the condition of 40°C/60%.

. This study measured local skin temperatures at four local body parts; considering the skin temperature was not the same in different parts of the body**Error! Reference source not found.**, and the current models like PHS model**Error! Reference source not found.**, predicted the mean skin temperature from the whole, the area-weighted method**Error! Reference source not found.** was also adopted for calculating mean skin temperature.

The PHS model is a widely used rational model, but it predicts human heat strain for average people rather than at individual level**Error! Reference source not found.**. In laboratory experiments, to minimize the individual differences, researchers would screen the subjects strictly, considering ages, gender, weight, height, BMI, etc **Error! Reference source not found.Error! Reference source not found.**. This study selected subjects through pre-tests and excluded subjects whose physiological indices responded outside the normal range. However, in real working place, due to the complexity, there are so many factors indirectly influencing the physiological response of human body and heat stress or specific strains must adequately account for an individual's personal attributes. These include the location (region and micro-climates)**Error! Reference source not found.**, daily habits, health status, clothes and metabolic rates**Error! Reference source not found.Error! Reference source not found.**, which are unable to be calculated in the CDC method in this study, or quantified algebraically using models. In particular, the thermal history and acclimatization from people would modify the settings of the physiological thermoregulation system themselves, leading to different responses to continuous exposure to heat**Error! Reference source not found.Error! Reference source not found.**. As a result, the uncertainties of individual differences make it difficult for current models for proper application to heat stress prediction**Error! Reference source not found.Error! Reference source not found.**. In this context, the CDC method in the current study provides a comprehensive index to evaluate the heat exposure risk, which enables to identify the high-risk environments and individuals in a quantitative way.

However, the current study providing the CDC method to identify the risk bases on a relative comparison from the point of view of a group of people, or a series of thermal conditions. We assume that the high CDC values are relatively risky and should be paid attentions to. However, the current study is limited to answer which ranges of CDC values for physiological indices are safe and which ranges are in risk during heat exposure. Future work should be developed for the CDC method to determine the baselines: at which CDC limits workers should be protected, to which degree the interventions should be provided. This is expected to provide better grades/levels for risk assessment for heat stress within/without building environment.

6. Conclusions

This study induced a three-dimensional indices of *Absolute Variation* (AD), *Coefficient of Variation* (CV) and *Skewness* (SKEW) and evaluated the physiological response differences of rectal temperature (Tre), skin temperature (Tsk) and heart rate (HR) responding to environment and individual, based on a heat exposure experiment. The results showed the AD and CV of subjects' Tre, Tsk and HR increased with temperature and humidity while the SKEW decreased. The inter-individual variability was verified, revealing a different body controllability responding to heat stress.

A *Comprehensive Deviation Coefficient* (CDC) method was developed through introducing Simulated Mass System and Moment of Inertia, and the values of CDC_{Tre}, CDC_{Tsk} and CDC_{HR} responding to different temperature and humidity and among 10 subjects were calculated. The outcomes identified the thermal environment of 40°C/60% and the potential vulnerable subject with the most high-risk.

The CDC method enables to quantify the response of physiological indices and compare the inter-individual differences. It can afford a timelier response to examine the high-risk environments and sensitive populations in practical working places. The outcomes are expected to guide hot environment management, identify high-risk populations, make interventions for workers, contributing to minimizing the risks of heat accident occurrences in advance and mitigating the impacts of extreme climates on people's health and safety.

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