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Sports health quantification method and system implementation based on multiple thermal physiology simulation

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Abstract

People exercising under high ambient temperature will cause changes in physiological indicators. In order to study the thermal physiological state of the human body, we randomly selected 18 volunteers into the thermal environment exercise group and the room temperature exercise group. Two groups of volunteers performed aerobic exercises in different thermal environments. In the case of exercise performed every 15 min, the volunteers' hemorheology, physical performance rating (RPE) value and rectal temperature (T_{re}) were tested. At the same time, we recorded the physiological indicators of the volunteers and simulated the thermal physiology. The results showed that there was a difference in the thermal physiology of the two groups of volunteers, and the hemorheology and the self-strain rating scale were highly correlated in the thermal environment ($r=0.839$, $P<0.01$). For this reason, we can conclude that exercising in a hot environment will make people have a heavier heat stress response, and thus render them more likely to undergo muscle fatigue. It is advised that exercising at high temperatures may be avoided as much as possible.

Keywords: multiple thermal physiology simulation, exercise quantification, thermal regulation, thermal adaptation, physiological changes, health

AMS 2010 codes: 35K05

1 Introduction

Like breathing, heart rate, and blood pressure, body temperature is also a critical life characteristic of a person. Its relative stability is necessary to ensure the regular progress of the body's metabolism and life activities. The occurrence of heat illnesses will endanger physical health and life safety. Therefore, the body's adjustment ability and physiological changes during fitness exercises and training competitions in a hot environment have

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attracted much attention. Some scholars pointed out that the most important factor is the environmental temperature, contributing up to 70% to the multi-element thermophysiological simulation [1]. Domestic related research primarily focuses on the comprehensive discussion of the effects of multiple thermophysiological simulations on the body, and there are few targeted human experiments. Based on relevant elements of research observed in the literature, we combined the particular geographical location and temperature conditions. We conducted targeted experiments on the adjustment ability and physiological changes of college students in a thermal environment. Simultaneously, the paper obtains multiple physiological signs data closely related to human sports health through simulation calculations and uses these physiological signs data to predict human sports physiological responses under multi-scene experimental conditions to help people understand the human physiological health level different environments and activities groups. The paper aims to achieve the purpose of predicting and analysing the physiological state of the human body.

2 Research objects and methods

2.1 Research objects and groups

We randomly divided 18 male college students (without training experience) who volunteered to participate in the experiment into two groups. The control group (NE) group was a standard room temperature exercise group ($n=9$, $26\pm 1^{\circ}\text{C}$), and the high fever group (HE) group was a thermal environment exercise group ($n=9$, $38\pm 1^{\circ}\text{C}$). The relative humidity (%RH) is $73\%\pm 3\%$. The subjects had no history of disease on physical examination and we ensured that all subjects had rest time and regular diet 5 days before the experiment [2]. They do not consume coffee, alcohol, and other stimulants, and they wear suitable clothing to participate in the test. The basic situation is shown in Table 1.

Table 1 Basic situation and grouping of subjects

Grouping	NE	HE
Age (years)	21.3 ± 0.3	20.5 ± 0.7
N	9	9
Height (cm)	170.3 ± 0.5	168.6 ± 0.8
Weight (kg)	63.3 ± 3.8	65.0 ± 3.5
HRrest (b/min)	73.6 ± 5.6	75.1 ± 5.7
VO ₂ max (ml/kg/min)	50.8 ± 4.6	52.3 ± 5.3

HE, high fever group; NE, control group.

2.2 Test indicators and methods

We use POWER MAXV II power car and POLARS 810 equipment to measure heart rate. The subjective physical performance rating (RPE) was assessed using the BorgRPE scale. Before exercise and immediately after training, we take 20 μl of micro finger blood, use the micro whole blood diacetyl mono oxime method (we add the blood to a test tube containing 0.5 ml of 1% sodium fluoride, immediately add 1.5 ml of 10% trichloroacetic acid, shake well, 3000 rpm/min centrifugation for 10 min), 721 spectrophotometers to measure the blood urea (BUN) level. Standard Rectal Thermistor measures the rectal temperature (Tre), and the miniature probe is placed 6–8 cm in the rectum.

The two groups of subjects were pedalling for 60 min at room temperature and the thermal environment with 55% VO₂max. HR, RPE and Tre were recorded before exercise, every 15 min during practice and immediately after exercise; and BUN concentration and fatigue index (FI) was measured immediately after exercise. The experiment was conducted in the exercise physiology laboratory in July 2019.

2.3 Thermal physiology model

2.3.1 Thermal regulation mechanism modelling

Body temperature is an essential signal of the human body's internal thermal regulation system, and it is also an important indicator to measure the human body's health status. Studying body temperature distribution and human thermal regulation behaviour and building a human body thermal regulation model is indispensable in sports physiological simulation. The human body is regarded as a heat transfer system containing internal heat sources [3]. The biochemical reactions of human tissues produce energy. Most of this energy will gradually be transformed into heat, which continuously exchanges heat with the external environment through conduction, convection, radiation and evaporation. After this transformation, the human body temperature is maintained at about 37°C. Especially in exercise, the process of internal energy generation and conversion of the human body occurs continuously and intensely, which will inevitably lead to a rapid increase in human body temperature and activate the human body's thermal regulation system. In thermal regulation, the human body temperature sensor will collect the current temperature of each node of the body and transmit it to the body temperature regulation centre. After this, the body temperature regulation centre sends out control signals for production and heat dissipation to various human body tissues and uses human skin blood flow, sweat glands and skeletal muscle activities to achieve thermal regulation behaviour to maintain the thermal stability of the human body during exercise.

In this section, through the analysis and processing of the components of the 25-node human body model and its heat transfer characteristics, the thermal regulation mechanism is modelled and analysed from five aspects: skin layer, fat layer, the muscle layer, inner core layer and central blood pool [4]. The heat balance equation of each segment of the body in the human body model is as follows.

Inner core heat balance equation:

$$C(i, 1) \frac{dT}{dt} = Q_{qb(i,1)} - Q_{b(i,1)} - Q_{d(i,1)} - Q_{res(i,1)} \quad (1)$$

Muscle layer heat balance equation:

$$C(i, 2) \frac{dT}{dt} = Q_{qb(i,2)} - Q_{b(i,2)} - Q_{d(i,1)} - Q_{d(i,2)} + Q_{w(i,2)} + Q_{cchill(i,2)} \quad (2)$$

Fat layer heat balance equation:

$$C(i, 3) \frac{dT}{dt} = Q_{qb(i,3)} - Q_{b(i,3)} - Q_{d(i,2)} - Q_{d(i,3)} \quad (3)$$

Skin layer heat balance equation:

$$C(i, 4) \frac{dT}{dt} = Q_{qb(i,4)} - Q_{b(i,4)} - Q_{d(i,3)} - Q_{e(i,4)} - Q_{s(i,4)} \quad (4)$$

The heat balance equation of the central blood pool:

$$C(i, 5) \frac{dT}{dt} = \sum_{i=1}^6 \sum_{j=1}^4 Q_{b(i,j)} \quad (5)$$

where i is the segment number of the human body; j is the layer number of a particular segment; $C(i, j)$ represents the heat capacity of a node (i, j) ; T denotes the body temperature of the human node $Q_{qb(i,j)}$ represents the heat generated by basal metabolism; $Q_{b(i,j)}$ represents the blood circulation heat conduction between the body nodes; $Q_{d(i,j)}$ represents the heat conduction between adjacent layers of the same segment; $Q_{res(i,j)}$ is the respiratory heat loss; $Q_{w(i,j)}$ is the heat generated by the exercise work; $Q_{cchill(i,j)}$ is the heat generated by the muscle tremor; $Q_{e(i,j)}$ is the dry heat loss between the skin surface and the environment; and $Q_{s(i,1)}$ is the moist heat exchange on the skin surface, mainly due to evaporative heat loss [5]. In human thermal interaction, the physiological adjustment phenomena that affect the change of heat distribution mainly include vasomotor, sweat gland activity and muscle movement.

2.3.1.1 Vasomotor

The heat transfer between human tissues mainly depends on the convective heat exchange in the blood circulation process. The vasomotor directly determines the changes in blood flow in the tissues, thereby affecting the temperature distribution from the inner core of the human body to the skin.

$$\begin{cases} S_{dil} = D_{cdil}S_{err(1,1)} + D_{sdil}(S_{wrms} - S_{clds}) + D_{pdil}S_{wrms(1,1)}S_{qrms} \\ S_{con} = -D_{ccon}S_{err(1,1)} + D_{scon}(S_{clds} - S_{wrms}) + D_{pcon}S_{cld(1,1)}S_{clds} \\ V_{bf(i,j)} = \frac{V_{bf(i,j)} + W_{dil(i)}D_{dil}}{1 + W_{con(i)}D_{con}}q \\ Q_{b(i,j)} = \alpha\rho C(i,j)V_{bf(i,j)} \times (T(i,j) - T(25)) \end{cases} \quad (6)$$

where $V_{bf(i,j)}$ is the blood flow rate; $V_{bf(i,j)}$ is the introductory blood flow rate; S_{dil} is the vasodilation signal; S_{con} is the vasoconstriction signal; $S_{err(1,1)}$, $S_{wrms(1,1)}$, $S_{cld(1,1)}$, S_{wrms} , S_{clds} are the temperature error signal, warm signal, cold signal, human body comprehensive warm signal, comprehensive Cold signal; D_{cdil} , D_{sdil} , D_{pdil} are the control coefficients of vasodilation; D_{ccon} , D_{scon} , D_{pcon} are the control coefficients of vasoconstriction; $W_{dil(i)}$ and $W_{con(i)}$ are the weight coefficients of vasodilation and contraction of each segment; q is the local influence factor; α is the reverse heat exchange ratio, here being 1; and ρ is the body node density.

2.3.1.2 Sweat gland activity

During exercise, the human sweat glands secrete a large amount of sweat. The evaporation of this sweat will take away the excess heat in the body, accelerate the body's heat dissipation to the external environment and maintain the body's thermal balance.

$$\begin{cases} S_{swe} = D_{cswe}S_{err(1,1)} + D_{sswe}(S_{wrms} - S_{clds}) + D_{pswe}S_{wrms(1,1)}S_{wrms} \\ V_{rsw(i)} = \frac{S_{swe}W_{swe(i)}}{W_{fg}}q \\ d = \int_0^t \sum_{i=1}^6 (V_{rsw(i)}A(i))dt \\ R_{dap} = \frac{d}{m} \times 100\% \end{cases} \quad (7)$$

where S_{swe} is the sweat control signal; $V_{rsw(i)}$ is the sweat rate of segment i ; D_{cswe} , D_{sswe} , D_{pswe} are the sweat control coefficients; $W_{swe(i)}$ is the sweat weight coefficient of each component; h_{fg} is the sweat vaporisation heat; $A(i)$ is the node i is the body surface area; d is the amount of human sweat (approximately equal to the amount of dehydration); m is the bodyweight; and R_{dap} is the dehydration ratio.

2.3.1.3 Muscle movement

Muscle movement refers to the phenomenon of the human body trembling; that is, when the body temperature of the human body is lower than a particular critical value, a heat generation phenomenon is formed by the voluntary contraction of skeletal muscles, which is used to regulate the thermal state of the human body.

$$\begin{cases} S_{chi} = -D_{cchi}S_{err(1,1)} + D_{schil}(S_{clds} - S_{wrms}) + D_{pchil}S_{cld(1,1)}S_{clds} \\ Q_{chil(i,2)} = W_{chil(i)}S_{chi} \end{cases} \quad (8)$$

where S_{chil} is the tremor control signal; D_{cchil} , D_{schil} , D_{pchil} is the tremor control coefficient; and $W_{chil(i)}$ is the tremor weight coefficient of each segment.

2.3.2 Modelling of heart rate regulation mechanism

With the changes in the body's metabolic level and the body's thermal environment, the body's cardiovascular activities will make adaptive adjustments. The cardiac output and the blood flow of various tissues and organs can meet the current metabolic needs and maintain arterial pressure's relative stability. One of the most significant adaptive changes is exercise heart rate regulation. Studies have shown that when the human body completes a minor intensity exercise, the heart rate will rise rapidly in the early stages of training and maintain a stable range for a more extended period after reaching a certain level. The internal system functions are also in a relatively stable state [6]. As the exercise continues, the balance of system functions is disrupted, and the heart rate will rise again until the maximum heart rate is reached. When the human body completes more extraordinary intensity exercise, due to the high metabolic level, the function of each system cannot be maintained in a relatively stable state, and so the heart rate will continue to increase until the maximum heart rate.

In heart rate regulation, neuroregulation and body temperature regulation are two essential mechanisms that affect heart rate changes. Among them, the neuroregulation mechanism is responsible for controlling the sudden rise and fall of the heart rate; the body temperature regulation mechanism is responsible for maintaining the stability of the heart rate in a short period [7]. Based on this principle, this section models and analyses the heart rate adjustment mechanism. The non-linear adjustment equation of the human body exercise heart rate is:

$$V_{hr} = N(M) + B(T) + g \quad (9)$$

where V_{hr} is the heart rate; $N(M)$ is the neuromodulation function; $B(T)$ is the kernel temperature regulation function; and g is the noise.

Neuromodulation function:

$$N(M) = \begin{cases} (kM + b) \left(1 - \frac{1}{\exp cMt}\right), & 0 \leq t \leq t_0 \\ (kM + b) \frac{1}{\exp \frac{d(t-t_0)}{M}}, & t > t_0 \end{cases} \quad (10)$$

Core temperature adjustment function:

$$B(T) = p_2 T^2 + p_1 T + p_0 \quad (11)$$

where M represents the current exercise metabolism; and T denotes the core temperature. Since the core temperature of the human chest is most related to the heart rate, we choose the chest core temperature as a variable and use a quadratic function to represent the difference between the core temperature and the heartrate-dependent equation. A model parameter $g, b, c, d, k, p_2, p_1, p_0$ can be estimated based on a large amount of experimental data.

Heart rate changes are related to human exercise health. Too high or too low a heart rate will increase the burden on the heart, causing symptoms such as nausea, dizziness, chest tightness etc. Maintaining a reasonable heart rate range is necessary to ensure exercise effects and exercise safety [8]. The target heart rate and the maximum heart rate are two standard heart rate health judgement thresholds. Target heart rate (V_{thr}) refers to the ideal heart rate during exercise, and exercise within the target heart rate range is generally healthy and reasonable. Maximum heart rate (V_{mhr}) refers to the maximum tolerable heart rate during training, which exceeds the maximum heart rate value; and in case of there being any such excess, there will be resultant health risks, and you should slow down or stop exercising at this time. The calculation formulas for maximum heart rate and target heart rate are:

$$\begin{cases} V_{mhr} = -0.018a^2 + 1.16a + 163 \\ V_{thr} = (V_{mhr} - V_{thr})e + V_{rhr} \end{cases} \quad (12)$$

where a is age; e is exercise intensity; and V_{rhr} is human resting heart rate.

2.4 Data processing

The experimental data is represented by the mean and standard deviation ($X \pm SD$). We use the SPSS11.5 statistical software to use repeated measures one-way analysis of variance (ANOVA) to process the data statistically. The Pearson correlation coefficient represents the correlation between HR and RPE. The level of academic significance difference was set to 0.05.

3 Results

3.1 The impact of exercise on HR and RPE in a thermal environment

The heart rates of the two groups of subjects before exercise were 73.6 ± 5.6 times and 75.1 ± 5.7 times, respectively ($P > 0.05$). They exercised in room temperature and thermal environment and showed a gradually increasing trend every 15 min. The heart rate rose fastest at 15 min before exercise, the heart rate at the end of 15 min in the NE group was 110.7 ± 8.5 , the HE group was 113.3 ± 7.8 , and the HE group was slightly higher, but there was no significant difference ($P > 0.05$). At 30 min, 45 min and 60 min of exercise, the heart rate of the HE group was significantly higher than that of the NE group ($P < 0.01$). Immediately after training, the heart rates of the two groups were 143.8 ± 8.8 and 155.9 ± 9.1 , reaching their respective highest heart rates during exercise.

Fig. 1 The effect of exercise on HR and RPE in a thermal environment. HE, high fever group; RPE, physical performance rating.

Fig. 2 Scatter plot of HR and RPE in a thermal environment. RPE, physical performance rating.

The RPE levels of the two groups of subjects before exercise were very relaxed, and the RPE values were 8.1 ± 0.2 and 8.0 ± 0.2 , respectively ($P > 0.05$). With the prolongation of exercise time, the HR and RPE values showed an increasing trend. At the end of the exercise for 15 min, the RPE of the NE group and HE group was significantly higher than before training ($P < 0.05$). NE group felt more relaxed than the HE group immediately after exercise (RPE were 15.2 ± 0.4 , 16.1 ± 0.5 , $P < 0.01$). The RPE of the NE group was significantly lower than that of the HE group at the three-time points of 30 min, 45 min and 60 min ($P < 0.01$). Rehydration was performed at the end of the exercise. After 2 h of rest, the RPE of NE and HE groups were 8.4 ± 0.4 and 8.9 ± 0.4 , respectively. See Figure 1 (1A represents the correlation between the HR of the two groups and exercise time, and 1B illustrates the correlation between the RPE of the two groups and exercise time). From 15 min of movement to the end of training in the HE group, the correlation coefficient between HR and RPE was 0.839 ($P < 0.05$), as shown in Figure 2.

3.2 The effect of exercise on Tre in a hot environment

Comparison between groups: There was no significant difference in the Tre of the two groups before exercise ($P = 0.12$). After 15 min of training, the Tre of the NE group and the HE group were $36.97 \pm 0.09^\circ\text{C}$ and $36.91 \pm 0.06^\circ\text{C}$, respectively ($P = 0.069$); after 30 min of exercise, they were, respectively, $37.46 \pm 0.07^\circ\text{C}$ and $37.71 \pm 0.05^\circ\text{C}$ ($P < 0.01$). Intra-group comparison: At the end of training for 15 min, 30 min, 45 min and 60 min, the Tre of the NE group and the HE group were significantly higher every 15 min than the previous 15 min, but the increase in the two groups was different: the rise in Tre slowed down in the NE group after 30 min of exercise; however, in the HE group, it continued to increase. In general, with the extension of exercise time, the Tre of the two groups improved significantly, but the difference between the groups is indeed more and more significant. See Figure 3.

Fig. 3 Changes in the Tre of the subjects under exercise in the two environments. HE, high fever group; NE, control group; Tre, rectal temperature.

3.3 The effect of exercise on body weight, sweating rate, and sweating volume in a hot environment

After 60 min of exercise, the NE group and the HE group lost 0.72 ± 0.07 kg and 0.93 ± 0.07 kg. There was a significant difference between the two groups ($P < 0.01$). The total sweat volume of the NE group and the HE group were 0.864 ± 0.081 L and 1.059 ± 0.083 L, respectively. The total sweat rate of the NE group and the HE group were $56.1\% \pm 3.1\%$ and $65.7\% \pm 2.8\%$, respectively. The total sweat volume of the NE group The real sweating rate was significantly lower than that of the HE group ($P < 0.01$).

3.4 The effect of exercise on BUN and FI in a hot environment

There was no significant difference in BUN between the two groups before exercise ($P = 0.357$). The BUN of the NE group was significantly lower than that of the HE group immediately after exercise (3.63 ± 0.11 mmol/L

and 4.63 ± 0.32 mmol/L, $P < 0.01$). The two groups' FI was $78.6\% \pm 8\%$ and $86.4\% \pm 7\%$, which were also significantly different ($P < 0.01$).

4 Analysis and discussion

4.1 The impact of exercise on HR and RPE in a thermal environment

Participants at room temperature and thermal environment at 55% VO_2max exercise, HR and RPE all gradually increased with the extension of exercise time, but the changes in each period were different [9]. Although the increase in the first 15 min was the largest, there was no significant difference in HR at the end of 15 min between the NE group and the HE group ($P = 0.138$). It increased significantly after 30 min of exercise. Controlling the exercise time within 30 min can more effectively avoid adverse effects; if it is to adapt to the training and competition in the thermal environment, the single exercise time is better than 30 min, so the stimulation caused by this is more profound, and the heat is easier to form.

However, the specific exercise intensity and time of thermal acclimatisation are still controversial. Some scholars believe that increasing VO_2max by about 15% is the standard for thermal acclimatisation. Some scholars have proposed that intermittent or continuous training with an intensity of 50% VO_2max can improve the body's heat resistance. Some scholars have found that training with 59% VO_2max submaximal intensity for 10–12 days can make the body adapt to the thermal environment.

The RPE indicator is a quantitative indicator of the stimulation of muscles, respiration, cardiovascular etc. that are transmitted to the brain during exercise. The brain responds to its working ability. Physiologists generally believe that the RPE index can reflect the body's functional state to a certain extent. When the RPE value (level) increases significantly, it indicates a decline in the body's function. The results of this experiment showed that at the end of 15 min, the RPE value of the HE group was significantly higher than that of the NE group ($P < 0.05$), but the corresponding HR during the same period did not change significantly ($P > 0.05$). RPE in the NE group continued to increase during 15–30 min of exercise, but the increase was slow. The RPE value of the HE group increased significantly during the same period, and the difference between the groups was very significant ($P < 0.01$), but the corresponding HR during the same period was not significantly different. The increase in value may be related to the psychological impact of the thermal environment [10]. The RPE value of exercisers in the thermal environment (40°C) is significantly higher than that of exercisers at room temperature (23°C). It is believed that exercise in a thermal environment significantly increases psychological stress. The study results suggest that for a short period of moderate-intensity movement in a high-heat environment, the influence of temperature may play a significant role.

When the Swedish physiologist Borg developed the RPE scale, he did not count the correlation between RPE and HR in a thermal environment. From the results of this experiment, we observe that the correlation coefficients of RPE and HR are highly correlated ($r = 0.839$, $P < 0.05$) when exercising in a thermal environment. It should be noted that the subjects in this experiment are college students with no training experience, and their adaptability to multiple thermophysiological simulations is not as good as that of professional athletes, so that the results may reflect the correlation between RPE and HR in a high-heat environment more objectively.

4.2 The effect of exercise on the deep temperature in a thermal environment

The energy consumption of exercise in a hot environment is about 20 times higher than that in a calm state, of which no more than 25% is used for muscle work, and the excess heat energy must be discharged. Heat energy is transferred from the muscles to the blood and gradually reaches the deep part of the body. The temperature of the deep part is not easily changed, so it can better reflect the degree of heat accumulation in the body. It can be seen from the experimental results that in the early stage of the exercise, exercise causes changes in the perception of the hypothalamic thermal regulation centre, triggers blood circulation regulation and blood redistribution between internal organs and muscles, and causes the deep temperature to rise moderately. At this

time, the environmental temperature has an impact on the deep climate, although this is not big. After 30 min of continuous exercise, T_{re} increased sharply in the HE group ($P < 0.01$). After 45 min of training, the increase of T_{re} in the NE group slowed down. Ordinary people exercise for 60 min at a sub-maximal intensity under average humidity and temperature environment. After 35 min or 45 min of exercise, the deep temperature has a plateau, and the deep temperature shows a steady state. This reflects the human body's good adjustment ability when exercising in a typical environment; the continuous increase in T_{re} in the HE group is consistent with the results of Marino et al. The analysis is mainly due to excessive heat accumulation in the body due to exercise in a thermal environment, and delayed heat dissipation. The ability of autonomous body temperature regulation is unbalanced [11]. At this time, the body temperature exceeds the average temperature of the cells, and if the time is too long, the cells will be damaged. If the body temperature is $>42^{\circ}\text{C}$, it will cause substantial damage to the cells. Athletes can bear the temperature of $39\text{--}41^{\circ}\text{C}$ in the deep part for a long time. Still, the safety range of their body temperature that can be adjusted in strenuous exercise is limited, and the thermal limit is 42°C . When T_{re} reaches $40\text{--}41^{\circ}\text{C}$, central nervous system dysfunction will occur, accompanied by symptoms such as nausea, dizziness, reduced sweating rate and confusion; if T_{re} reaches $43\text{--}44^{\circ}\text{C}$, it is easily capable of causing cell damage, brain damage and even death. Therefore, it is imperative to control and maintain the deep temperature within a safe range when exercising in a hot environment.

4.3 The effect of exercise on body weight, total sweating volume, and total sweating rate in a hot environment

As a result of exercise in a hot environment, the loss of K^{+} , Na^{+} and Mg^{+} is considerable, and the body sweats perceptibly. It is prone to dehydration. The body temperature increases significantly; muscle cramps, heat exhaustion and other symptoms can also be observed. In this experiment, the weight of the HE group decreased significantly after exercise, and the total sweating volume and total sweating rate of the HE group were also significantly higher than those of the NE group ($P < 0.01$). After exercise, four subjects in the HE group had small calf gastrocnemius muscles. Comprehensive analysis believes that dehydration and electrolyte loss are the main threats when exercising for a long time in a hot environment. Dehydration causes a decrease in plasma volume and a decrease in circulating blood volume, resulting in decreased return blood volume and reduced stroke output [12]. At this time, it can only rely on increasing the heart rate to compensate for the insufficient circulating blood volume, which increases the burden on the heart and reduces work efficiency. Excessive sweating (dehydration) of the body is one reason for the increase in HR and T_{re} . The experimental results also confirmed that weight loss, excessive sweating and increased sweating rate are related. This situation also reflects the compensatory effect of the increased heart rate in the HE group and the adverse effect of the continuous increase in T_{re} . Therefore, it is imperative to avoid dehydration and reduce the loss of electrolytes in the body when exercising in a hot environment.

4.4 The effect of exercise on BUN and FI in a hot environment

After exercise, the BUN and FI values of the HE group were significantly higher than those of the NE group ($P < 0.01$), reflecting a greater degree of HE fatigue. Our analysis is an exercise in a thermal environment. The heat inside the body is mainly moved to the skin through blood circulation. A large amount of blood supply in the body maintains heat dissipation. Excessive sweating increases the burden on the heart and reduces the output power. Also, the influence of the thermal environment on the psychological aspect cannot be ignored. The combined effect of physiological and psychological factors leads to the increase of FI in the HE group. The subjects still need to complete a fixed-intensity exercise when the heart output rate is reduced and only increases the muscle output power. Still, the plasma volume caused by dehydration is reduced, the blood is thick and the circulating blood volume is reduced [13]. A series of changes takes place, so that the elimination of ammonia, the blood supply of tissues and organs (mainly the liver) etc. are affected, and this may cause a significant increase in BUN. Besides, the exercise time is longer, and amino acids and branched-chain amino acids participate in the energy supply. Since more ammonia enters the blood, the accumulation of plasma NH_4^{+} may also increase the

BUN level [14]. Still, the contribution of this pathway to BUN is not the main one – because, during exercise, branched-chain amino acids account for only a tiny part of the energy supply [15].

5 Conclusions

1. For a moderate-intensity exercise in a hot environment, from a fitness point of view, the exercise time should be <30 min; if you want to form thermal acclimatisation, the single exercise time is better than 30 min. In sports practice and temperature conditions, the relative humidity of the sports environment should also be considered.
2. Borg's RPE scale reflects the excellent correlation between HR and RPE, which is also applicable in thermal environments.
3. Exercise in a hot environment can quickly accumulate heat in the body, leading to an increase in deep temperature, which is hugely detrimental to health. And exercise in a hot environment makes the body's BUN and FI higher, and this is more likely to cause body fatigue.

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