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Original article

Effects of heat and different humidity levels on aerobic and anaerobic exercise performance in athletes

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Abstract

Previous studies suggest that the maximum oxygen uptake (VO_{2max}) and the Wingate anaerobic test performances are decreased in hot environments, but it is unknown whether humidity changes in a hot environment further affect the results of the VO_{2max} and Wingate anaerobic test. Nine male athletes performed VO_{2max} and Wingate anaerobic tests under three environmental conditions: (1) 21 °C/20% relative humidity (R.H.) (control); (2) 33 °C/20% R.H. (hot–dry); and (3) 33 °C/80% R.H. (hot–wet). The participants' weight, oral temperature, and skin temperature were recorded pre-exercise and postexercise. The heart rate was monitored continuously throughout the exercise. Compared to the control condition, the hot–dry and the hot–wet conditions had lower VO_{2max} values (control at 3779.0 ± 234.3 mL/min vs. hot–dry at 3528.2 ± 467.4 mL/min and hot–wet at 3595.9 ± 274.6 mL/min; $p < 0.05$). However, there was no difference in the VO_{2max} between the hot–dry and the hot–wet conditions. A decrease in the postexercise oral-to-skin temperature gradient was strongly correlated with decreased VO_{2max} (mL kg^{-1} min^{-1}) in all conditions ($r = 0.835$, $p < 0.001$). There was no significant difference between the conditions in the peak power and anaerobic capacity during the Wingate anaerobic test. The VO_{2max} was impaired in the hot–dry and in the hot–wet conditions, compared to the control condition; however, the different humidity levels (i.e. hot–dry vs. hot–wet) had no effect on the VO_{2max}. The postexercise oral-to-skin temperature gradient was in line with the variance in VO_{2max} in all three different environmental conditions. The Wingate anaerobic test performance was not affected by the hot–dry or the hot–wet conditions, compared to the control environment. These results suggest that different relative humidity conditions do not affect the VO_{2max} or the Wingate anaerobic test performance in hot environments.

Keywords: Aerobic performance; Anaerobic performance; Oral temperature; Skin temperature

Introduction

Ambient temperature has a significant influence on human physiological responses to physical activity.[1,2] A combination of high environmental temperatures and elevated relative humidity (R.H.) create substantial stress for athletes training and competing under such conditions.[3–11] However, the effects of high environmental temperature and different relative humidity levels on aerobic and anaerobic exercise performance are an important question with no definitive answer.[2,12,13] The answer could have important implications because athletes could use this information to prepare better or to anticipate potential changes in performance at athletic events in which the environmental conditions at the competition site differ from their training location.

There is conflicting evidence on the effects of elevated environmental temperature on VO_{2max} and exercise performance. Some studies report that high environmental temperature significantly reduces VO_{2max}.[14–17] and impairs aerobic perfor-

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mance.[18–20] In one study, heat stress reduced VO_{2max} in men and in women in proportion to the increases in core temperature and skin temperature.[2] By contrast, some studies demonstrate that high environmental temperature has no effect on VO_{2max}.[21,22] However, these studies did not report core and skin temperature[21,22] or did not investigate the effects of different environments on VO_{2max}; this makes it difficult to make appropriate comparisons.[22,23] It is possible that in these studies, core temperature and/or skin temperature were not elevated high enough to decrease VO_{2max}.

There has only been one report on the effects of different humidity levels on VO_{2max}. Stensrud et al.[24] report that VO_{2max} increased significantly from 40% to 95% R.H. at thermoneutral conditions (20 °C) in subjects with exercise-induced bronchoconstriction. However, it remains unclear whether VO_{2max} is affected by elevated environmental temperatures in combination with high R.H. or with low R.H. in comparison to a thermoneutral condition in athletes. Athletes could use this information to better prepare for competitions or to anticipate possible performance changes during athletic events where the local environmental conditions differ from those conditions at their training location.

During exercise in hot conditions (and especially at a high R.H.), the core-to-skin temperature gradient is small and the necessary convective heat transfer requires a large increase in skin blood flow.[25] The increase in skin blood flow will affect cardiovascular function by decreasing the central blood volume and stroke volume and by impairing muscle blood flow.[26] Therefore, the oral-to-skin temperature gradient (as an estimate of the core-to-skin temperature gradient) could be an important factor that may influence VO_{2max}.

The temperature and humidity effects on short-term high intensity exercise have not been thoroughly studied; moreover, the reported findings are equivocal.[13,27,28] Some studies demonstrate that the Wingate anaerobic test performance was not different in the control environment (~22 °C/30–55% R.H.), the hot-wet environment (~30 °C/85% R.H.) or the hot/dry environment (~38-40 °C/25–40% R.H.).[13,27] It has been demonstrated that combined heat and dehydration could impair the mean power and peak power.[29] By contrast, other researchers have found that the Wingate anaerobic test performance improved significantly in a hot condition than in a thermoneutral environment.[28] A potential mechanism for increased anaerobic performance may be linked to the elevated muscle temperature induced by a hot and humid environment,[30] although one study reports that elevations in the muscle temperature induced by 40 °C/18% R.H. hot–dry environment could, in fact, impair the power output.[31] Thus, it is unknown whether the Wingate anaerobic test performance would improve at a high temperature and at different relative humidity levels.

The purpose of this study was to determine the effects of three different environmental conditions—21 °C/20% R.H. (control), 33 °C/20% R.H. (hot–dry), 33 °C/80% R.H. (hot–wet)—on the VO_{2max} and Wingate anaerobic test performance in Chinese athletes. Our hypotheses were that (1) VO_{2max} would be impaired in the hot–dry and hot–wet conditions in comparison to the control condition, and the hot–wet condition would be lower than hot–dry condition; and (2) the Wingate anaerobic test performance would not be affected by either the hot–dry condition or the hot–wet conditions.

Methods

Participants

Nine endurance-trained, male athletes from the Beijing Sport University were recruited to participate in this study. Their average age was 21.6 ± 1.2 years; height, 175.2 ± 4.5 cm; and weight, 69.8 ± 6.9 kg. The study was approved by the appropriate institutional review boards. The participants were track and field athletes who had been training and competing for an average of 5.6 ± 1.5 years. The study was performed in accordance with the Declaration of Helsinki and conducted during the spring season to avoid any natural heat acclimatization from the summer. Before participation, all study participants provided a written, informed consent. Participants were requested not to change their dietary habits or to perform physical activity in the 24 hours preceding the test, and to drink at least 1.5 L of noncaffeinated fluid the day of the test.

Preliminary testing and familiarization

One week of preliminary testing and familiarization preceded the experimental trials. Weight (to the nearest 0.1 kg) and height (to the nearest 0.1 cm) were measured (Model RCS-I, Beijing, China). Participants underwent a VO_{2max} and the Wingate anaerobic test for familiarization. During the familiarization week, the participants' urine specific gravity (USG) and body weight were measured every morning. On the day of testing, the participants were considered euhydrated (EU) if the USG was less than 1.02 and the nude body weight was within 1% of the 7-day average.[32]

Experimental protocol

Oral temperature was obtained from an electronic thermometer (OMRON MC-141N, Dalian, China) after a warm-up period and at the completion of each trial in an environmental chamber. To get a stable temperature reading, the subjects were instructed to close their mouths for approximately 30 seconds until a stable value was observed. Using the pulmonary artery temperature as the gold standard, several studies have supported oral thermometry as an accurate representation of a person's core temperature.[33–35] Skin temperature was measured continuously by using thermocouples (composed of copper and constantan) on the skin at selected body areas (e.g., head, chest, abdomen, upper-arm, forearm, thigh, and calf); the mean skin temperature was calculated from the equation presented by Nadel et al.[36]

The trials were performed under the following three environmental conditions: (1) 21 °C/20% R.H. (control); (2)

33 °C/20% R.H. (i.e., hot–dry); and (3) 33 °C/80% R.H. (i.e., hot–wet). The environmental chamber was made by Tianjin CNRO Science-Technology Development Co., Ltd. (Tianjin, China). Two days after the last familiarization test, a VO_{2max} test was performed in same environmental condition. It was followed by a Wingate anaerobic test on the next day. The participants completed the VO_{2max} test and Wingate anaerobic test in a counterbalanced order. A fan set at 0.5 m/sec circulated the air in the chamber. There were seven days between testing sessions.

On the morning of each experimental testing trial, a participant's nude body weight and USG were measured for comparison against the individual's seven-day average of the preceding week. The participant's dry nude body weight was measured before entering the environmental chamber and after the exercise. Before entering the environmental chamber, the participants were instrumented for measuring the heart rate (HR) (SUUNTO T6, SUUNTO Instruments, Helsinki, Finland). The skin temperature was measured continuously by using thermocouples composed of copper and constantan on the skin at selected body areas (e.g., head, chest, abdomen, upper arm, forearm, thigh, and calf); the mean skin temperature was calculated from the equation reported by Nadel and colleagues.[36]

VO_{2max} test

The VO_{2max} was measured with an automated open-circuit system (Mijnhault Oxycon Champion, Jaeger, Germany). Before initiating the VO_{2max} protocol, the participants performed a 5 minute warm-up at a self-selected comfortable speed on a motorized treadmill (model 10198; h/p/cosmos Sports & Medical Gmbh Company, Bayern, Germany). To elicit VO_{2max}, the study participants ran at 8.0 km/h with the speed of the treadmill increasing by 0.8 km/h every 1 minute until reaching 16 km/h. At this point, the speed remained constant and the grade increased by 1% every 1 minute until volitional exhaustion. The heart rate was measured continuously during the test. Ratings of perceived exertion (RPE) were recorded before exercise and then every 3 minutes during exercise. The subjects were familiarized with the RPE scale before the test. The VO_{2max} was achieved if both of the following criteria were met: (1) the respiratory exchange ratio (RER) was 1.10 or higher and (2) the maximal HR was within 10 beats of the age/gender predicted maximum HR.[37]

Wingate anaerobic test

The 30-second Wingate anaerobic test was used to evaluate anaerobic performance in this study. The participants performed a 5-minute warm-up period at 50 W on a cycle ergometer (MONARK 839E, Uppsala, Sweden). The HR was measured before exercise, and then continuously during the exercise testing period. During the last 5 seconds of each minute of the warm-up period, the participants were requested to cycle at their maximum pedaling rate to provide a specific warm-up.[28] One minute following the warm-up, the participants performed a 30-second Wingate anaerobic test. The resistance for the Wingate anaerobic test was determined according to a participant's body weight (75 g/kg body weight). The power output was calculated every 5 seconds, the peak power was the highest 5-second power output recorded, and the mean power was calculated from the average power during the 30 seconds of the test. The anaerobic capacity was the total work completed during the test duration. The fatigue index was calculated as the difference in power between the highest and lowest power and was presented as a percentage of the highest power.

Body fluid sampling

Venous blood samples (1 mL) were collected into pre-chilled EDTA-containing tubes before and after the VO_{2max} test for hemoglobin and hematocrit test by using the COULTER A^C.T diff 2 Analyzer (Beckman Coulter Inc, Miami, FL, USA). After testing, changes in the plasma volume were calculated from the hemoglobin and hematocrit values by using equations described previously.[38] Before the warm-up, and at 1 minute, 3 minutes, 5 minutes, 6 minutes, 8 minutes, and 10 minutes after the Wingate anaerobic test, 20 μL of blood were collected from a participant's fingertip for lactate measurements (Yellow Springs Instrument 1500, Yellow Springs, OH, USA).

Statistical analysis

The results were expressed as the mean ± the standard deviation (SD). A univariate, one-way analysis of variance (ANOVA) was used to test the significance of the mean differences in the VO_{2max} and the Wingate anaerobic test performances. Repeated measures ANOVA was used to test the significance of the mean differences in oral temperature and skin temperature. The nonparametric Spearman test was used to assess the relationship between the oral-to-skin temperature gradient and the VO_{2max} in the three conditions. The statistical calculations were performed by using SPSS software for windows (version 16.0; IBM Corporation, Armonk, NY, USA). A probability (p) value of less than 0.05 was statistically significant.

Results

VO_{2max} test

Table 1 shows the VO_{2max} [in mL/min and in mL/(kg·min)], exercise time, HRmax, and oral-to skin temperature gradient in the three environmental conditions. The ANOVA indicated significant differences in the VO_{2max} values and exercise time in the different conditions ($p < 0.05$). Compared to the control condition (3779.0 ± 234.3 mL min^{-1}), the hot–dry condition and the hot–wet condition had lower VO_{2max} values (3528.2 ± 467.4 mL/min and 3595.9 ± 274.6 mL/min, respectively; $p < 0.05$). However, there were no significant differences in the VO_{2max} values between the hot–dry and hot–wet conditions ($p > 0.05$). A comparison between the means indicated that the maximum RPE (RPEmax) values were

Table 1
VO_{2max} performance and oral-to-skin temperature gradient in three conditions.

	Control	Hot–dry condition	Hot–wet condition
VO_{2max} (mL min^{-1})	3779.0 ± 234.3	3528.2 ± 467.4*	3595.9 ± 274.6*
VO_{2max} (mL kg^{-1} min^{-1})	54.3 ± 5.4	50.1 ± 7.2*	50.8 ± 4.3*
Exercise time (min)	12.62 ± 1.68	11.12 ± 1.39*	10.79 ± 0.91*
HRmax (bpm)	195.7 ± 10.7	197.5 ± 6.9	200.7 ± 15.5
RPEmax	15.7 ± 2.1	16.8 ± 1.7*	17.4 ± 1.7**
Oral-to-skin temperature gradient (°C)	2.2 ± 0.5	1.8 ± 0.7*	1.6 ± 1.0*

bpm = beats per minute; HRmax = maximum heart rate; RPE = rating of perceived exertion; VO_{2max}, maximum oxygen uptake.
Values are expressed as the mean ± the standard deviation.
*Indicates a significant difference from the normal condition, $p < 0.05$.
**Indicates a significant difference from the normal condition, $p < 0.01$.

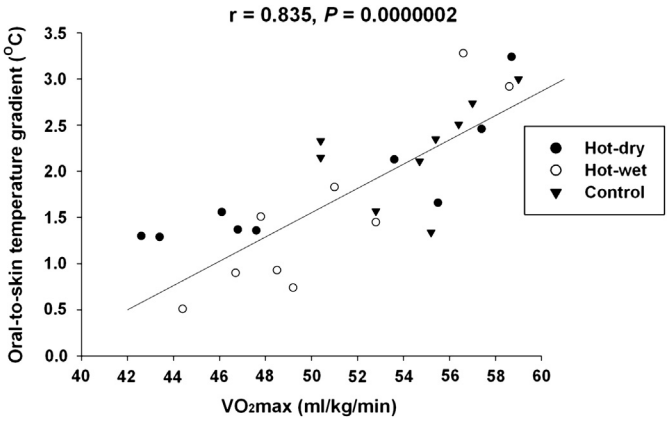

Fig. 2. The Spearman relationship between the oral-to-skin temperature gradient and VO_{2max} in the three conditions.

higher in the hot–dry and hot–wet conditions than in the control condition ($p < 0.05$). The hot–dry and hot–wet conditions had a lower oral-to-skin temperature gradient, compared to the control condition ($p < 0.05$). However, there was no significant difference between the hot–dry and the hot–wet conditions in the oral-to-skin temperature gradient ($p > 0.05$).

Fig. 1 plots the oral and skin temperatures before the VO_{2max} test and 1 minute after the VO_{2max} test in the three conditions. There were significant pre-exercise and post-exercise differences in the oral temperature in all three conditions ($p < 0.01$). In addition, the postexercise skin temperature was increased only in the control condition ($p < 0.05$). There was no significant difference between the hot–dry condition and the hot–wet condition in the pre-exercise or postexercise skin temperature ($p > 0.05$).

The postexercise oral-to-skin temperature gradient was strongly correlated with VO_{2max} [mL/(kg min)] in all three conditions ($r = 0.835$, $p < 0.001$) (Fig. 2). However, neither the pre-exercise oral-to-skin temperature gradient nor the pre-exercise and postexercise oral and skin temperatures were associated with the VO_{2max} or the Wingate Anaerobic performance ($p > 0.05$).

Table 2 shows the plasma volume and body weight changes during VO_{2max} test in the three conditions. The ANOVA indicated that the different conditions did not induce any significant differences in the loss of body weight ($p > 0.05$).

Wingate anaerobic test

Table 3 presents the Wingate anaerobic test and blood lactate results of the three conditions. The anaerobic performance was expressed by using the peak power, anaerobic capacity, and fatigue index parameters. The ANOVA indicated no significant differences between the conditions in peak power, anaerobic capacity, and blood lactate maximum parameters ($p > 0.05$). However, the hot–wet condition had a higher fatigue index, compared to the control condition ($p < 0.05$). Fig. 3 plots the oral and skin temperatures before and after the Wingate anaerobic tests in the three conditions. There were no significant differences between the pre-exercise and postexercise oral temperature or skin temperature in all three conditions ($p > 0.05$).

Discussion

There were several important findings from this study. The VO_{2max} performance was impaired in the hot–dry and the hot–wet conditions in comparison to the control, but there was

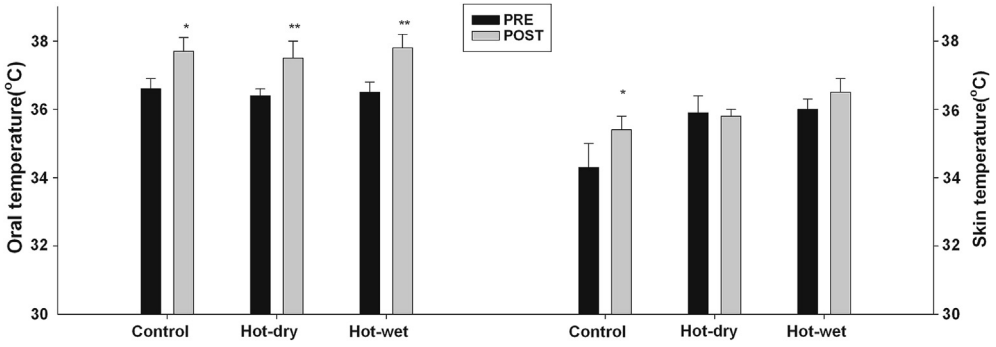

Fig. 1. Oral and skin temperature changes in the three conditions during the VO_{2max} test. *Indicates a significant difference from the pretest within the same condition, $p < 0.05$. **Indicates a significant difference from the pretest within the same condition, $p < 0.01$.

Table 2
Percent changes in plasma volume and body weight during VO_{2max} test in three conditions.

	Δ Plasma volume from rest (%)	Body weight		
		Pretest (kg)	Posttest (kg)	Δ Body weight (%)
Control condition	−1.26 ± 1.59	71.26 ± 7.16	70.40 ± 8.07	−1.21 ± 0.81
Hot–dry condition	−1.64 ± 1.40	72.01 ± 8.21	70.89 ± 8.49	−1.56 ± 1.36
Hot–wet condition	−1.84 ± 1.23	71.47 ± 7.93	70.14 ± 9.21	−1.86 ± 1.32

Values are expressed as the mean ± standard deviation.

no difference between the hot–dry condition and the hot–wet condition. Therefore, high humidity in our group of elite Chinese athletes did not seem to further augment the decrease in VO_{2max} observed in hot environments.[12,39,40] Our results agree with those of other researchers[12,39,40] in that the VO_{2max} is decreased in a hot environment. We also found that humidity changes did not further affect VO_{2max}. The VO_{2max} was also strongly correlated with the postexercise oral-to-skin temperature gradient in the three conditions ($r = 0.835$, $p < 0.001$). The anaerobic performance using the Wingate test (i.e. peak power and anaerobic capacity) was not affected by the hot–dry conditions or the hot–wet condition in comparison to thermoneutral environments. The finding of impaired aerobic performance in the heat is not a new concept. However, the current study is one of the first to systematically investigate the effects of a hot environment and different humidity levels on VO_{2max} and Wingate anaerobic test performance in the laboratory.

VO_{2max} test

The effects of a hot environment on aerobic performance have not been well documented.[41,42] In addition, there are only few studies investigating VO_{2max} at different humidity levels in a hot environment.[2,12,13] The present investigation demonstrated a significant reduction in VO_{2max} while participants exercised in a hyperthermic environment ($p < 0.05$) (Table 1). Compared to the control condition, the hot–dry and hot–wet conditions had lower maximal oxygen consumption levels ($p < 0.05$). Aerobic performance is influenced heavily by cardiovascular function. Hot environments increase skin blood flow, which alters cardiovascular function. The elevated skin blood flow reduces the central blood volume and impairs muscle blood flow.[26] Therefore, the decrease in VO_{2max} could result from the reduction in the oral-to-skin temperature gradient, which increases requirements for skin blood flow and augments cardiovascular strain.[26,43,44] Dehydration has negative effects on physiological responses and trail running speed.[45] By contrast, dehydration is an unlikely cause for the reduction in VO_{2max} since there was no difference in the USG before each test and the plasma volume changes were similar under all conditions. There are numerous publications that report larger changes in plasma volume after intense exercise.[46–48] However, the papers that have demonstrated a high plasma volume shift primarily used a longer exercise duration (i.e., time period greater than one hour)[47]; by contrast, our testing protocol was less than 15 minutes. We did not observe a decrease in the VO_{2max} in the hot–wet condition in comparison to the hot–dry condition. This unexpected finding may have been because the cardiovascular strain (reflected by the oral-to-skin temperature gradient) induced during these protocols were not different between the conditions.

The maximum heart rates were comparable under all conditions, suggesting similar maximal effort. However, the maximum RPE at hot temperatures were significantly higher in comparison to the control condition (Table 1). The skin temperature has been shown to increase almost linearly with the RPEmax.[49] We also found a moderate correlation between the skin temperature and the RPEmax ($r = 0.570$, $p = 0.002$). Therefore, it is likely that a high RPE was partly the result of a high skin temperature at the end of the VO_{2max} test. Other afferent signals that may influence the RPE are psychophysical phenomena such as pain and discomfort.[50] Increased discomfort may arise from subjective thermal comfort and exercise fatigue.

Table 3
Wingate anaerobic performance and blood lactate level in three conditions.

	Control condition	Hot–dry condition	Hot–wet condition
Peak power (W)	806.2 ± 95.7	825.8 ± 112.4	857.8 ± 164.7
Peak power (W/kg)	11.5 ± 1.2	11.6 ± 1.4	11.9 ± 2.0
Anaerobic capacity (W)	577.7 ± 49.2	562.1 ± 61.7	553.3 ± 74.7
Anaerobic capacity (W/kg)	8.3 ± 0.6	7.9 ± 0.6	7.7 ± 0.7
Fatigue index (%)	57.5 ± 6.5	61.5 ± 7.5	63.2 ± 6.5*
Blood lactate maximum (mmol/L)	13.7 ± 1.9	13.8 ± 1.8	12.3 ± 1.9

W = watts.
Values are expressed as the mean ± the standard deviation.
*Indicates a significant difference, $p < 0.05$.

Correlation between oral-to-skin temperature gradient and VO_{2max}

In our study, there was a strong correlation between the postexercise oral-to-skin temperature gradient and the VO_{2max} [mL/(kg min)] ($r = 0.835$, $p < 0.001$). Our data supports a recent study[51] that suggests that the widened core-to-skin temperature gradient would reduce the skin blood flow requirement at a given workload and potentially allow a greater percentage of any given cardiac output to be directed to active skeletal muscle and thereby increase the VO_{2max}. In the present study, the postexercise oral-to-skin temperature gradient explained nearly 70% of the variance in the VO_{2max}. However, this statistical descriptor should be taken with care since correlation does not imply causation.

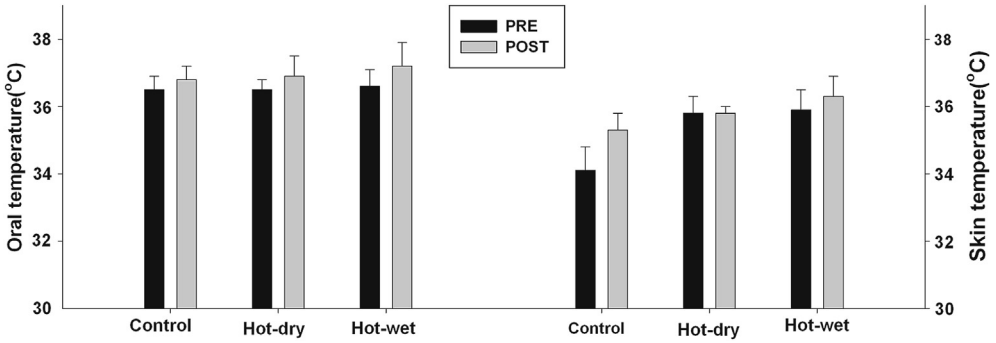

Fig. 3. Oral temperature and skin temperature changes in the three conditions during the Wingate Anaerobic test.

Wingate anaerobic test

There were no differences measured in the peak power, anaerobic capacity, or blood lactate maximum levels between the different conditions ($p > 0.05$) (Table 3). Our observations are in agreement with the findings of Backx et al.,[13] who report no effect of heat and humidity on Wingate anaerobic test performance. However, the results from the present study do not support claims that hyperthermia reduces power output during repeated sprints.[31] It seems that conflicting results in the literature may primarily stem from two sources. First, the blood lactate maximum in the 30-second Wingate anaerobic test during this study was not significantly different among the three environmental conditions. However, Drust et al.[31] report that lactate levels were increased significantly between the hot environment (40 °C and 17% R.H.) and the thermoneutral environment (20 °C, 24% R.H.). Second, hyperthermia reduced the power output during the repeated sprints, although an elevated muscle temperature should promote sprint performance.[31] In our study, participants did not show a significant difference between the different conditions in the pre-exercise oral temperature and skin temperature.

Conclusions

This study demonstrated that the VO_{2max} was impaired in the hot–dry and the hot–wet conditions, compared to the control condition, but there was no difference between the hot–dry and hot–wet conditions; therefore, different R.H. levels do not seem to further affect VO_{2max} in hot environments. The postexercise oral-to-skin temperature gradient is in line with the variance in VO_{2max} in all three environmental conditions. The Wingate anaerobic test performance was not affected by the hot–dry condition or by the hot–wet condition, compared to the control environment.

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