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Exploring on the Prediction Model of Human Skin Temperature and Rectal Temperature under Heat Stress

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Abstract: Hot environments cast direct influence on people's well-beings and health besides working productivity during the accelerating global warming. The systematic mechanism is not entirely clear due to the complex human physiological response which also handled human heat strain protection. This study carries out mathematical derivation on the rectal temperature and skin temperature under human heat strain based on the PHS model of ISO 7933 standard. The experimental validation was conducted in a climate chamber with continuously monitoring the typical physiological parameters of 10 subjects in 9 hot working environments. Physiological parameters of subjects were analyzed on average difference (AV), coefficient of variation (CV) and skewness (SKEW) to explore their mutual linkages. Both experimental and theoretical result shows that certain relationship existed between the rectal temperature and skin temperature. The Poisson's ratio on their average value, coefficient of variation, average difference and skew were 0.957, 0.991, 0.990 and 0.941 respectively. Linear relation with coefficient of 0.73 was found between rectal temperature and skin temperature coupling with the constant of 12.09. Comparison on the dynamic changes of rectal temperature and skin temperature was carried out and verified under PHS model. The results showed that rectal temperature was adjusted earlier and more forcefully than skin temperature indicating that human core temperature was better protected under heat stress. The findings contribute to a convenient method of human heat strain prediction when taking rectal temperature as the best physiological threshold with fast human skin temperature and environment parameters monitoring in complex high temperature working environments.

Keywords: Hot environment, Relative humidity, Physiological response, Heat stress, Prediction model.

Nomenclature			
AD	Average deviation	RH	Relative humidity
ADu	DuBois body surface area	SD	Standard deviation
AV	Average value	SKEW	Skewness
BMI	Body Mass Index	T_{re}	Human rectal temperature
CV	Coefficient of variation	T_{sk}	Human skin temperature
HR	Heart rate	T_a	Mean air temperature
I_{cl}	Total thermal insulation of clothing	T_{cr}	Human core temperature
M	Total metabolic rate	$T_{cr, eq}$	Human core temperature as a function of the metabolic rate
Max	Maximum value	Δt	Time element
Min	Minimum value	t_i	Time point after i*Δt
min	Minutes	T_r	Mean radiant temperature
N	Sample size	$T_{sk, eq}$	Skin temperature as a function of the metabolic rate
Pa	Water vapour partial pressure	v_a	Mean air velocity
p	The change rate of dynamic T_{re} on time	x	Variable parameter
q	The change rate of dynamic T_{sk} on time	α	The change rate of dynamic T_{re} on time element Δt
$T_{re, 0}$	The initial value of rectal temperature	β	The change rate of dynamic T_{sk} on time element Δt
$T_{sk, 0}$	The initial value of rectal temperature	C_1	Synthesis constant based on experimental design
f(t)	Time function	C_2	Synthesis constant based on experimental design

g(t)	Time function	C_3	Synthesis constant based on experimental design

1 Introduction

The frequency of extreme hot weather is becoming higher worldwide with the gradual intensification of global warming and the summer temperature in many places has risen sharply which has aroused worldwide concern [1-4]. The problem of occupational hazards in such high temperature environments has been paid more and more attention these years [5-8].

It is generally believed that when the ambient temperature exceeds 29°C, the high temperature environment will cast direct impact on human productivity and health [9]. Heat stress has been an alerting potential occupational hazard in the workplace especially in the hot working environments that air-conditioning cannot be reached [10-13]. Many occupational health problems arise due to the lack of understanding and application of heat protection technologies such as controlled airflow, temperature, humidity and cooling rate [14-15]. Previous studies have shown that China is experiencing a huge urbanization process and the number of labor-force is constantly increasing [16]. Existing literature has shown that high temperature hazard accidents have covered many aspects of people's living and working environment including but not limited to various actual work scenarios such as energy industry, material industry, agriculture, construction industry, tourism, military and sports application [17-19]. However, a large number of high temperature safety accidents have occurred due to the relatively research on heat protection lagging behind and inadequate implementation of standards on human heat stress [20]. How to evaluate the impact of environmental heat stress hazards on human safety has always been the most urgent research field of heat stress research [17, 18, 21].

Researchers have been paying attention to the environmental factors that influence the body's physiological responses since the 16th century when Bladgen published the first paper on the heat load of the human body in 1775 [19]. There have been a lot of heat stress indicators and safety limits subsequently and amounts to more than 50 kinds of related indicators in the world currently [22-24]. These indicators can be generally divided into three categories including direct indicators, theoretical indicators and empirical indicators with the continuous development of experimental analysis of human physiological response under heat stress [19]. However, typical heat-related physiological parameters such as rectal temperature (T_{re}) and skin temperature (T_{sk}) have been generally recognized as the most important physiological parameters in human heat stress prediction models using as direct indicators or intermediate variables in modern research [25-28].

Existing studies mainly focus on the change characteristics of human physiological indicators [29-31], and provide the basic changes of human physiological indicators under different environmental conditions or different heat exposure [32, 33]. The results have shown that the changes in the physiological parameters of the human body are not an independent function but a system of interconnections between different physiological parameters [34-37]. Due to the human active thermal adaptation and complex physiological regulation being not fully revealed, the human body's control over the physiological parameters behind its fluctuations remains largely unexplored [38-40]. A large number of experimental studies often ignore the relationship between different physiological parameters in addition to the traditional statistical analysis of physiological parameters [41], especially in the different dimensions of low-order and high-order analysis [42]. An in-depth theoretical and experimental study is still needed to fully understand the interaction response of typical physiological parameters during heat exposure [43].

As an uncertain threat from the environment, high temperature injury affects human life and production. However, human heat stress is still a branch subject of ergonomics in the research of several centuries, and it is also an extremely complex interdisciplinary subject. However, lots of heat stress prediction models still show some shortcomings in real life, such as the inaccurate prediction, or cannot be directly applied due to the restrictions of region, race, and working style. Relevant researchers have been unable to reach an agreement on the unification of application standards for a long time. Then more than 100 heat stress indices and models have been developed with varying complexity. Based on the 672 experiments in 8 European thermal physiology laboratories and 237 field experiments, ISO 7933 was improved and proposed the modified index-the Predicted Heat Strain model (PHS) in 2001 as the most commonly used human heat stress evaluation indicator nowadays. But the human heat stress evaluation still faces problems nowadays which restrict the indicators' application. In conclusion, there are still some problems [44-46] despite of the current studies on the physiological response of human body in hot working environments [47, 48], and more adequate experimental and theoretical studies are required on [49-53]:

(1) the coupling relationship between different physiological parameters is still limited, and the connection between them is not completely clear;

(2) the traditional single-dimension on the basic fluctuation characteristics of physiological parameters is insufficient and unable to fully present the internal and dynamic relations among human physiological parameters.

Most importantly, the monitoring of human heat strain must be efficient, non-invasive and convenient which do not affect the working process. The traditional heat stress monitoring on the typical physiological thresholds of core temperature and rectal temperature is obviously unable to achieve the aim. As a result, a fast, efficient and accurate forecasting method is needed to simplify the monitoring during working.

To solve the above problems, this study put forward a hypothesis on theoretical relationship between different physiological indicators based on the classical human heat stress theory [1, 4]. The T_{re} and T_{sk} were continuously monitored under nine high temperature environments with wind speed of 0.1m/s, temperature of 35℃, 38℃, 40℃, and relative humidity of 25%, 40%, and 60%, respectively. The comprehensive variation characteristics of these physiological parameters were discussed with the introduction of average deviation (AD), coefficient of variation (CV) and skewness (SKEW). The relationship is further studied based on the comprehensive fluctuation performance of T_{re} and T_{sk}. It provides a scientific and efficient mechanism on the rapid detection and early warning in complex high-temperature environments in reality, which contributes to the effective detection and controlling on the large-scale public health security caused by extreme high-temperature environments.

2. Theoretical analysis on T_{re} and T_{sk}

The T_{re} and the T_{sk} of the human body are two of the most important intermediate variables and the prediction of T_{re} and T_{sk} have been carried out in many heat stress prediction models or heat stress indexes [4] such as the HSI, SW_{req}, PHS models. Currently, the ISO 7933 standard, which was developed by the Technical Committee ISO/TC159, Ergonomics, Subcommittee SC5, Ergonomics of the physical environment [19] is the most widely accepted heat stress prediction standard based on Predicted Heat Strain model (PHS) [1]. It describes a method for predicting the sweat rate and the internal core temperature that the human body will develop in response to the hot environment. Given the aims of this study, the relationship between T_{re} and T_{sk} based on the current PHS model in ISO7933 standard was adopted for theoretical analysis. The description of T_{re} and T_{sk} in the PHS model is shown in Table 1.

Table 1 Description of T_{re} and T_{sk} of human body in the PHS model

Parameters	Description
T_{cr}	$T_{cr,i} = 36.8 + (T_{cr,eq} - 36.8) \times \left(1 - \exp\left(\frac{-t}{10}\right)\right)$ $T_{cr,eq} = 0.0036(M - 55) + 36.8$
T_{sk}	$T_{sk,i} = 0.7165 T_{sk,i-1} + 0.2835 T_{sk,eq}$ $T_{sk,eq,cl} = 12.17 + 0.020T_a + 0.044T_r - 0.253v_a + 0.194p_a + 0.005346M + 0.51274T_{cr}$
T_{re}	$T_{re,i} = T_{re,i-1} + \frac{2T_{cr,i} - 1.962T_{re,i-1} - 1.31}{9}$

The expressions of T_{re} and T_{sk} prediction in the PHS model are both iteration function changing over time which are the iteration from time point "i-1" to "i" by minutes as shown in Table 1. Meanwhile, the prediction of T_{re} and T_{sk} takes the human metabolic rate and environmental parameters such as T_a, T_r, p_a, v_a into consideration. Therefore, the conversion for the T_{re} and T_{sk} was first carried out by describing them into separate time-based functions with the environmental parameters. The Eq. 1 and Eq. 2 are obtained as following equations.

$$T_{re,i} = T_{re,i-1} + \frac{2 \times \left[36.8 + 0.0036(M - 55) \times \left(1 - \exp\left(\frac{-t}{10}\right)\right)\right] - 1.962T_{re,i-1} - 1.31}{9} \tag{1}$$

$$T_{sk,i} = 0.7165T_{sk,i-1} + 0.2835 \times \left\{12.17 + 0.020T_a + 0.044T_r - 0.253v_a + 0.194p_a + 0.005346M + 0.51274 \times \left[36.8 + 0.0036(M-55) \times \left(1 - \exp\left(\frac{-t}{10}\right)\right)\right]\right\} \quad (2)$$

When the body was in a stable environment, the environment parameters and the specific metabolic rate remained constant for the individuals. the T_{re} and T_{sk} can be described under the same functional form through further transformation for equations 1 and 2 as shown in Eq. 3 and Eq. 4.

$$T_{re,i} = m_1 \times T_{re,i-1} + m_2 \times f(t) + m_3 \quad (3)$$

$$T_{sk,i} = n_1 \times T_{sk,i-1} + n_2 \times f(t) + n_3 \quad (4)$$

The definition of m_1, m_2, m_3 and n_1, n_2, n_3 is shown in Table 2 below which refer to the definitions in the PHS model in ISO 7933 standard.

Table 2 definition of m_1, m_2, m_3 and n_1, n_2, n_3 in Eq. 3 and Eq. 4

Definition	Expression
m_1	0.782
m_2	$0.0008(M-55) \times \left(1 - \exp\left(\frac{-t}{10}\right)\right)$
m_3	8.032
n_1	0.7165
n_2	$0.0005233(M-55) \times \left(1 - \exp\left(\frac{-t}{10}\right)\right)$
n_3	$0.2835 \times (31.0388 + 0.020t_a + 0.044t_r - 0.253v_a + 0.194p_a + 0.005346M)$

The X_i and X_{i-1} are the value of variable at the time of "i-1" and "i" while the coefficient of m_1, m_2, m_3, n_1, n_2, n_3 is the constant values as the metabolic rate and environmental parameters are determined in specific high temperature working environments. The f(t) is the function of time by minute and the description of f(t) corresponds to the same form of $\left(1 - \exp\left(\frac{-t}{10}\right)\right)$ for T_{re} and T_{sk} in Table 2. According to the current research, human rectal temperature is recognized as a temperature index that is difficult to measure and very close to the human abdominal cavity temperature or core temperature [4].

Suppose that $T_{re,\,0}$ and $T_{sk,\,0}$ are the subject's initial rectal temperature and initial skin temperature. The time element Δt represent change from t_{i-1} to t_i, since the change in time t in the same labor environment is consistent with the change in the above two parameters. On the other hand, the value of f(t) can be taken as a constant once the working time t is high temperature working determined.

Therefore, the above equation 3, 4 is simplified into the following equation 5, 6.

$$T_{re,i} = m_1 * T_{re,i-1} + p \sum_1^t g(t) \tag{5}$$

$$T_{sk,i} = n_1 * T_{sk,i-1} + q \sum_1^t g(t) \tag{6}$$

Where p and q are constants, representing the change rate of $T_{re,\,i}$ and $T_{sk,\,i}$ with the accumulation of working time respectively.

The concept of time element Δt is introduced in a stable working environment at high temperature, and the initial rectal temperature $T_{re,0}$ and the initial skin temperature $T_{sk,\,0}$ can be measured according to the linear relationship in Equations 5, 6. On this basis, the change slope α of T_{re} and the change slope β of T_{sk} with time element Δt can be defined, then equation 5, 6 can be converted to equation 7, 8.

$$T_{re,i} = m_1 * \left[T_{re,0} + \alpha * (i-1)\Delta t\right] + p \sum_1^t g(t) \tag{7}$$

$$T_{sk,i} = m_1 * \left[T_{sk,0} + \beta * (i-1)\Delta t\right] + q \sum_1^t g(t) \tag{8}$$

Introduction of constants value on C_1, C_2 and C_3 are made, the above equation is further simplified to equation 9 and 10.

$$T_{re,\ i} = m_1 * \alpha * (i-1)\Delta t + C_1 \tag{9}$$

$$T_{sk,\ i} = n_1 * \beta * (i-1)\Delta t + C_2 \tag{10}$$

Continue to transform the above formula, and expand the calculation for different time points $T_{re,\ i}/T_{re,\ i-1}/T_{sk,\ i}/T_{sk,\ i-1}$ respectively, and finally obtain the following Equation 11.

$$\frac{T_{re,i} - T_{sk,i}}{T_{re,i-1} - T_{sk,i-1}} = \frac{(i-1)\Delta t * (m_1\alpha - n_1\beta) + C_3}{(i-2)\Delta t * (m_1\alpha - n_1\beta) + C_3} \tag{11}$$

If the above formula $(T_{re}-T_{sk})$ is taken as the overall change quantity, then $(T_{re}-T_{sk})$ presents a linear change relationship with gradual accumulation of time element Δt. The expression of constant C_3 is calculated by combining the above derivation process and Table 2.

$$C_3 = \left[m_1 * T_{re,0} + m_2 * f(t) + m_3\right] - \left[n_1 * T_{sk,0} + n_2 * f(t) + n_3\right] \tag{13}$$

Where α, β, $m_1/m_2/m_3/n_1/n_2/n_3$ can be calculated through the above Table 2. The equation 11 can be deduced on the linear change Slope (K) as shown in equation 12 below based on the experimental environment of this study.

$$Slope\ (K) = \frac{T_{re,i} - T_{sk,i}}{T_{re,i-1} - T_{sk,i-1}}$$
$$= \frac{(i-1)\Delta t(0.782 * 0.778 - 0.717^2) + \left[m_1 * T_{re,0} + m_2 * f(t) + m_3\right] - \left[n_1 * T_{sk,0} + n_2 * f(t) + n_3\right]}{(i-1)\Delta t(0.782 * 0.778 - 0.717^2) + \left[m_1 * T_{re,0} + m_2 * f(t) + m_3\right] - \left[n_1 * T_{sk,0} + n_2 * f(t) + n_3\right]}$$

Where parameters $m_1/m_2/m_3/n_1/n_2/n_3$ are defined in Table 2 above.

On the other hand, human rectal temperature is currently recognized as one of the most important indicators to evaluate human heat stress. It is also an index which is difficult to measure but very close to the human abdominal cavity temperature or core temperature [1-4]. Therefore, the T_{re} can be deduced by the T_{cr} [19] which contributes to the current difficulty on the dynamic measurement for the T_{re} in reality.

In conclusion, the m_1, m_2, m_3, n_1, n_2, n_3 are constant values based on the definitions in Table 2. Meanwhile, the value of f(t) is also a constant value when the corresponding time point is determined. The definition of T_{re} and T_{sk}, as well as the variations of both showed certain relationship in the stable high-temperature environment based on the deduction of the PHS model from the ISO 7933 according to Eq.12.

3. Experimental verification

The above theoretical analysis proposed the relationships between the variations of T_{re} and T_{sk}. The research team has conducted a series of heat exposure experiments in a well-controlled climate chamber. Human exposure experiment to high temperature and high humidity conditions was adopted in order to further verified the relationship and responded to the hypothesis. The details of the experiments can be referred to the published studies [1, 4, 16].

3.1 Heat exposure experiments

3.1.1 Subjects selection

A group of 25 healthy males who had been engaged in labor work for more than ten years were selected from a local labor market in Chongqing, China. They participated in the pre-experiment by walking at 0.5 m/s in 60 minutes in the environment with dry bulb temperature of 38℃, relative humidity of 40% and air velocity of 0.1 m/s. Their individual T_{sk} and T_{re} were compared with AD and SD to choose typical subjects for the following formal experiments [16, 19]. Finally, ten subjects were selected in this study for further verification with the basic information shown in Table 3. The clothing insulation of subjects was 0.4 clo based on the reference values for clothing ensembles and garments in ISO 9920-1995.

Table 3 Basic information of the 10 subjects

Index	Age (yr)	Height (m)	Weight (kg)	BMI (kg/m^2)	ADu	Resting HR (bpm)
AV	40.50	1.68	61.11	21.70	1.69	67.20
SD	4.06	0.046	4.17	1.15	0.075	5.90
Max	48	1.75	69.20	23.21	1.83	76

Min	35	1.61	56.90	19.73	1.59	57

Note: BMI for Body Mass Index, ADu for Dubois index, AV for average value, SD for Standard deviation, Max for the maximum value, Min for the minimum value.

3.1.2 Experimental design

The formal experiment in the climate chamber was conducted from June to September with a total of 90 trails. The 9 experimental conditions combing three temperature levels (35℃/38℃/40℃) and three relative humidity levels (25%/40%/60%) were conducted to explore the fluctuation characteristics of human physiological responses to the heat stress.

The tests lasted for 120 minutes. The dry-bulb temperature, globe temperature, relative humidity and wet bulb globe temperature (WBGT) were measured by AZ8778 Environment Test Device with the accuracy of ±0.1℃, ±0.1℃, ±0.1% and ±0.1℃ respectively. The air velocity was measured by Anemometer TSI 9525 with the accuracy of ±0.025m/s. Measurement instruments were placed in the central position of the climatic chamber at the height of 120cm above floor.

Subjects were asked to walk on the treadmill, with the velocity of 0.5 m/s, about 160 W/m^2 of actual activity level [16]. The rectal temperature and local skin temperatures were measured by TMCx-HD thermocouple temperature probe and recorded by U12-0064-channel data logger with the accuracy of ±0.2℃ and the sampling frequency was defined at 1s once. Subjects' rectal temperatures were measured by placing sterilized thermocouple probe into the their rectum for 10cm through the anus [19]. Before each test, subjects whose initial rectal temperature were higher than 37.4℃ were inhibited to participant in tests [4]. Besides, tests would be terminated during the periods according to three criterions:

1) the HR exceeded 180 bpm for more than 3 minutes;

2) the T_{re} exceeded 39℃;

3) subjects complained with headache, nausea or other symptoms.

The Fig. 1 bellow shows the onsite testing scene of the designed experiment in the artificial climate chamber.

Fig 1. The onsite testing scene in the climate chamber

3.2 Data collection and statistical analysis

The T_{re} and local skin temperatures of each subject were measured and collected based on experiment design. The Ramanathan four-point method [3] was chosen for calculation on the mean skin temperature T_{sk}. Though the AV and SD indices can reflect the basic fluctuation of subjects' physiological parameters for analysis, the change characteristics of each physiological parameter still requires more comprehensive analysis in different dimensions because:

(1) subjects with weak compatibility were liable to behave more violently in physiological response during tests;

(2) the activities of subjects affected the T_{re} and T_{sk} monitoring inevitably;

(3) subjects may keep sweating and had strong perspiration on skin surface so that the temperature probe and sensors was likely to be in poor contact with human skin surface which leads to measuring errors.

Given these impacting factors, this study further introduced the indicators of AD, CV and SKEW to evaluate the differences more objectively.

3.2.1 Average difference (AD)

The AD takes mean value as reference system and is less susceptible to be affected by extreme values compared to the SD. The SD is calculated from the variance by squaring but AD is a process of logic judgment with absolute value. The calculation of AD is more straightforward especially when there are frequent extreme values. The definition of AD is shown in Eq. 14.

$$\mathrm{AD} = \frac{\sum|\mathrm{x}-\bar{\mathrm{x}}|}{\mathrm{N}} \tag{14}$$

3.2.2 Coefficient of variation (CV)

The SD reflects the degree of fluctuation of a random variable. However, it sometimes produces unreasonable phenomena [54, 55]: 1) there is no practical significance for comparison if the random variables have different dimensions, 2) the relative size of the two random variables brings about a problem that random variables with larger values allow for a greater SD if the random variables have same dimension. The CV is a measure of dispersion of data relative to the AV [56-58] and has demonstrated better performance [59]. Since CV is a dimensionless measure, it can be used to compare the variation of data with significant different concept and cluster sizes. Generally, the larger the CV value is, the greater variability the data presents [60]. It takes advantages of cross dimensions analysis and has been widely applied in biomedicine, environmental analysis, manufacturing, dynamics study and many other research fields [61-66]. The basic expression of CV is shown in Eq.15.

$$\mathrm{CV} = \frac{\mathrm{SD}}{\mathrm{AV}} \tag{15}$$

3.2.3 Skewness (SKEW)

The SKEW represents a measure of the asymmetry and reflects the third-order central moment of the variables, which was introduced to measure the degree of skewness. The SKEW for a normal distribution is zero, and the negative values for the SKEW indicate data that are skewed left and positive for skewed right. The expression of SKEW is shown in Eq. 16.

$$\mathrm{SKEW} = \frac{N}{(N-1)(N-2)}\sum\left(\frac{x_i - AD}{SD}\right) \quad (16)$$

3.2.4 Pearson Product-moment Correlation Coefficient (PPCC)

The Pearson Product-moment Correlation Coefficient (PPCC) is an indicator for measurement of the degree of linear correlation between two random variables with the correlation coefficient between -1 and +1. It is commonly accepted that the result of $|r| \geq 0.8$ can be regarded as highly relevant. Meanwhile, the Covariance is used to measure the "covariates" between the two variables, representing the influence of the two variables on each other. The greater value of the Covariance indicates an increased influence between the two variables. Therefore, the PPCC and Covariance analysis were introduced to examine the relationship between T_{re} and T_{sk} based on the experiment data. Definition of the Pearson coefficient and the Covariance of T_{re} and T_{sk} are as shown in Eq. 17 and Eq. 18.

$$r=\frac{n\sum_{i=1}^{n}(T_{re,i}\times T_{sk,i})-\sum_{i=1}^{n}T_{re,i}\times\sum_{i=1}^{n}T_{re,i}}{\sqrt{n\sum_{i=1}^{n}{T_{re,i}}^{2}-(\sum_{i=1}^{n}T_{re,i})^{2}}\times\sqrt{n\sum_{i=1}^{n}{T_{re,i}}^{2}-(\sum_{i=1}^{n}T_{re,i})^{2}}} \quad (17)$$

$$\mathrm{COV}(T_{re}, T_{sk}) = E[T_{re} \times T_{sk}] - E[T_{re}]E[T_{re}] \quad (18)$$

3.3 Experimental results

3.3.1 Experiment termination

Table 3 shows the result of experiment termination based on the requirements in Section 3.1.2. It can be seen that there was no termination when the relative humidity was 25% and the number of terminations increased with the increase of dry-bulb temperature under relative humidity of 40% and 60%. The number of subjects' termination reaches 10 when the dry bulb temperature reached 38°C and 40°C under relative humidity of 60%. Thus, the relative humidity is one of the potential dangers which can accelerate the process of reaching human physiological thermal tolerance limits. The 85.7% (30 out of 35 subjects) was caused by the T_{re} exceeding the limits, the T_{re} is a relatively more sensitive safety evaluation indicator in hot environments compared to HR and subjects' feelings according to the experiment. However, the T_{re} monitoring is largely restricted in many working places due to the safety issue and subject acceptance, when the existing sensor has to be put through the anus of the human body in common practice.

Table 4 The numbers and reasons of experiment termination

Conditions	T_{re} exceeding the limit	HR exceeding the limit	Subjects' complaints	Terminated number	Complete number
35℃/30%	0	0	0	0	10
35℃/45%	0	0	0	0	10
35℃/60%	6	0	0	6	4
38℃/30%	0	0	0	0	10
38℃/45%	2	0	0	2	8
38℃/60%	9	0	1	10	0
40℃/30%	0	0	0	0	10
40℃/45%	5	0	2	7	3
40℃/60%	8	0	2	10	0
Total	30	0	5	35	55

3.3.2 Variation of T_{re} and T_{sk}

(1) Rectal temperature

The average T_{re} of the ten subjects over time in the nine conditions are shown in Fig. 2. The data was collected to the time point when the first subject terminated to ensure data integrity. ANOVA analysis on initial rectal temperature was carried out that there was no significant difference in the initial the T_{re} ($p=0.389$) between different subjects. Meanwhile, the initial T_{re} in different conditions showed no significant difference ($p=0.068$) which ensured comparability for different hot environments. Overall, the initial T_{re} in the experiment were concentrated in a small range of 36.98℃ to 37.13℃. The T_{re} showed a similar trend in conditions 1, 2, 4, 7 with relatively lower temperature and relative humidity but not in other conditions. The multivariate Pillai's Trace analysis showed that the T_{re} represented a significant difference ($p<0.001$) with different relative humidity. There was no significant difference in T_{re} when relative humidity was 25% and 40% at 35℃ and the T_{re} was significantly higher when relative humidity was 60%. Also, there was a significant difference in T_{re} with different relative humidity when the temperature was 38℃ and 40℃. The result revealed that the temperature would be a dominant factor affecting T_{re} when the relative humidity was lower (25%, 40%). However, there were significant increase in T_{re} due to the limited evaporation cooling on the skin surfaces when the relative humidity increased (60%).

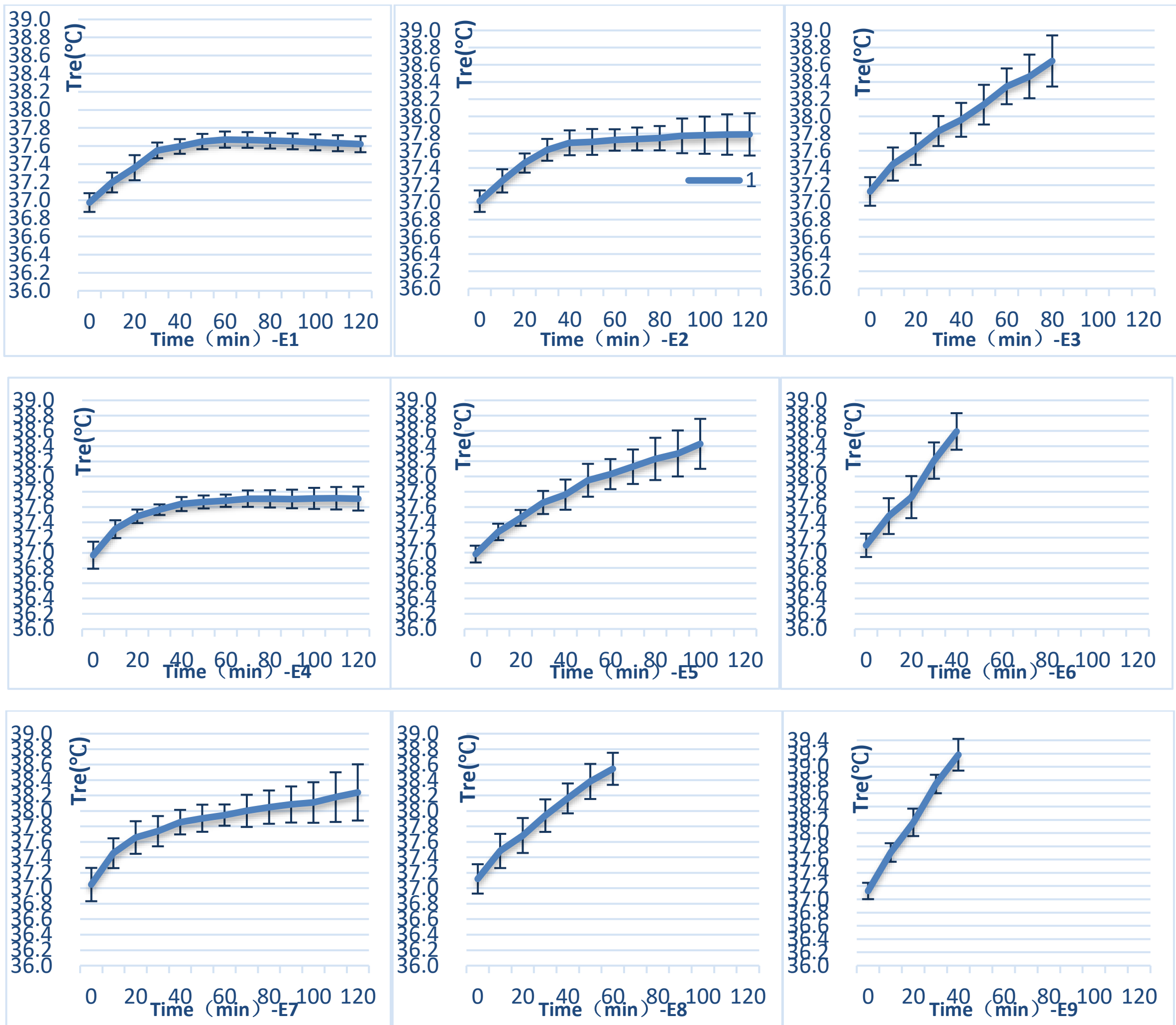


Fig. 2 T_{re} variation over the 120 min in the 9 different experiment conditions

Y Axis represents the T_{re} (℃) and X Axis represents time (min)

Nine conditions from left to right and from top to bottom represents the environment (temperature/humidity, E1-E9) of 35℃/25%, 35℃/45%, 35℃/60%, 38℃/25%, 38℃/40%, 38℃/60%, 40℃/25%, 40℃/40%, 40℃/60% representatively.

(2) Skin temperature

The fluctuation of T_{sk} over time is shown in Fig. 3 which is similar with the changing trend of the T_{re}. The T_{sk} shows a significant increase over a period of time and then reach stability in conditions 1, 2, 4, 7 with relatively lower temperature and humidity. The subjects' initial T_{sk} in different conditions was compared by the two-way ANOVA method. It also shows no significant difference ($p = 0.201$) between the initial T_{sk} of different subjects. The statistical analysis finds that the T_{sk} represents a significant difference ($p<0.001$) with different relative humidity. There is no significant difference in T_{sk} when relative humidity is 25% and 40% at 35°C, and the T_{sk} is significantly higher when relative humidity reaches 60%. There is also a significant difference in T_{sk} with different relative humidity when the temperature is 38°C and 40°C. This indicates that the temperature will be the dominate factor when the relative humidity is low (25%, 40%). This shows a similar change trend with T_{re} in Fig.2.

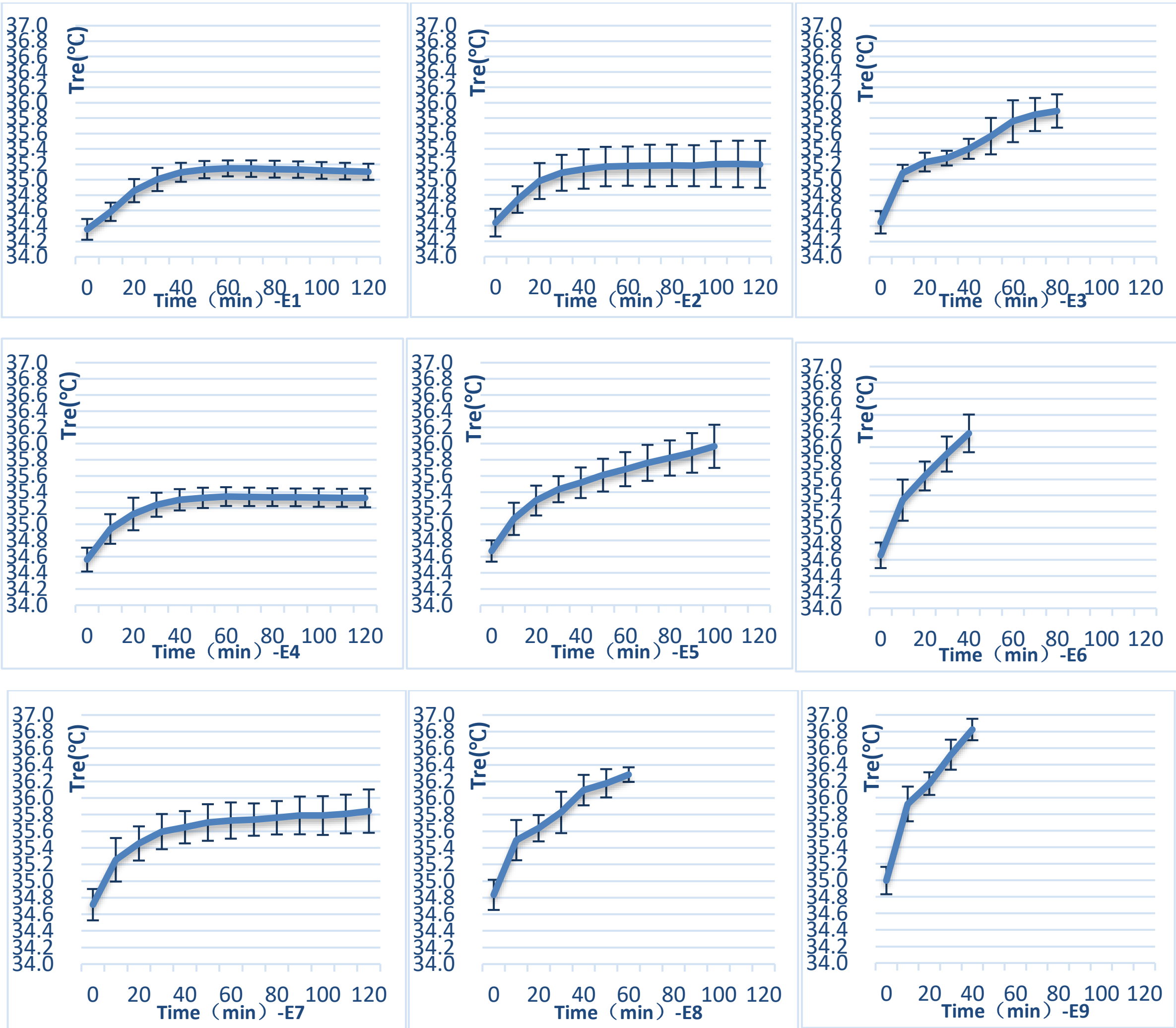


Fig. 3 T_{sk} variation over the 120 minutes in the 9 different experiment conditions

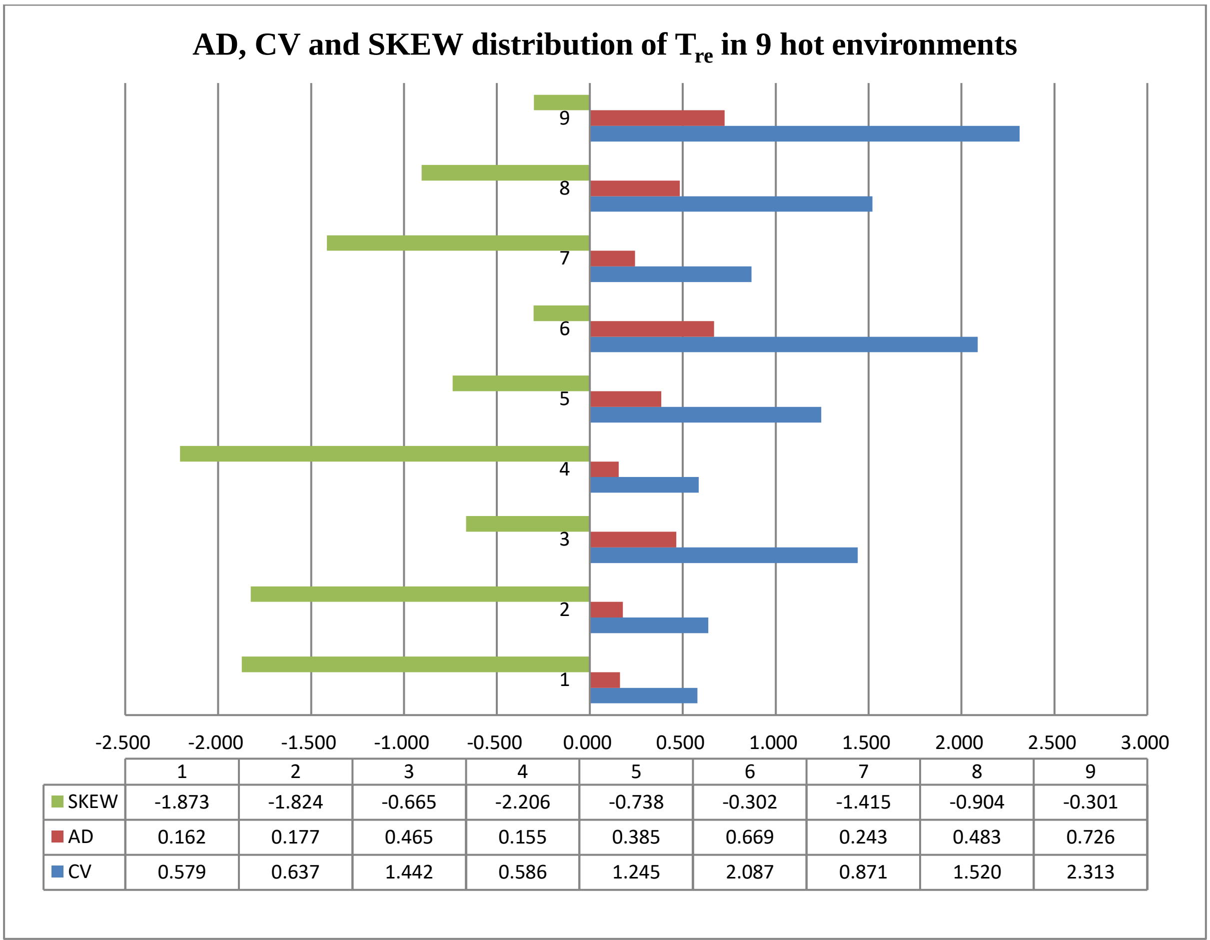
Y Axis represents the T_{sk} (°C) and X Axis represents time (min)

Nine conditions from left to right and from top to bottom represents the environment (temperature/humidity, E1-E9) of 35°C/25%, 35°C/45%, 35°C/60%, 38°C/25%, 38°C/40%, 38°C/60%, 40°C/25%, 40°C/40%, 40°C/60% representatively.

3.4 Verification of the relations between T_{re} and T_{sk}

3.4.1 Comprehensive variation of T_{re} and T_{sk}

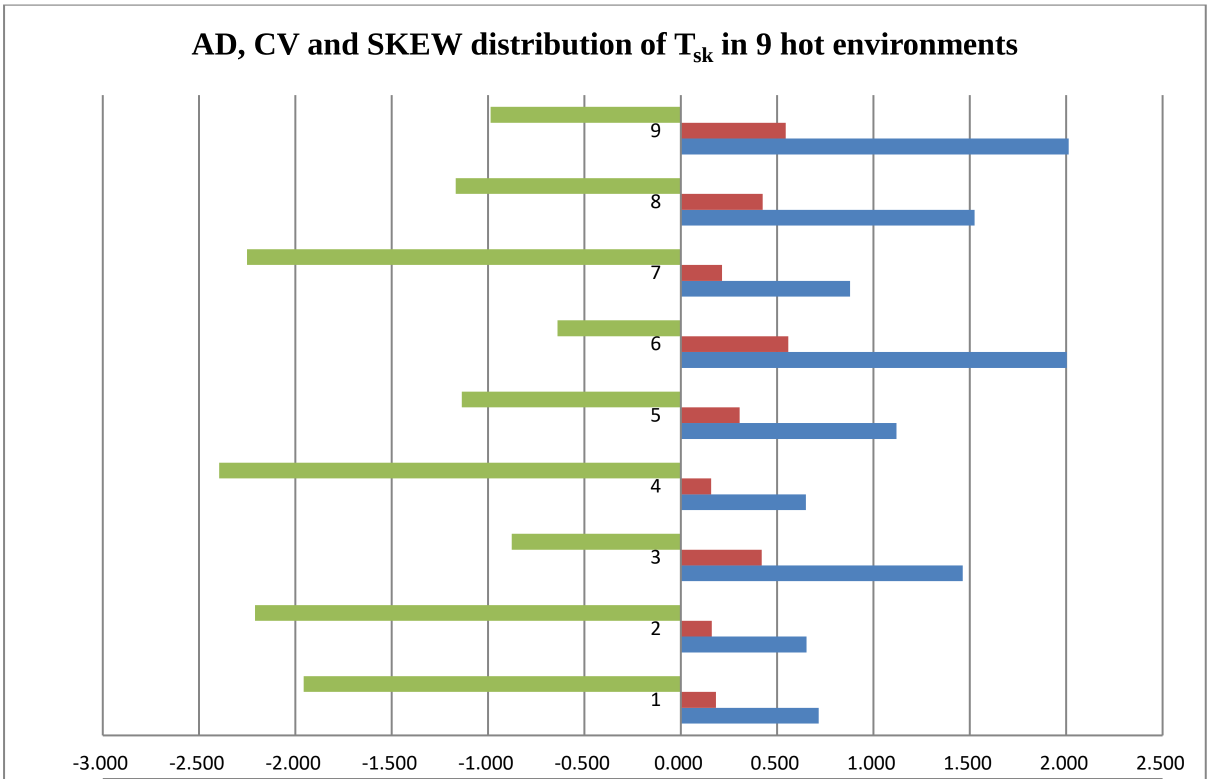
According to Fig. 2 and 3, the T_{re} and T_{sk} had shown faster growth with larger SD when the temperature and relative humidity increased. The fluctuations reflected the body's ability to adapt to the heat stress environments. Therefore, Fig. 4 shows the comprehensive changes of T_{re} on AD, CV, and SKEW in the 9 conditions. The variation of T_{re} increased along with increased relative humidity. Meanwhile, the T_{re} showed increased volatility with higher temperature under the same humidity level. There were obvious combined effects of temperature and relative humidity in conditions 3, 6 and 9 indicating that the T_{re} was significantly affected by temperature and relative humidity at the same time. The SKEW of T_{re} was negative in all the experiment conditions, indicating the T_{re} distribution was left skewed and the negative second derivative showed weakened increase on T_{re}. In general, the effect of strengthening inhibitory of the rectal temperature played a decisive role in the protection of body's heat regulation.



	1	2	3	4	5	6	7	8	9
SKEW	-1.873	-1.824	-0.665	-2.206	-0.738	-0.302	-1.415	-0.904	-0.301
AD	0.162	0.177	0.465	0.155	0.385	0.669	0.243	0.483	0.726
CV	0.579	0.637	1.442	0.586	1.245	2.087	0.871	1.520	2.313

Fig. 4 AD, CV and SKEW distribution of T_{re} of the 10 subjects in 9 hot environments

Fig. 5 shows the analysis on comprehensive change of T_{sk}. It can be found that the variability of T_{sk} changed in a similar way compared to that of T_{re}. The T_{sk} remained between the ranges of 34.45℃ to 36.84℃ and did not appear the larger range of the ambient temperature as 35℃ to 40℃. The changes of T_{sk} and T_{re} were also similar to each other on SKEW distribution. However, the average value of SKEW of T_{sk} in the 9 conditions was larger than that of the T_{re} (1.513> 1.137) in general. Human skin surface had the better heat transfer process by direct contacting with the ambient environment and sweat evaporation although the T_{re} and T_{sk} were linked by the regulation of circulatory system.



	1	2	3	4	5	6	7	8	9
SKEW	-1.957	-2.210	-0.877	-2.397	-1.136	-0.640	-2.252	-1.168	-0.987
AD	0.182	0.160	0.420	0.157	0.306	0.557	0.214	0.424	0.544
CV	0.715	0.652	1.462	0.649	1.119	2.003	0.878	1.524	2.013

Fig. 5 AD, CV and SKEW distribution of T_{sk} of the 10 subjects in 9 hot environments

According to Fig. 4 and 5, the AD, CV and SKEW of T_{re} and T_{sk} in the 9 conditions showed obvious similarities with each other. As a result, a comprehensive comparison on AD, CV and SKEW of the 10 subjects was carried out and the results are shown in Fig. 6. The main changing trend of T_{re} and T_{sk} were similar in all 9 conditions but the SKEW of T_{sk} was higher than that of T_{re} in each condition, which would be discussed in the following.

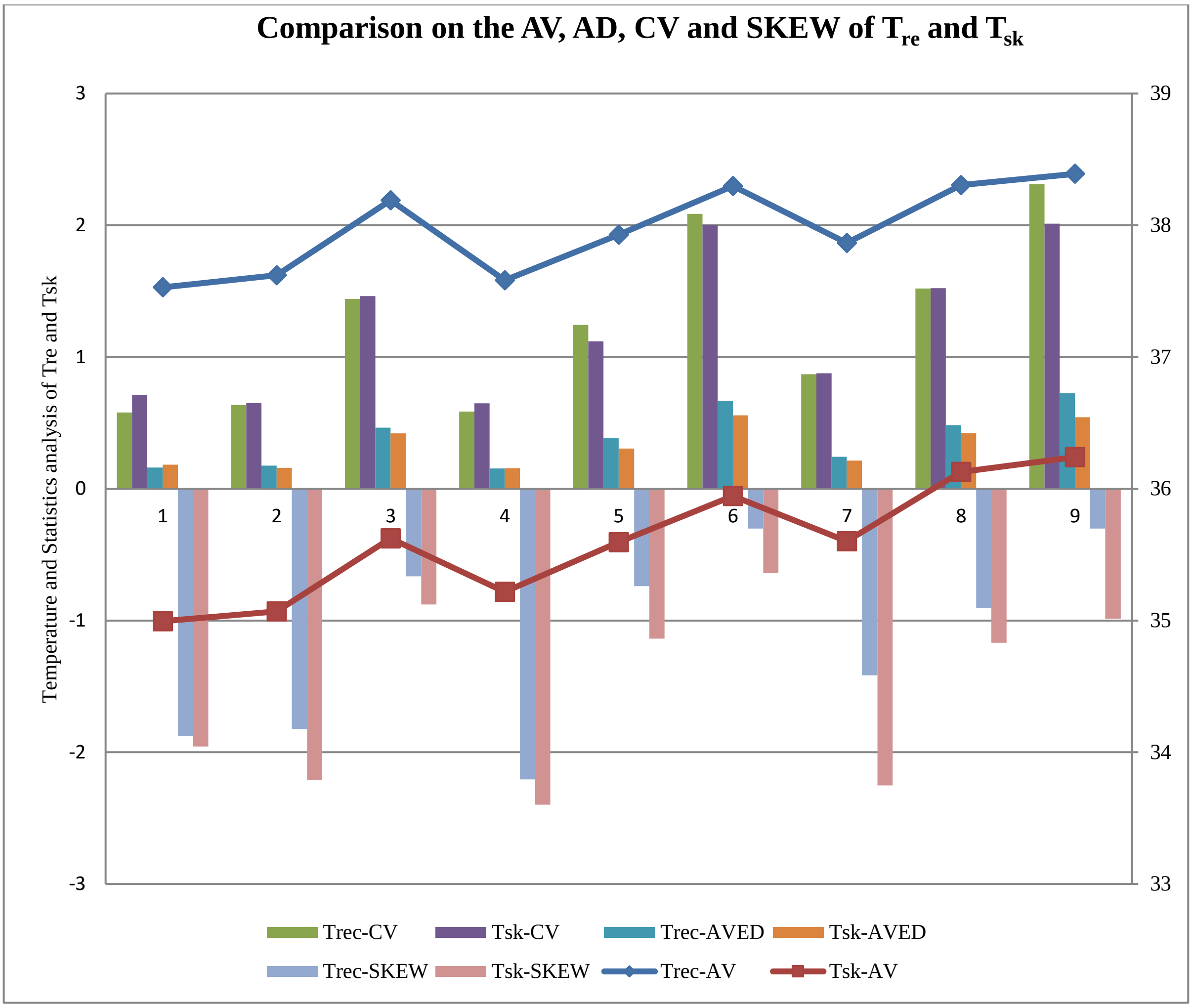


Fig. 6 Comparison on the mean value and average value of AD, CV and SKEW of T_{re} and T_{sk} among the 10 subjects in the 9 hot environments

3.4.2 Verification on the predicted model based on experimental results

The mathematical expression between T_{re} and T_{sk} is proposed by the PPCC with the predicted slope and intercept based on the method in Section 3.2.4. The PPCC is calculated for the mean value of AV, CV, AD and SKEW of T_{re} and T_{sk} of the 10 subjects in 9 hot environments. The result is shown in Table 5.

Table 5 Poisson coefficient and Covariance analysis on AV, CV, AD, SKEW of T_{re} and T_{sk}

Statistics		AV		CV		AD		SKEW	
Parameters		T_{re}	T_{sk}	T_{re}	T_{sk}	T_{re}	T_{sk}	T_{re}	T_{sk}
Nine conditions	1	37.53	35.00	0.58	0.72	0.16	0.18	-1.87	-1.96
	2	37.62	35.07	0.64	0.65	0.18	0.16	-1.82	-2.21

	3	38.19	35.62	1.44	1.46	0.47	0.42	-0.67	-0.88
	4	37.58	35.22	0.59	0.65	0.16	0.16	-2.21	-2.40
	5	37.93	35.59	1.25	1.12	0.39	0.31	-0.74	-1.14
	6	38.30	35.95	2.09	2.00	0.67	0.56	-0.30	-0.64
	7	37.87	35.60	0.87	0.88	0.24	0.21	-1.42	-2.25
	8	38.31	36.13	1.52	1.52	0.48	0.42	-0.90	-1.17
	9	38.39	36.24	2.31	2.01	0.73	0.54	-0.30	-0.99
Linear analysis	PPCC	0.96		0.99		0.99		0.94	
	Covariance	0.13		0.31		0.031		0.41	
	Prediction slope	0.73		1.16		1.33		0.98	
	Prediction intercept	12.09		-0.17		-0.05		0.35	

The relationship between T_{re} and T_{sk} based on the experimental data can be shown in Eq. 19 When taking the nine environmental conditions as fixed factor. The Poisson's ratio of the AV, CV, AD and SKEW of T_{re} and T_{sk} have all exceeded 0.9 from the statistical analysis in Table 5, indicating the higher correlation between them. The experimental data has shown good consistency with theoretical derivation on the deduction of the prediction relationship. In addition, the covariance of the AV, CV and AD of T_{re} and T_{sk} was not significant (0.130, 0.314%, 0.031 respectively), indicating a stable relationship between T_{re} and T_{sk} with a stable slope coefficient in Eq. 19.

$$T_{re,i} = 0.73T_{sk,i} + 12.09 \quad (19)$$

3.5 Verification on time dimension of the correlation between T_{sk} and T_{re}

The fluctuation of AV/SD/SKEW in multiple dimensions of the above study can show the correlation of physiological parameters in the stable state in certain environments. However, the control characteristics of human body on different physiological parameters include multiple dimensions: (1) absolute fluctuation in the low dimension (AV/AD/SD) and variability in high dimensions (CV/SKEW), as well as (2) correlation in time dimension (such as hysteresis). Exploring the logic of time fluctuation of thermal physiological indexes is the key to verify whether the mathematical relationship of T_{sk} and T_{re} obtained can be applied in complex hot working environment and it is also the scientific basis for reasonable arrangement on scientific working-resting time scheme design. This section further studies and verifies the dynamic fluctuations of T_{sk} and T_{re} of each subject in time dimension.

3.5.1 Dynamic fluctuations of human rectal temperature

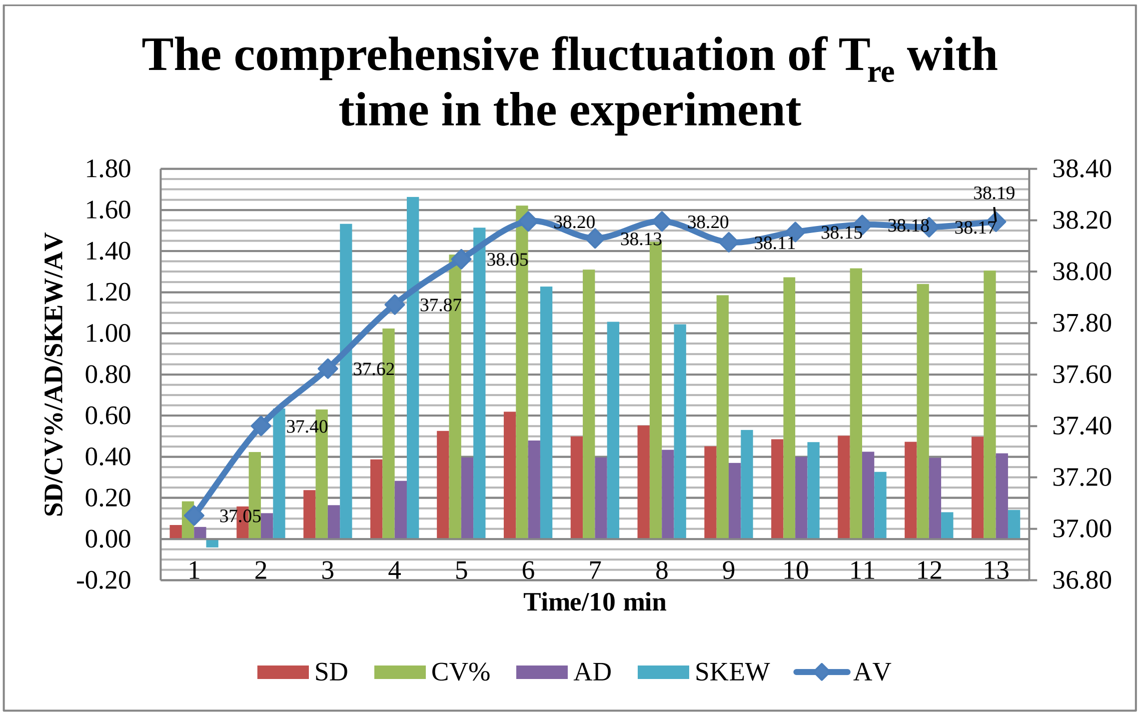


Fig. 7 The dynamic fluctuations of Tre with time

Fig. 7 shows the comprehensive fluctuation characteristics of the T_{re} of the subjects in the experiment under time dimension. The AV, SD, CV of T_{re} were adjusted by human body in the first 60 minutes and then stabilized. The maximum SKEW of T_{re} appeared at around 40 minutes in the experiment indicating the strongest adjustment on the subjects on their rectal temperature appeared at the first 40 minutes after their start of work. Rectal temperature varies between 37-38℃which is relatively smaller compared to the huge fluctuation range of ambient temperature and ambient humidity. It can be seen that the standard deviation of rectal temperature among different subjects reached 0.4℃ from the above analysis while the SKEW reached 1.6 among subjects showing a large difference. The variability index CV is small and there are no individual extreme values among the samples which ensures the consistency of the experiment. The coefficient of variation also gradually decreased after 60 minutes of the experiment and gradually reached a stable state from the perspective of data variability, which was consistent with the experimental results. SD of T_{re} also showed its own deviation after 60 minutes but not clearly manifested before 60 minutes, proving that 60 minutes was the time limit for T_{re} to reach stability during the experiment.

3.5.2 Dynamic fluctuations of human skin temperature

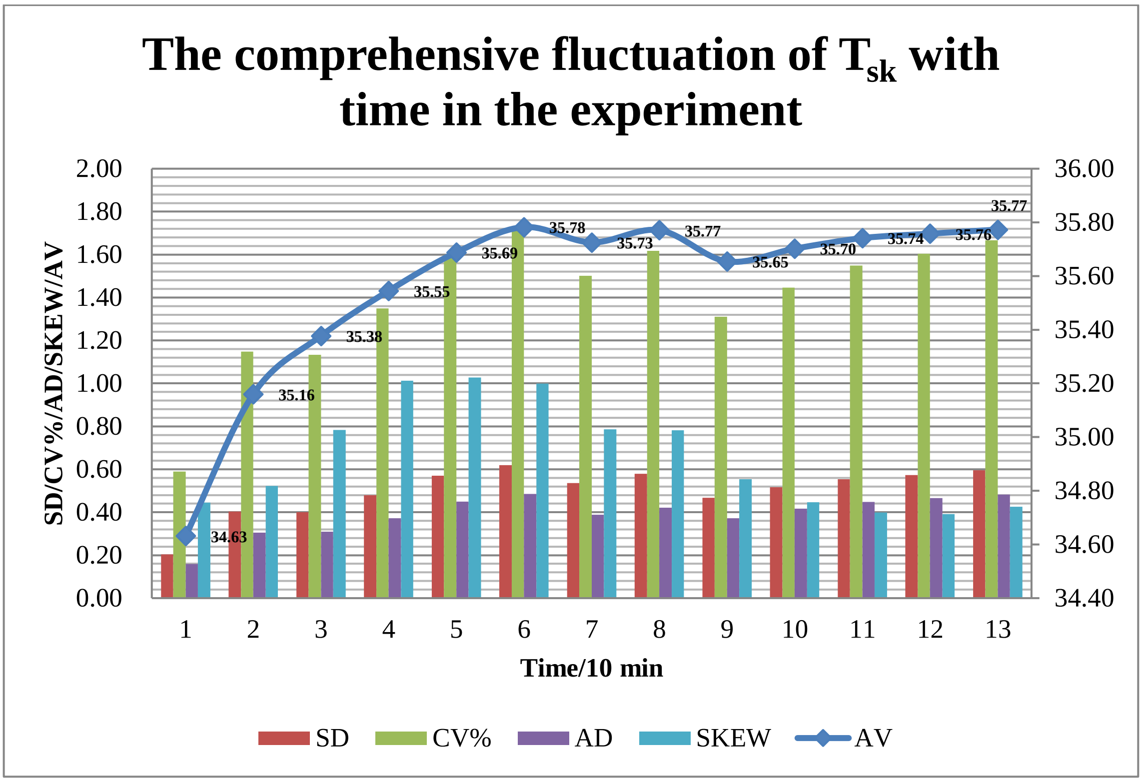


Fig. 8 The dynamic fluctuations of T_{sk} with time

It can be seen in Fig. 8 that the change trend of skin temperature and rectal temperature showed similar characteristics when completing adjustment within 60 minutes and then reach stabilization. The maximum skew of the T_{sk} appears at 50 minutes which is later than that of the T_{re} and is slightly different from that of the T_{re} indicating the maximum control ability of the human body on the skin temperature appears at about 50 minutes in hot working environment. The skin temperature varies between 34.5-35.8 ℃and the change range is also smaller compared to the change range of the environment although the skin is in direct contact with the external environment and is affected by the convection and radiation heat exchange between the external environment. The SD of T_{sk} in different subjects was about 0.5°C after T_{sk} reached its stability and the SD of T_{sk} was greater than that of T_{re}. There is no major change on skin temperature and the coefficient of variation does not appear extreme values although the skin temperature was severely affected by the external environment, indicating that the human body still has a strong control ability over the skin temperature through the joint action of the blood circulation system and the perspiration system even the skin is in direct contact with the outside environment.

3.5.3 Comparison of dynamic rectal temperature and skin temperature

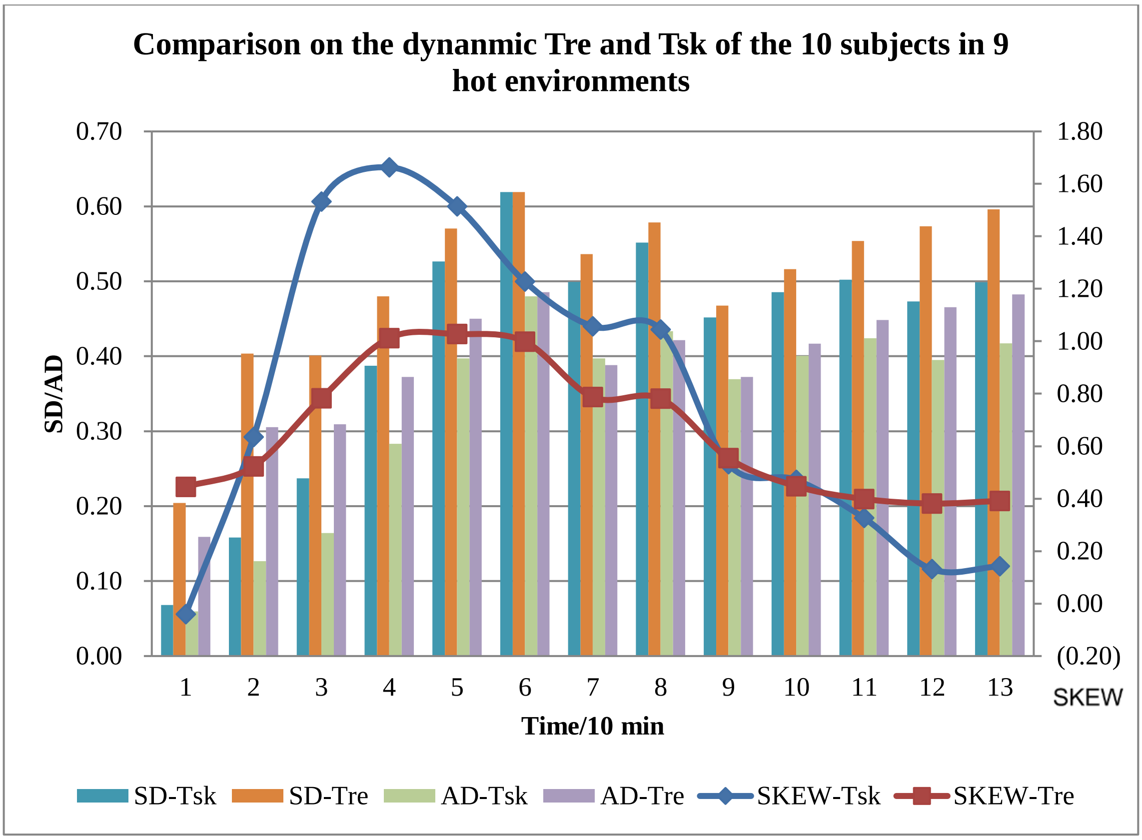


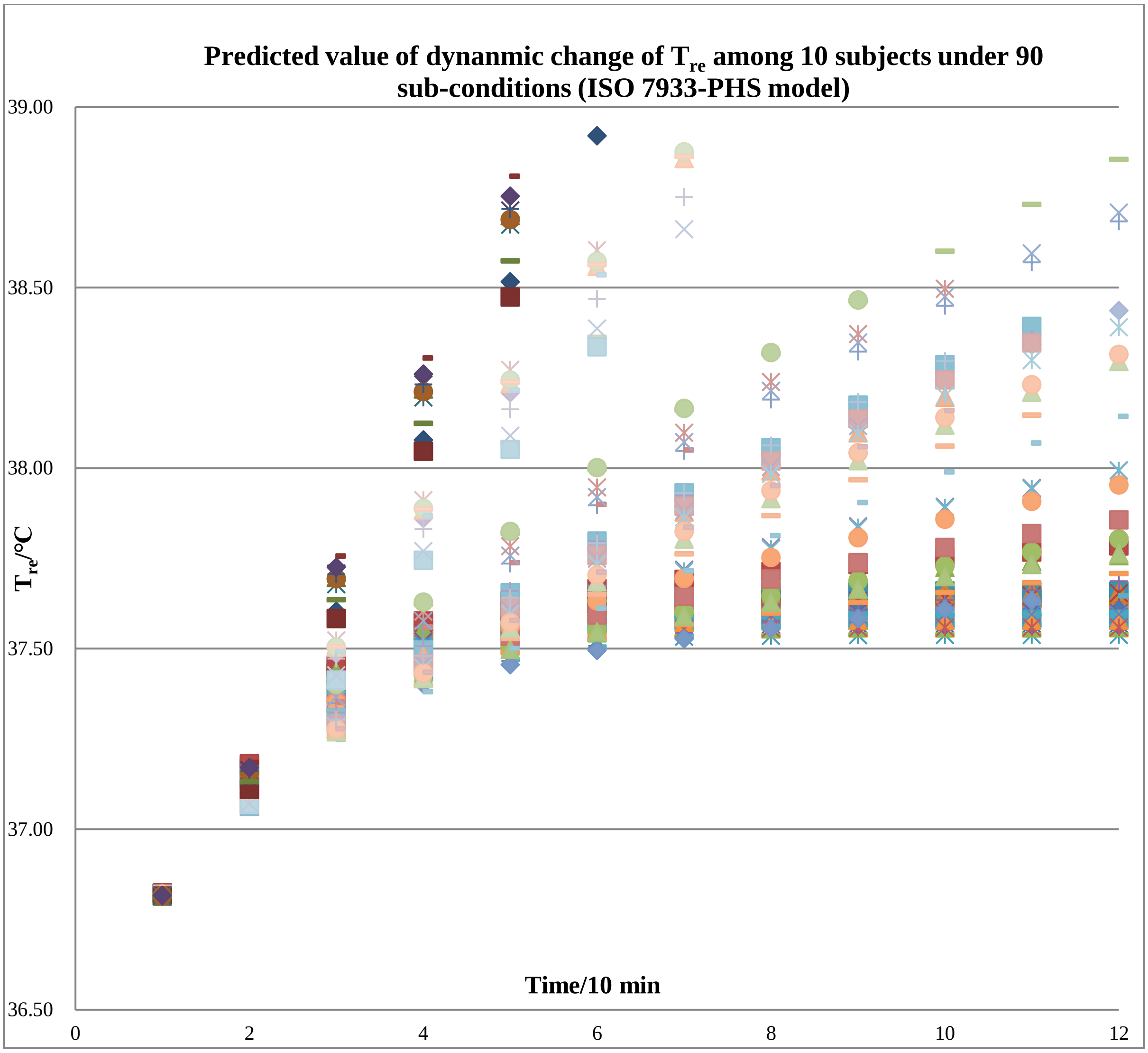
Fig. 9 Comparison on the T_{re} and T_{sk} fluctuation trend over time

The existence of relationship between T_{re} and T_{sk} in this experimental environment has been proved from the perspective of theoretical derivation and experimental verification in Section 3.4 of this study. Fig. 9 shows the comparison on the dynamic fluctuation of T_{re} and T_{sk} among the 10 subjects in 9 hot environments. On one hand, the T_{re} and T_{sk} still show the similar dynamic change trend in high temperature working environment. On the other hand, they also show different characteristics in their fluctuation although T_{sk} and T_{re} show strong correlation in the different hot environments. Both rectal temperature and skin temperature underwent a rapid adjustment and then reached a stable process. It can be found that rectal temperature and skin temperature had gone through an obvious adjustment stage in the first 60 minutes according to the dynamic changes of AV, SD, CV and AD, then a relatively stable state was reached after 60 minutes. Specifically, skewness of different physical parameters can indirectly reflect the control ability of human body over them in this experiment. It can be found that the adjustment of T_{re} is 10 minutes earlier than that of skin temperature through the study of SKEW (extremum point showed up earlier) and the strongest adjustment state occurred during the period of 30-50 minutes. The change of SKEW (T_{re}) is not only earlier in time but also larger in absolute value showing stronger control ability compared to that of the

SKEW (T_{sk}). The curvature change of T_{re} appears earlier with larger curvature which reflects that the human body's control ability on rectal temperature is significantly more effective than that of skin temperature in hot working environment according to the changing curve of the two parameters.

3.5.4 Verification on the predicted result of PHS model of ISO 7933

In addition, PHS model of ISO 7933 standard was used for prediction verification based on the design environment conditions and the basic information of the subjects in the experiment in order to verify the validity and accuracy of the measured values in the above dynamic tests. Fig. 10 shows the comparison between the predicted value of rectal temperature under the PHS model and the measured value in the laboratory taking a typical experiment condition of 33℃/30% as an example. It can be found that the change trend of the measured value was consistent with the predicted change trend of PHS model when T_{re} reached stability after 60 minutes from the dynamic changes of the measured and predicted data of T_{re} in Fig. 10, which also reflected the validity of the experimental results and the rationality of deducing model between T_{sk} and T_{re} by using the basic theory of PHS model in this study.


Predicted value of dynanmic change of T_{re} among 10 subjects under 90 sub-conditions (ISO 7933-PHS model)
39.00
38.50
38.00
37.50
37.00
36.50
T_{re}/°C
Time/10 min
0
2
4
6
8
10
12

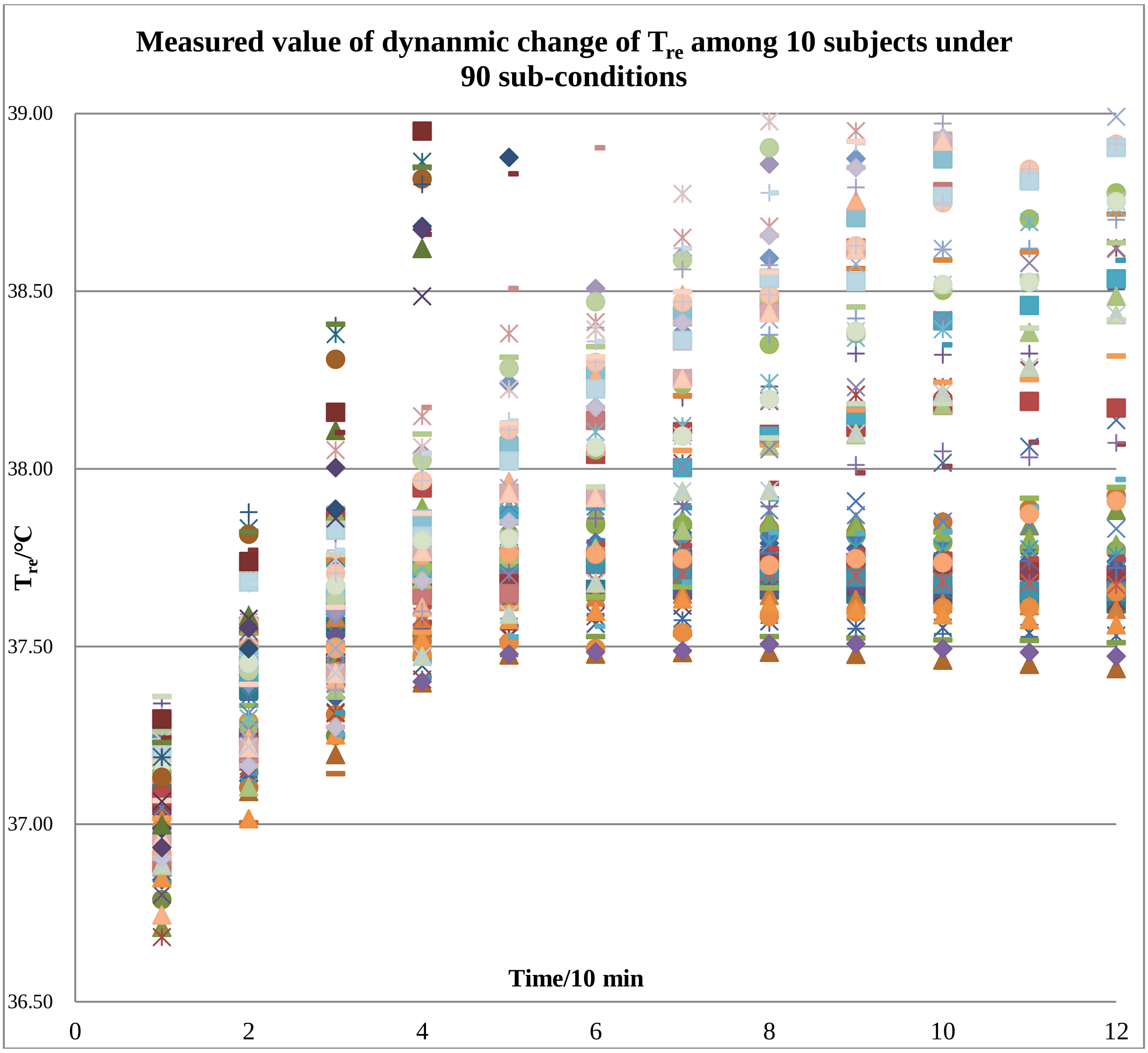


Fig. 10 The predicted T_{re} by the PHS model and the measured T_{re}

In summary, the mathematical model between T_{re} and T_{sk} derived in this study shows a good agreement with the experimental results when the human body reaches static thermal equilibrium in various hot working environments, and during the dynamic heat adaptation process among the subjects. Both the experiment testing results were also consistent with the dynamic prediction results of ISO 7933 standard demonstrating its practical significance in application.

4 Discussion

4.1 Physiological response differences in different environment conditions

The SKEW of T_{re} and T_{sk} could reflect the curvature and the second derivative in its changing trend according to Fig. 4-5. The larger SKEW indicated larger curvature and the control of human rectal temperature and skin temperatures gradually strengthened in order to avoid their excessive increase. In the case of small SKEW (conditions 3, 6, 9), the change trend of T_{re} has approximately formed a linear relationship over time and the coefficient of SKEW was approaching zero when the linear growth exacerbated (-0.3012 in condition 9 compared to conditions 3 and 6). However, when the AD and CV of T_{re} increased, the SKEW became smaller (condition 3, 6, 9). The curvature of the growth became smaller with SKEW and the changing trend of T_{re} reflects a constant relation.

In addition, the mean value of SKEW decreased by 0.208 from the comparison of T_{re} in conditions 4, 5, 6 and conditions 7, 8, 9, while the T_{sk} was less affected compared to T_{re} (mean value of SKEW decreased by 0.078). The SKEW of both T_{re} and T_{sk} increased with increased humidity (conditions 1, 4, 7 compared to 3, 6, 9 respectively). This can be explained that the relative humidity affected the human body's perspiration directly while the cooling dissipation by sweat evaporation accounted for the largest part of the heat exchange between the human body and the environment, especially when the ambient temperature was higher than skin temperature. An interesting finding was that the maximum SKEW of both T_{re} and T_{sk} appeared in condition 4. This can be explained that compared to conditions 1, 2, 3, condition 4 provided stronger heat stimulation. on the other hand, the body heat transfer was restricted and the ability for body heat regulation could not be fully dispatched due to the higher ambient temperature though the subjects had stronger heat stimulation in conditions 5, 6, 7, 8, 9.

4.2 Advantages of this study

The traditional heat stress evaluation of PHS model in ISO 7933 standard has introduced a large number of environmental and physiological parameters (such as $A/W/I_{cl}/h_r/h_c/pa/H/V_a$, $HR/M/T_{cr}/T_{sk}$) and adopted time iteration for dynamic prediction (t_i-t_{i+1}), which leads to inconveniences and the occurrence of random errors in reality measurement. Besides, there are dynamic changes in environmental exposures in practical applications which cannot be avoided (such as fluctuations of wind, instantaneous switching among different high temperature scenes, as well as complex irregular changes in body movements, instant surge in working metabolic rate and so on). The monitoring of environmental and physiological parameters becomes extremely complicated as a result. The measurement of the complex parameters like human rectal temperature, not only brings difficulty to the use of instruments which can easily leading to the system errors, but also have a direct impact on the humans' working activities and safety. This study found the quantitative relationship between the core temperature of human body and the changes of skin temperature under heat exposure based on theoretical deduction of ISO 7933 and experimental verification. The prediction model was further proposed based on the experimental data. The quantitative relation provides a convenient method for individual monitoring, especially on indirect prediction for human core temperatures when the skin temperatures are in suitable measurement on practical working sites. Besides, the linkages between different human physiological indicators in different variation dimensions can also contribute to the accuracy of the current heat stress prediction models.

4.3 Outlook of this study

However, some limitations should be addressed when elaborating the results from this study. The different physiological responses of human body to heat exposure could be achieved by both congenital factors and acquired factors which remain unexplored. The individual difference of physiological responses among working groups or even working populations should be paid attentions. The relation in this study is based on specific working group in certain hot environments as designed. More representative working groups and working environments such as the different heat adaption abilities of different populations in different climate zones are expected, to further elaborate the relation.

5 Conclusion

This study proposed a theoretical model between human rectal temperature and skin temperature. Validation was conducted based on heat exposure experiments of the 10 subjects in 9 different hot environments in a climate chamber. Further analysis on the fluctuation in the different dimensions of average difference, coefficient of variation and skew was carried out. Some conclusions are drawn as follows:

(1) The mean value and the volatility of the skin temperature and rectal temperature have all increased with increasing temperature and relative humidity. A significant increase of each parameter was found in higher temperature-humidity environment.

(2) The adjustment of human rectal temperature is slightly earlier compared with that of skin temperature and the strongest adjustment occurs in the first 30-50 minutes in hot working environment. The curvature change of rectal temperature appears earlier and the curvature appear larger according to the dynamic change two physical parameters reflecting that the human body's control ability on core temperature is earlier and more effective than that of skin temperature under hot working environments.

(3) There was a significant relation between the rectal temperature and skin temperature with Poisson's ratio of average difference, coefficient of variation and skewness. Mathematical relation between rectal temperature and skin temperature were obtained by theoretical

deduction and validated by experimental data, when combined with environmental parameters (coefficient of $m_1/m_2/m_3/n_1/n_2/n_3$) and skin temperature in practices. The work contributes to fast and convenient prediction of rectal temperature through measuring the dynamic skin temperatures and the working environment which benefits to the practical applications in human heat strain protection on the complex hot working sites.

Ethics ratification

This study was conducted with the approval of the Ethics Review Committee for Life Sciences Study of Central China Normal University with Project Ethics Ratification ID CCNU-IRB-2009-003.

Acknowledgement

The authors would like to thank "Chongqing Construction Technology Plan, NO. 20220184", "Chongqing Postdoctoral Research Project Special Support, NO. 2211013357670761" and "National Key R&D Program of China, NO. 2022YFC3801504". The Authors declare that there is no conflict of interest, and authors contributed equally in the preparation of this manuscript.

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