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Effects of hot and humid environments on thermoregulation and aerobic endurance capacity of Laser sailors

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ABSTRACT

Objectives: The purpose was to investigate the effects of hot and humid environments on thermoregulation and aerobic endurance capacity and whether high skin temperature serves as a more important thermoregulatory factor affecting aerobic exercise capacity.

Methods: A randomized cross-over design was applied to this study, in which nine Laser sailors performed the 6 km rowing test (6 km test) in both a warm (ambient temperature: 23 ± 1.4 °C; relative humidity: 60.5 ± 0.7%; wind speed: 0 km/h; WARM) and hot environment (ambient temperature: 31.8 ± 1.1 °C; relative humidity: 63.5 ± 4.9%; wind speed: 3.5 ± 0.7 km/h; HOT).

Results: The time for completing 6 km test of HOT group was significantly longer than that of WARM group ($P = 0.0014$). Mean power of 3–4 km, 4–5 km and 5–6 km were significant lower in HOT group ($P = 0.014$, $P = 0.02$, $P = 0.003$). Gastrointestinal temperature and skin temperature were significantly higher in HOT group during the 6 km test ($P = 0.016$, $P = 0.04$). Heat storage at 5 min and 15 min of HOT group were significantly higher than that of WARM group ($P = 0.0036$; $P = 0.0018$). Heart rate and physiological strain index of HOT group were significantly higher than that of WARM group during the 6 km test ($P = 0.01$, $P < 0.01$).

Conclusion: When skin temperature and core temperature both increased, high skin temperature may be the more important thermoregulatory factor that affected the aerobic endurance performance in hot and humid environments. The high skin temperature narrowed the core to skin temperature gradient and skin to ambient temperature gradient, which may result in greater accumulation of heat storage. The greater heat storage led to the lower muscle power output, which contributed to the reduction of the heat production.

1. Introduction

Olympic class sailing is a competitive and complex sport, which requires sailing athletes to possess good muscular strength, aerobic capacity and anaerobic capacity.[1] Olympic sailing is usually held in the summer at sea and sailors face the challenge of hot temperatures and high humidity conditions. The hot ambient temperature is defined as ≥30 °C and the high relative humidity is defined as ≥60%.[2] Laser sailors wear wetsuits and/or lycra shirts to protect themselves from cold exposure. However, the garments are not conducive to the sweat evaporation, which may limit heat dissipation as well as aerobic endurance capacity.[3] Thus, measures to facilitate heat dissipation are required to maintain the aerobic endurance capacity for sailing athletes.

Hadad et al.[4] found that aerobic endurance performance in the heat is mainly determined by the critical core temperature (>40 °C). However, the core temperature usually exceeds 40 °C in marathon runners during competitions held in hot environments, whereas a degradation of aerobic endurance performance was not observed among these marathon runners. Thus, the critical core temperature was not necessarily the main factor that affected aerobic endurance performance.[5] Cuddy and colleagues suggested that heat gradient is the main factor affecting aerobic endurance performance in hot environments.[6] Heat gradient refers to the

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Abbreviations

ATP	Adenosine triphosphate
BM	Body mass
HR	Heart rate
HS	Heat storage
PSI	The physiological strain index
RPE	Rating of perceived exertion
RH	Relative humidity
TS	Thermal sensation
TC	Thermal comfort
T_a	Ambient temperature
T_{gi}	Gastrointestinal temperature
T_{sk}	Mean skin temperatures
T_b	Mean body temperature
T_{core}	Core temperature
USG:	Urine specific gravity
VO_2	Oxygen uptake

thermal gradient between skin and core temperature.[7] If the skin temperature is higher than the core temperature, the body gains heat; otherwise, the body dissipates heat.[8] Therefore, the greater core to skin temperature gradient, the greater the heat loss. Skin temperature may also play an important role in mediating aerobic endurance performance. High skin temperature refers to a skin temperature that is above 35 °C; warm skin temperature ranges from 30 °C to 34.9 °C; and cool/cold skin temperature is below 30 °C.[9] Cold skin temperature may lead to a decrease in muscle temperature and consequently reducing strength and muscle endurance.[9] The metabolic energy is converted into thermal energy that needs to be dissipated during exercise.[10] Evaporation is the main means for heat dissipation in hot and humid environments during aerobic endurance exercise.[11] Exceeding the 61% relative humidity threshold has the adverse effects on aerobic exercise capacity.[12] Interestingly, recent research reported that an increase in ambient or black globe temperature, but not RH, increased the risk of a heat-related medical event.[13] Skin temperature is more important in hot and humid environments.[14] High skin temperature could increase the burden of evaporation and affect the efficiency of evaporative heat dissipation.[3] Thus, skin temperature may play an important role in affecting aerobic endurance performance in hot and humid environment.

Subjective thermal strain and perception of effort play modulating roles in aerobic endurance performance. Thermal sensation (TS) identifies the relative intensity of the temperature being sensed while thermal comfort (TC) is subjective indifference with the thermal environment.[15] Thermal comfort is intimately driven by core temperatures and thermal sensation is largely determined by skin temperature during exercise.[16] Rating of perceived exertion (RPE) integrates signals from both central nervous system and peripheral nervous system in origin.[17] RPE is a reliable tool for accessing exercise intensity.[18] It is dictated by the thermoregulatory and cardiovascular responses during exercise.[19] However, thermal comfort and perceived exertion can independently affect the aerobic endurance performance.[19] The nature of subjective thermal strain and perceived exertion in modulating aerobic endurance performance in hot environments remains unclear.

The aim of study was to investigate the effects of hot and humid environments on thermoregulation and aerobic endurance capacity and whether high skin temperature serves as a more important thermoregulatory factor affecting aerobic exercise capacity. We hypothesized that hot and humid environments increased thermoregulatory burden and decreased the aerobic endurance capacity. High skin temperature may play a greater role in heat loss to affect the aerobic endurance capacity.

2. Methods

2.1. Participants

Nine well-trained male Laser sailors from the Shanghai sailing team (Shanghai, China) who did not have intestinal disease participated in this study (age: 20.8 ± 2.2 years; height: 179.7 ± 5.1 cm; body mass: 73.4 ± 2.4 kg; body mass index: 22.8 ± 1.3; HR_{max}: 199.2 ± 2.2 bpm; body surface area: 1.9 ± 0.1 m^2; training years: 5.2 ± 2.3 years). Methods and procedures were approved by the Ethics in Human Research Committee of Shanghai University of Sport (102772020RT082) and all the athletes signed an informed consent form before the study.

2.2. Research design

A randomized cross-over design was applied to this study, in which each athlete exercised in both a warm and hot environment. The warm environment referred to an ambient temperature (Ta) of 23 ± 1.4 °C and a relative humidity (RH) of 60.5 ± 0.7% (WARM). The WARM group performed the indoor 6 km test with a wind speed of 0 km/h. The hot environment was similar to the conditions of Tokyo during the Olympic Games (Ta = 31.8 ± 1.1 °C, RH = 63.5 ± 4.9%; HOT). The HOT group performed the outdoor 6 km test with a wind speed of 3.5 ± 0.7 km/h. To avoid interaction with the circadian rhythm, two exercise tests were separated by 7–14 days and were scheduled at the same time of the day.[20,21] The Laser sailors replicated food and fluid intake, refrained from alcohol, vigorous activity, coffee and tea for 24 h prior to each 6 km test. The athletes drank 500–600 ml of water 2–3 h prior to the 6 km test to ensure proper hydration. Fluid and food were not allowed from 1 h prior to the 6 km test until the end of the protocol.

2.3. Experimental protocol

Each athlete ingested a gastrointestinal temperature capsule 3 h prior to the test. HR sensors were attached to the chest of athletes. iButtons were attached to the chest, arm, thigh and calf of athletes for the measurement of skin temperature. Urine samples and body mass were collected before and after the 6 km test. The sailors performed a standardized 10 min warm-up (4 min jog, 1 min walk, 4 min run, 1 min walk) followed by 5 min of rest.[22] Then, the sailors performed the 6 km test (Model D, Concept 2, Morrisville, Vermont, USA). The drag factor on the rowing machine was standardized as “4”. Athletes were required to do their best to finish the 6 km test. The time for completing the 6 km test and mean power output per 1 km were recorded. Physiological samples were collected within 30 min after 6 km test. (Fig. 1).

2.4. Measurements

2.4.1. 6 km test performance

The 6 km test was conducted on a Concept 2 rowing ergometer. The rowing ergometer was used for the daily aerobic training for the Laser sailors. The total time for completing the 6 km and split power (W) per 1 km was recorded and considered for further calculations. The criteria for the termination of ergometric testing were based on these symptoms, such as dizziness, incoordination, progressive chest pain or shortness of breath.[23]

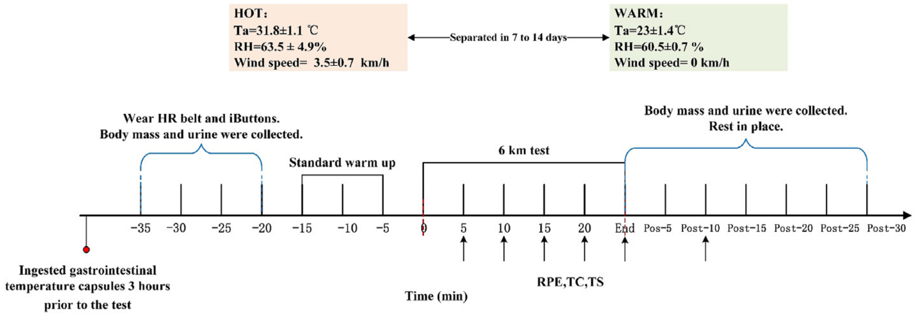

Fig. 1. Overview of the experimental protocol. “0 min” represented start of 6 km test, “End” represented the end of 6 km test, “Post-5,10,15.,.min” represented the 5, 10,15 min after 6 km test.

2.4.2. Thermoregulatory responses

The sailor's Gastrointestinal temperature (T_{gi}) was measured via an ingestible telemetric pill (e-Celsius® Performance capsule, BodyCAP, France) that transmits temperature data every 30 s in the form of continuous low-frequency radio waves to an external logger (e-Viewer® Performance monitor, BodyCAP, France). The e-Celsius® Performance capsule was sensitivity to 0.2 °C with a working range of 25.0–45.0 °C. Each athlete ingested a gastrointestinal temperature capsule 3 h prior to the 6 km test and the time for ingesting the capsules was kept consistent in the 6 km tests under the two experimental conditions.

Skin temperature was measured at 30 s intervals throughout the study using iButtons (DS1922L-F5#, Maxim Integrated, San Jose, CA, USA). The iButtons were sensitivity to 0.1 °C with a working range of −45.0 to 85.0 °C. Mean skin temperatures (T_{sk}) from the four dermal patch sites was calculated using a Ramanathan formula[24]: $T_{sk} = 0.3\,(T_{chest} + T_{arm}) + 0.2(T_{thigh} + T_{calf})$.

Mean body temperature (T_b) was calculated using the formulas: (1) Colin et al.[25]: $T_b = 0.79T_{re}+0.21T_{sk}$ at rest; (2) Burton[26]: $T_b = 0.87T_{re}+0.13T_{sk}$ during exercise. T_{re} is the rectal temperature. Heat gradient was calculated by core temperature minus skin temperature in this study.

Heat storage (HS) was calculated at 5 min increments using the formula of Adams et al.[27]: $HS\ (W \cdot m^{-2}) = 0.965 \times BM \times \triangle Tb/A_D$, where 0.965 is the specific heat storage capacity of the body(-$W \cdot kg^{-1}{}^{\circ}C$), BM is body mass (kg), and A_D is body surface area (m^2): $A_D = 0.202 \times BM/kg^{0.425} \times height/m^{0.725}$.[28]

The physiological strain index (PSI) was determined based on the core temperature (T_{core}) and HR to evaluate heat stress using the following calculation[29]: $PSI = 5(T_{core1}\text{-}T_{core0}) \times (39.5\text{-}T_{core0})^{-1}+5(HR_1\text{-}HR_0) \times (180\text{-}HR_0)^{-1}$, T_{core0} and HR_0 denote baseline and T_{core1} and HR_1 denotes a measurement taken at the respective time. The baseline of T_{gi} and HR was measured at rest before the 6 km test.

2.4.3. Fluid balance

Urine specific gravity (USG) was measured using the refractometry (CLINITEK Status®, Siemens, United Kingdom). The urine sample and body mass were collected prior and post to the 6 km test. Sweat rate was estimated using the formula: sweat rate ($L \cdot h^{-1}$) = pre-BM− post-BM + fluid ingested − urine excreted.[30]

2.4.4. Subjective perception

RPE, TC and TS were collected at every 5 min during the 6 km test as well as 10 min after 6 km test. RPE was obtained using the Borg scale modified by Foster et al. ranging from 0 to 10, in which 0 indicated “rest” and 10 indicated “Just like my hardest race”,[31,32] The 4-point TC Scale (1 very uncomfortable; 4 very comfortable) indicated how comfortable the athlete felt about the temperature.[21] The 7-point TS scale for thermal sensation ranged from −3 (cold) to +3 (hot) and indicated the extent to which the athlete experienced the ambient temperature.[21,33]

2.4.5. Statistical analysis

Statistical analyses were performed using SPSS software package (Version 25.0 for Windows; SPSS Inc., Chicago, IL, USA). All the data were presented as mean ± standard deviation and assessed for normality and sphericity prior to further statistical analyses. A two-way repeated measures ANOVA was conducted to evaluate the changes in the measured variables over time; the differences were delineated using a Bonferroni adjustment. The total time for completing the 6 km test and sweat rate were determined with independent sample t-tests. Statistical significance was set at $P < 0.05$ for all the comparisons.

3. Results

3.1. Aerobic endurance performance

The time for completing 6 km test in HOT group was significantly longer than in WARM group (1447.2 ± 62.4 s vs 1385.1 ± 26 s; $P = 0.0014$). A significant HOT*Time interaction was found in mean power output per 1 km ($P = 0.03$). Mean power output of 3–4 km, 4–5 km and 5–6 km in HOT group were significantly lower than in WARM group ($P = 0.014$, $P = 0.02$, $P = 0.003$, Table 1.). The time of 3–4 km was approximately 11 min–15 min in HOT and WARM group, which implied the mean power output began to significantly drop after 11 min.

3.2. Thermoregulatory responses

T_{gi} were no significant differences in the two groups at 0 min ($P = 0.688$; Fig. 2A). The HOT group showed a significantly higher T_{gi} than WARM group during the 5 min to end of 6 km test and post-5 to post-15 min ($P = 0.016$, $P = 0.037$).

T_{sh} were no significant differences in the two groups at 0 min ($P = 0.487$; Fig. 2B). The T_{sk} of HOT group were significantly higher than that of WARM group throughout the 5 min to the end of 6 km test ($P = 0.04$). Notably, T_{sk} was ≥35 °C after 15 min in HOT group while $T_{sk} \geq 35$ °C after 20 min in WARM group, the high T_{sk} of HOT group appeared 5 min earlier than that of WARM group. T_{sk} were no significant differences in the two groups from post-5 to post-15 min ($P = 0.061$).

There was no significant difference at the beginning of the 6 km test for T_b ($P = 0.688$; Fig. 2C). The T_b of HOT group were significantly higher than that of WARM group throughout the 5min to the end of 6 km test and post-5 to post-15 min ($P = 0.007$, $P = 0.033$). The heat gradients were no significant differences between the two

Table 1
Mean power per 1 km during 6 km test.

Group	Mean power per 1 km (W)						Interactive P value	Main effect of HOT	Main effect of time
	0–1 km	1–2 km	2–3 km	3–4 km	4–5 km	5–6 km			
WARM	246.9 ± 17.9	224 ± 13.7	218.9 ± 13.7	217.2 ± 15.3	214.7 ± 15.6	240.6 ± 17.9	0.021*	0.01	0.001
HOT	238.4 ± 17.8	219 ± 19	211.9 ± 23.9	195.1 ± 32.5*	183 ± 43.5*	206.1 ± 32.4*			

Note: *Significant interaction effect between HOT and time ($P < 0.05$).

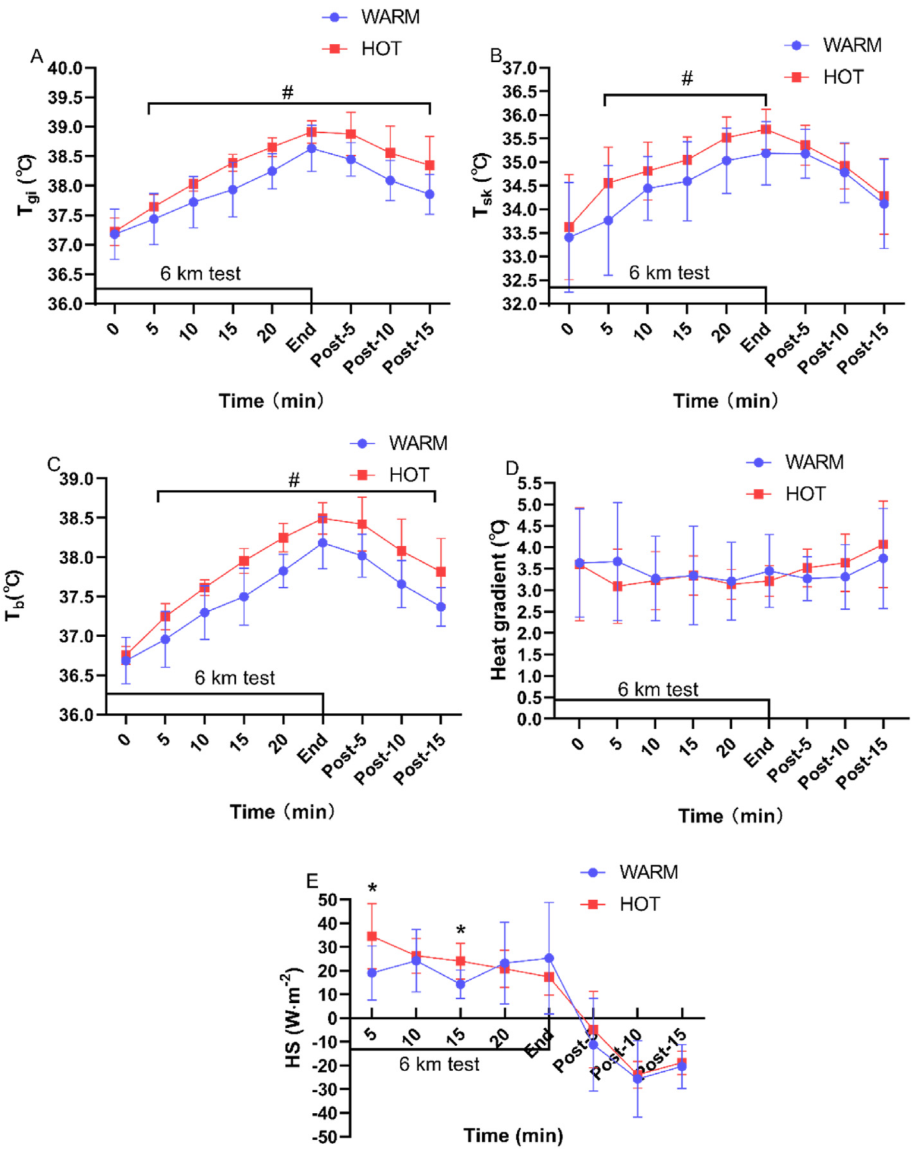

Fig. 2. The changes of T_{gi}, T_{sk}, T_b, heat gradient and HS during the trial. *Significant interaction effect between HOT and time ($P < 0.05$). # Significant main effect of HOT ($P < 0.05$).

groups throughout the 5min to the end of 6 km test and post-5 to post-15 min ($P = 0.461$; $P = 0.12$; Fig. 2D).

During the 6 km test, a significant HOT*Time interaction was found in HS ($P = 0.038$; Fig. 2E). HS of HOT group was significantly higher than that of WARM group at 5 min (34.5 ± 13.7 vs 19 ± 11.4, $P = 0.0036$) and 15 min (24.1 ± 7.5 vs 14.3 ± 6, $P = 0.0018$). HS were no significant differences between two groups from post-5 to post-15 min ($P = 0.0782$).

3.3. Cardiovascular responses

PSI in HOT group were significantly higher than in WARM group throughout the 5 min to the end of 6 km test. ($P = 0.01$; Fig. 3A). HR at rest was no significant difference between two groups ($P = 0.063$; Fig. 3B). HR were significantly higher in HOT group compared to WARM group throughout the 5min to the end of 6 km test and post-5 to post-15 min ($P < 0.01$, $P = 0.014$).

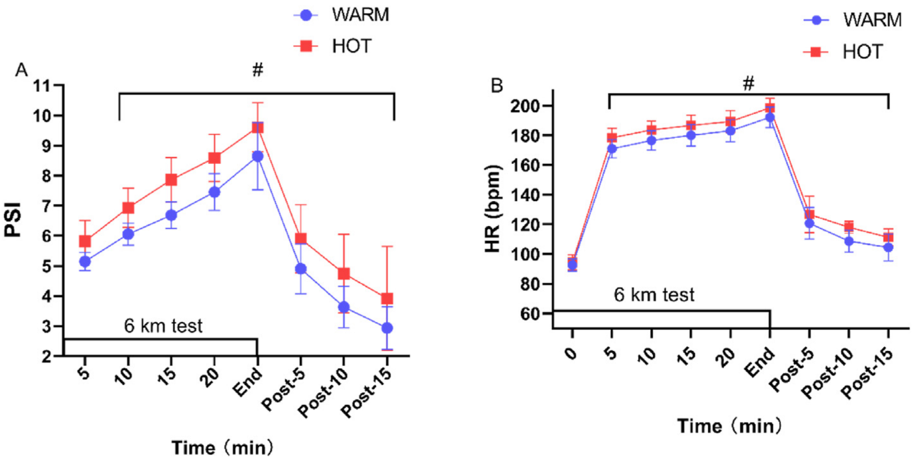

Fig. 3. Changes of PSI and HR during the trial. # Significant main effect of HOT ($P < 0.05$).

3.4. Fluid balance

No ad libitum water intake occurred during the 6 km test between trials. The USG was 1.009 ± 0.003 in HOT group and 1.011 ± 0.004 in WARM group prior to the 6 km test, indicated that laser sailors were well hydrated before 6 km test. The USG were no significant differences among the two groups in pre and post 6 km test ($P = 0.849$). Estimated sweat rate was no significant differences between HOT group and WARM group (2.0 ± 0.7 $L\ h^{-1}$ vs 1.5 ± 0.8 $L\ h^{-1}$, $P = 0.196$).

3.5. Subjective perception

RPE and TC of HOT group were significantly higher than that of WARM group throughout the 5 to the end of 6 km test ($P < 0.01$, $P = 0.031$; Fig. 4). TS of HOT group were significantly higher than that of WARM group throughout the 5–15 min ($P = 0.028$). Two groups had a score of “7” on TS at 15 min and end of 6 km test. RPE of HOT group was significantly higher than that of WARM group at post-15 min (5.6 ± 1 vs 3.9 ± 0.6, $P = 0.002$). No significant differences were found in TC and TS between the HOT and WARM groups at post-15 min ($P > 0.05$).

4. Discussion

We investigated the effects of hot and humid environments on thermoregulation and aerobic endurance capacity and whether high skin temperature serves as a more important thermoregulatory factor affecting aerobic exercise capacity. The main finding of the current study suggested that high skin temperature may be the more important thermoregulatory factor that affected the aerobic endurance performance in hot and humid when skin temperature and core temperature both increased, environments. High skin temperature narrowed the core to skin temperature gradient and skin to ambient temperature gradient, which resulted in further accumulation of heat storage. Greater heat storage led to lower muscle power output, which may contribute to the reduction of the heat production.

The hot and humid environments contributed to higher heat storage and resulted in lower muscle power output to reduce the heat production during exercise. The HS of HOT group was higher than that of WARM group at 5 min and 15 min, which indicated that the heat storage largely increased from 0 min to 15 min due to the hot and humid environments. Notably, the mean power output of HOT group significantly decreased since 3–4 km, corresponding to the 11–15th minutes of the test. The results indicated that the higher heat storage limited the muscle power output. Besides, the mean power output of HOT group was still significantly lower than that of WARM group from 4 to 5 km and 5–6 km. While the HS of HOT and WARM group was similar at 20 min and the end of 6 km test, which indicated that the higher muscle power output increased heat production, allowing the WARM group to catch up with the HOT group in HS. Similarly, research also reported that the aerobic exercise capacity in hot environments was directly related to the rate of heat storage.[34] The results showed that hot and humid environments increased the heat storage during exercise, resulting in lower muscle power output and thus a reduction of the heat production. HS is mainly calculated by $\triangle T_b$. A greater $\triangle T_b$ is associated with larger change of heat storage. In this study, T_b of HOT group was higher than that of WARM group during exercise. Body temperature increased from 0.2 °C to 0.5 °C in the hot and humid environments. The change of body temperature might be a potential physiology factor reflecting aerobic endurance performance in hot and humid environments.[35] The $\triangle T_b$ was 0.4 °C in HOT group and 0.2 °C in WARM group at 15 min, while the $\triangle T_b$ was 0.1 °C in both HOT and WARM groups after 20 min. These data indicated that large changes in T_b could reflect the change of the heat storage.

Body temperature is composed by core temperature and skin temperature.[36] In this study, the differences in T_{gi} between HOT and WARM group ranged from 0.2 to 0.5 °C during 6 km test, and the differences in T_{sk} between HOT and WARM group ranged from 0.4 to 0.8 °C during 6 km test. The change rate within physiological range between core temperature and skin temperature were approximately 1/4 normal range. Sawka et al.[9] found that high core temperature alone did not impair aerobic endurance performance in a hot environment even when core temperature reached or exceeded 40 °C. This study found that despite the T_{gi} were higher in HOT group, the highest T_{gi} in both HOT and WARM group were below 40 °C during the 6 km test. The results indicated that though the core temperature could be related to the aerobic endurance performance, it is not the main thermoregulatory factor in modulating the aerobic endurance performance in the hot and humid environments. The core temperature is mainly affected by the metabolic heat production. And the increase of skin temperature is prone to be affected by the environment conditions.[9] T_{sk} of HOT group exceeded 35 °C 5 min earlier than WARM group, corresponding to a HR over 180 bpm 5 min earlier in HOT group than in WARM group. High skin is associated with a reflex increase in skin blood flow.[7] The cardiovascular system needs to provide sufficient

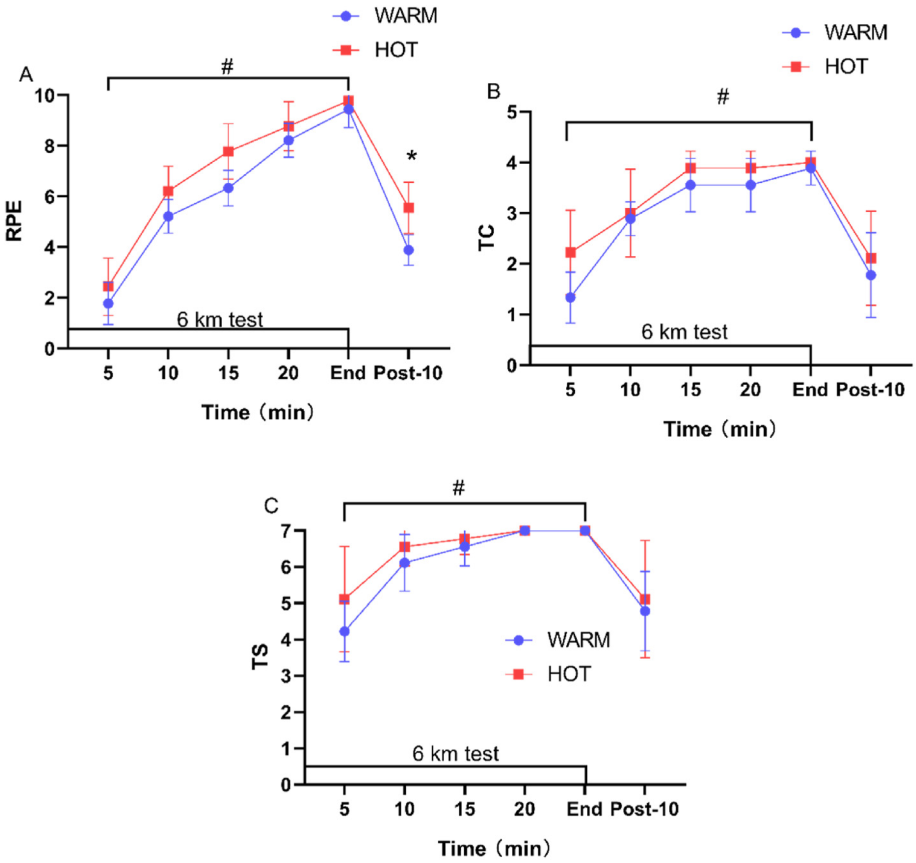

Fig. 4. Changes of RPE, TC and TS during the trial. # Significant main effect of HOT ($P < 0.05$). *Significant interaction effect between HOT and time ($P < 0.05$).

cardiac output to support skeletal muscle perfusion and skin blood flow,[37] which required an increase of HR. Chou et al.[38] investigated the role of T_{sk} in stimulating cardiovascular responses and found that high T_{sk} narrowed the core-to-skin temperature gradient progressively, which resulted in an increase in HR and a decrease in stroke volume. It is important to note that only the elevation in both T_{sk} and T_{gi} can cause the increases in HR.[37] Overall, high T_{sk} may be the more important thermoregulatory factors that affected the aerobic endurance performance when core temperature and skin temperature both increased.

It is established that skin temperature plays an important role in heat dissipation in hot and humid environments.[9] The metabolic heat production minus surface heat loss equals the heat storage.[39] The core to skin temperature gradient is the information reflecting heat dissipation capacity. In this study, the heat gradient were no significant differences between HOT and WARM group during the 6 km test, which indicated the similar heat loss between HOT and WARM group. However, Cuddy et al.[6] reported that higher ambient temperature narrowed the heat gradient. Kenefick et al.[40] found that with every 10 °C increase in ambient temperature, the heat gradient decreased by 4.5 °C. One possible explanation could be the conditions under which the tests were conducted. HOT group was tested outdoor with the wind speed of 4 km/h, while WARM group was tested indoor without the wind speed. The windless conditions of WARM group might not be conductive to the heat dissipation and could narrow the heat gradient, which resulted in the similar heat gradient in both HOT and WARM group. Notably, the temperature gradient between skin and ambient was 8–9 °C lower in HOT than WARM group, which might reduce the heat loss in the HOT group. Besides, the evaporation was the main way to heat dissipation in hot and humid environments.[39] While the sweat rate was similar between HOT and WARM groups, indicating similar heat dissipation efficiency between HOT and WARM group. Therefore, the results suggested that the hot and humid environments were the additional thermal load that increased the heat storage and affected the aerobic endurance performance. Besides, the muscle temperature might be directly affected by the hot and humid environments during exercise. The higher muscle temperature might affect the production of muscle ATP,[41] which may affect the aerobic endurance capacity. The effects of hot and humid environments on muscle temperature require further investigation.

Hot and humid environments increased thermal strain and perception of effort through high skin temperature and cardiovascular strain. TC and TS of HOT group were higher than that of WARM group during the 6 km test. Interestingly, TS were the same between the HOT and WARM group at 20 min and 25 min while the T_{sk} of HOT group was higher compared to WARM group. These findings differed from those of Flouris et al. who found that TS is largely determined by skin temperature.[17] One possible reason for the inconsistent results is that T_{sk} over 35 °C may determine the greatest thermal sensation, thereby modulating the aerobic endurance performance. While some research also reported that the thermal strain and perception could independently affect the aerobic endurance capacity.[19] Thermal strain is an important mediator of thermoregulatory behavior and the heat-induced reduction in aerobic endurance performance.[3,42] In line with previous literature, RPE of HOT group was higher during the 6 km test in the hot environment.[17] Some studies have demonstrated that the RPE is dictated by cardiovascular strain,[7,17] thereby mediating the aerobic endurance performance in the hot environment. It is likely that RPE modulates aerobic endurance performance and largely depends on the cardiovascular responses. However, Stevens et al.[43] and Mündel et al.[44] reported that the decrease in RPE independently improved aerobic endurance capacity in the hot environment. Therefore, the role of thermal strain and perception of effort in modulating aerobic performance in the hot and humid environment requires further investigation.

However, there were some limitations in this study. First, the microenvironments induced by different fabrics may have affected the results because the clothes were not standardized.[45] In addition, it would be better to use thermal environment meters for quantification of the environment conditions because it can provide more accurate information of environmental conditions such as radiation and wet bulb globe temperatures. In the future, the metabolic production (VO_2), skin blood flow and cardiac output etc. need to be measured to further discuss the heat balance.

5. Conclusions

When skin temperature and core temperature both increased, high skin temperature may be the more important thermoregulatory factor that affected the aerobic endurance performance in hot and humid environments. The high skin temperature narrowed the core to skin temperature gradient and skin to ambient temperature gradient, which may result in much more accumulation of heat storage. The greater heat storage led to the lower muscle power output, which contributed to the reduction of the heat production.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

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Consent for publication

This is not applicable as the study does not have individual person's data.

Author statement

XYX conceived, designed and wrote the manuscript. ZYC made critical suggestions and revisions on the study. GBH conceived and corresponded to the study. All authors read and approved the manuscript.

Declaration of competing interest

None of the authors have any conflicts of interest.

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