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To cite this article: Yoichiro Yamashita , Mitsuharu Kaya , Katsuhiro Koyama , Junzo Tsujita & Seiki Hori (2005) Decreased energy expenditure during prolonged sub-maximal exercise in a warm environment, European Journal of Sport Science, 5:4, 153-158, DOI: [10.1080/17461390500402368](https://doi.org/10.1080/17461390500402368)

To link to this article: <https://doi.org/10.1080/17461390500402368>



Published online: 19 Aug 2006.



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ORIGINAL ARTICLE

Decreased energy expenditure during prolonged sub-maximal exercise in a warm environment

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Abstract

The purpose of this study was to investigate the influence of a warm environment on thermoregulation and energy expenditure during sub-maximal prolonged exercise in humans. Six healthy male subjects cycled for 120 min at an intensity of 60% maximal oxygen uptake ($\text{Vo}_{2\text{max}}$) at three environmental temperatures (10°C, CT; 20°C, MT; and 30°C, WT). Although oxygen uptake at WT showed a significantly lower value compared to those at MT and CT, no significant differences of respiratory exchange ratio were observed among the three environmental trials. A remarkable decrease in total energy expenditure during the 120-min exercise at WT was observed in comparison with those at MT and CT ($p < 0.05$). Changes in rectal temperature, mean skin temperature, and mean body temperature at WT were significantly higher than those at both MT and CT. Although increases in mean body temperature from rest every five minutes during exercise were not different among three environmental temperatures, mean energy expenditures every five minutes at WT were lower compared with those at MT and CT ($p < 0.05$). These results suggest that the increase in energy expenditure for physical exertion is substantially reduced during prolonged sub-maximal exercise in a warm environment. This acute alteration in the energy metabolism may contribute to inhibition of excess heat production and enable prolonged exercise in a warm environment.

Keywords: *Energy expenditure, prolonged exercise, thermoregulation, warm environment*

Introduction

In humans, physiological reactions during exercise are under the influence of environmental temperature. Thermoregulation is one of the most important functions involved in maintaining homeostasis. During exercise, the increase in core temperature caused by thermogenesis results in increased skin blood flow (SkBF) and sweating (Gleeson, 1998; Kenney & Johnson, 1992; Nagashima et al., 1997). In addition, evaporation of sweat, which is required for heat dissipation during exercise, is considered to be essential for effective thermoregulation in adults (Kondo et al., 2000; Murray, 1992).

However, heat dissipation through skin is liable to decrease because prolonged exercise in a warm

environment results in excessive production of sweat on the extensive skin surface area (Gagge & Nishi, 1977). Furthermore, circulating blood volume is decreased due to dehydration, which is caused by excessive perspiration and lack of sufficient fluid intake (Cheuvront & Haymes, 2001; Morimoto & Itoh, 1998). These changes are disadvantageous to the maintenance of a low core temperature during prolonged exercise in a warm environment. Briefly, it is possible that heat dissipation through evaporation of sweat and heat transfer caused by increased blood circulation may not balance with heat production, mainly by working skeletal muscles during prolonged exercise in a warm environment. Therefore, we hypothesized that there would be a physiological system which reduces thermogenesis caused by

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exercise to a minimum in order to maintain the balance between heat dissipation and heat production, and that system would inhibit the exercise-induced increase in energy expenditure during prolonged exercise in a warm environment. Thus, the purpose of this study was to investigate the effect of a warm environment on thermoregulation and energy expenditure during prolonged sub-maximal exercise in humans.

Methods

Subjects

Six healthy non-athlete male volunteers (age: 19.2 ± 0.4 yrs, height: 171.9 ± 4.0 cm, body weight: 66.6 ± 4.8 kg, body fat: $12.9 \pm 0.6\%$; Vo_2max : 53.1 ± 3.4 ml $\text{kg}^{-1} \cdot \text{min}^{-1}$; body surface area: 1.80 ± 0.07 m²; mean $\pm$ SD) participated in the present study. The purpose, experimental procedure, and risks associated with the study were explained to the subjects, and written informed consent obtained.

Experimental Protocol

In the preliminary experiment, subjects performed a progressive cycle exercise test to determine their individual exercise intensity corresponds to 60% of their maximal oxygen uptake (Vo_2max) in a climatic chamber maintained at 20°C and 60% RH. Subjects began cycling at 60 W with resistance increased by 60 W every three minutes until exhaustion at a pedaling rate of 60 rpm.

Separated by an interval of three days, exercise experiments were randomly carried out in the chamber under the following three environmental conditions: 10°C and 60% RH (cold environmental temperature, CT), 20°C and 60% RH (median environmental temperature, MT), and 30°C and 60% RH (warm environmental temperature, WT). Each subject wore shorts and sports shoes after measurement of nude weight, and thermistors were attached for the measurement of rectal temperature (T_{re}) and mean skin temperature (T_{sk}). They then entered the chamber and rested for 30 min on a cycle ergometer before the experiment. Following this, subject underwent 120-min constant exercise on a cycle ergometer (Ergomedic 818, Monark, Sweden) at an intensity equivalent to 60% of individual Vo_2max ($55.1 \pm 0.9\%$ of maximal power output, 60 rpm) previously determined at MT. During the exercise test in all conditions, no fluid and food intakes were provided. Immediately after the 120-min experiment, nude weight was measured again for calculation of weight loss in order to predict sweat loss. The subjects took dietary food

(800 kcal) and water (500 ml) two hours before the experiment.

Analytic Techniques

Oxygen uptake (Vo_2), respiratory exchange ratio (RER), heart rate (HR), T_{re} , and skin temperature were measured at rest and during exercise. Vo_2 , RER, and HR were recorded at 5-min intervals over 120 min of exercise, using a respiromonitor and medical gas analyzer (RM-300 & MG-360, MIN-ATO Medical Science Co. Ltd., Osaka, Japan) and HR recorder (VANTAGE NV, Polar Electro, Kempele, Finland), respectively. Changes in T_{re} and skin temperature were recorded at 5-min intervals using a thermal data recorder (K710, TAKARA Thermistor Instruments Co. Ltd., Yokohama, Japan). A thermistor was inserted 12 cm beyond the anal sphincter. Skin temperatures at chest (T_{chest}), upper arm (T_{arm}), thigh (T_{thigh}), and calf (T_{leg}) were measured. Weight loss after exercise was used as an index of sweat loss. T_{sk} was calculated by the following equation (Ramanathan, 1964).

$$T_{\text{sk}} = (0.3 \times T_{\text{chest}}) + (0.3 \times T_{\text{arm}}) + (0.2 \times T_{\text{thigh}}) + (0.2 \times T_{\text{leg}}).$$

Then, mean body temperature (T_{b}), synthesized by core and surface temperature, was calculated as described previously (Burton, 1935; Gagge & Nishi, 1977; Hardy & Du Bois, 1938).

$$T_{\text{b}} \text{ at MT and WT} = (0.8 \times T_{\text{re}}) + (0.2 \times T_{\text{sk}}).$$

$$T_{\text{b}} \text{ at CT} = (0.65 \times T_{\text{re}}) + (0.35 \times T_{\text{sk}}).$$

Energy expenditure was calculated using RER and Vo_2 and expressed as kilocalories per square meter of body surface area per minute.

Statistical Analysis

To compare significant differences between the experimental conditions, a two-way (time by condition) repeated measures ANOVA was used followed by Turkey's multiple comparison. A value of $p < 0.05$ was considered significant. All values were expressed as mean $\pm$ SD.

Results

Under all three environmental conditions, nude body weights after exercise were significantly decreased compared to respective pre-exercise levels. Weight loss at WT, MT, and CT were 2.02 ± 0.9 kg, 1.18 ± 0.2 kg, and 1.05 ± 0.1 kg, respectively. Environmental temperature did not have an influence on changes in HR during exercise (data not shown). At the end of exercise, HR at WT, MT, and CT

were 160.2 ± 10.6 bpm, 161.5 ± 14.6 bpm, and 156.4 ± 13.4 bpm, respectively.

At rest, Vo_2 at WT, MT, and CT were 264.2 ± 36.6 ml min⁻¹, 314.5 ± 77.1 ml min⁻¹, and 341.3 ± 75.7 ml min⁻¹, respectively. During exercise at WT, increase in Vo_2 was significantly attenuated compared to those at MT and CT ($p < 0.05$). However, RER was not affected by environmental temperature (Figure 1).

Energy expenditure during 120 min of exercise was calculated under the three conditions (Figure 2). Energy expenditure during exercise at WT (485.7 ± 218.0 kcal m⁻²) was significantly lower than those at MT (750.1 ± 89.7 kcal m⁻², $p < 0.05$) and CT (731.4 ± 63.2 kcal m⁻², $p < 0.05$). However, no distinct difference was observed in the effects of environmental temperature on energy expenditure between MT and CT.

During exercise at WT, a significant elevation in T_{re} was observed compared to those at MT and CT. At the end of the exercise, T_{re} at WT, MT, and CT were $38.9 \pm 0.7^\circ\text{C}$, $38.3 \pm 0.3^\circ\text{C}$, and $38.1 \pm 0.4^\circ\text{C}$, respectively. Resting T_{sk} at WT ($33.8 \pm 0.4^\circ\text{C}$) was significantly higher than those at MT ($29.0 \pm 0.6^\circ\text{C}$) and CT ($28.1 \pm 0.4^\circ\text{C}$). During exercise, T_{sk} at WT was significantly higher compared to that at MT, and T_{sk} at MT was significantly higher than that at CT. At the end of the exercise, T_b at WT, MT, and CT were $37.8 \pm 0.7^\circ\text{C}$, $36.6 \pm 0.5^\circ\text{C}$, and $34.5 \pm 0.8^\circ\text{C}$, respectively. During exercise, T_b at WT was sig-

nificantly higher than those at MT and CT ($p < 0.05$, Figure 3).

The relationships between variations in T_b from rest and energy expenditure at 5-min intervals are presented in Figure 4. The mean variations in T_b from rest at WT, MT, and CT were $0.78 \pm 0.41^\circ\text{C}$, $0.94 \pm 0.44^\circ\text{C}$, and $0.39 \pm 0.20^\circ\text{C}$, respectively. There were no significant differences in the variations in T_b among the three environmental temperatures. On the contrary, mean energy expenditure at 5-min intervals at WT (20.2 ± 0.8 kcal m⁻²·5-min⁻¹) was significantly lower than those at MT (31.3 ± 1.7 kcal m⁻²·5-min⁻¹) and CT (30.5 ± 1.5 kcal m⁻²·5-min⁻¹) ($p < 0.05$, Figure 4).

Discussion

We observed that energy expenditure during prolonged sub-maximal exercise at WT was significantly smaller than those at MT and CT. In the present study, pedaling load of cycle exercise was fixed (i.e., corresponding to 60% of individual Vo_2max at MT), and substrate utilization estimated from RER was not influenced by environmental temperature. These results suggest that a warm environment has an inhibitive effect on exercise-induced increase in energy expenditure during prolonged exercise.

A number of previous studies have investigated the relationship between environmental temperature and oxygen uptake during exercise. Some reports have shown that oxygen uptake increases in a hot environment (Consolazio et al., 1963; Dolny & Lemon, 1988). Many researchers, however, have suggested that elevation of environmental temperature results

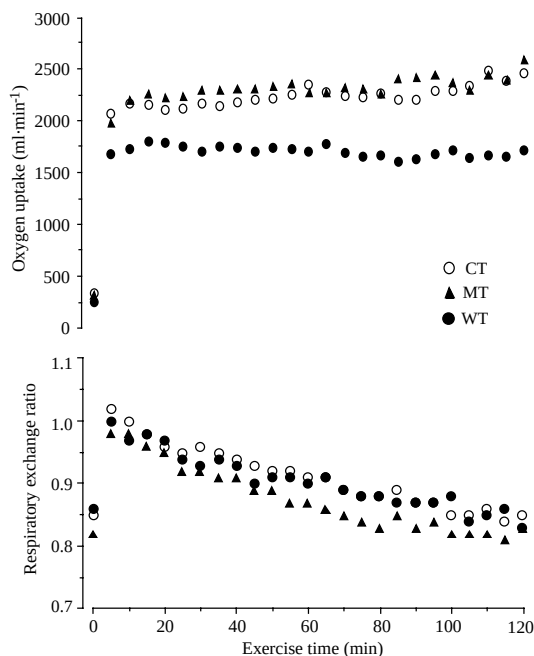


Figure 1. Oxygen uptake (Vo_2) and respiratory exchange ratio (RER) during 120 min of exercise at 60% Vo_2max in CT, MT, and WT. * indicates significant difference between CT and WT ($p < 0.05$); + indicates significant difference between MT and WT ($p < 0.05$).

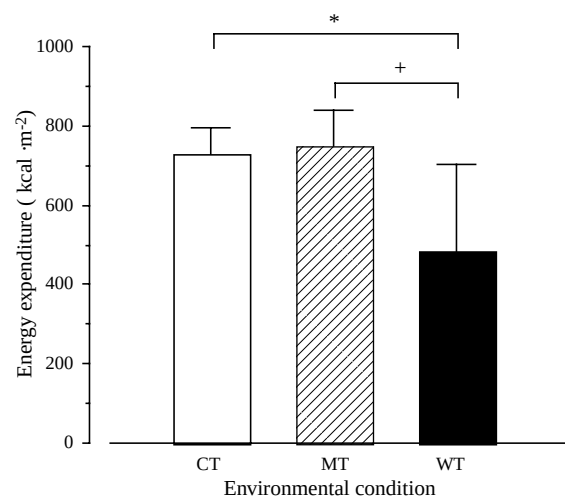


Figure 2. Total energy expenditure during 120 min of exercise estimated from Vo_2 and RER observed at 5-min intervals under the three environmental conditions. Values are expressed as mean $\pm$ SD. * indicates significant difference between CT and WT ($p < 0.05$); + indicates significant difference between MT and WT ($p < 0.05$).

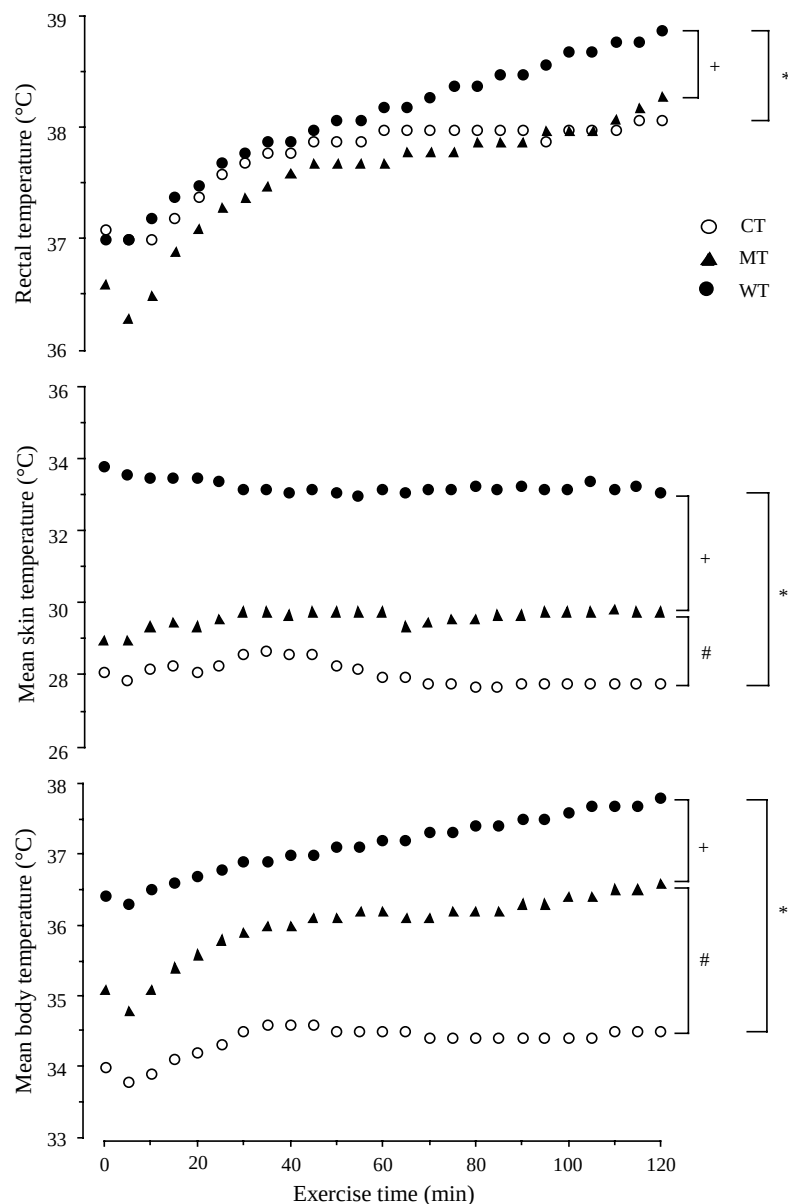


Figure 3. Rectal temperature (T_{re}), mean skin temperature (T_{sk}), and mean body temperature (T_b) during 120 min of exercise at 60% $\dot{V}O_{2max}$ under the three environmental conditions. * indicates significant difference between CT and WT ($p < 0.05$); + indicates significant difference between MT and WT ($p < 0.05$); # indicates significant difference between CT and MT ($p < 0.05$).

in a reduction in oxygen consumption during exercise (Claremont et al., 1975; Febbraio et al., 1994; Galloway & Maughan, 1997; Klausen et al., 1967; Kruk et al., 1990; Smolander et al., 1986; Suzuki et al., 1980; Timmons et al., 1985). With respect to thermoregulation, elevation in core temperature during exercise is controlled by heat dissipation from the body surface by increase in SkBF along with cutaneous vasodilation (Fritzsche & Coyle, 2000; Gleeson, 1998). Sweating is also facilitated for thermoregulation because heat dissipation is not sufficient to inhibit the elevation in core temperature during exercise (Kondo et al., 2000; Murray, 1992). Heat dissipation during exercise is considered to be directly dependent on the change in

T_{sk} , which is under the influence of changes in environmental temperature (Nadel et al., 1971; Nielsen & Nielsen, 1965; Stolwijk et al., 1968). Judging from the changes in T_{sk} in this study, enhanced SkBF might occur at WT in order to facilitate heat loss. In general, these responses tend to an upward drift in HR and a decline in stroke volume as exercise progresses because of reduced central blood volume and venous return with altering peripheral blood flow to the skin (Suzuki et al., 1980). Since environmental temperature has no significant effect on HR during exercise in our observation, cardiac output is probably decreased. There is a possibility that decreased energy demand for the cardiac muscles and decreased blood supply

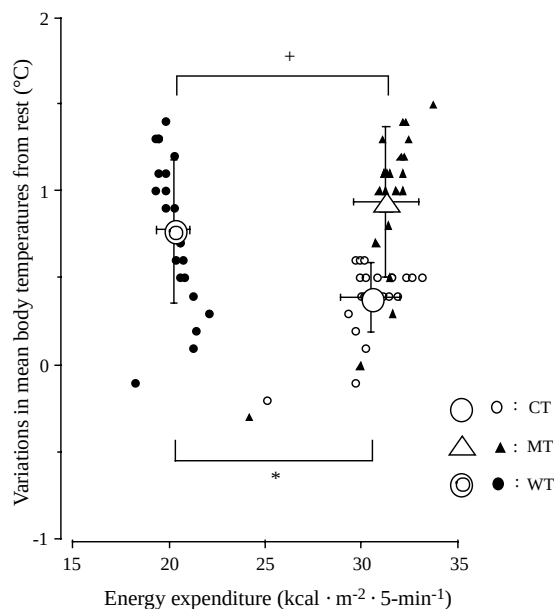


Figure 4. Relationships between variations in mean body temperatures from rest and energy expenditure at 5-min intervals during 120 min of exercise under the three environmental conditions. Large symbols indicate mean $\pm$ SD; * indicates significant difference between CT and WT ($p < 0.05$); + indicates significant difference between MT and WT ($p < 0.05$).

to skeletal muscles lead to the reduction of systemic energy expenditure during exercise in a warm environment. Furthermore, energy expenditures at 5-min intervals at WT were significantly smaller than those at MT and CT, despite no marked differences of T_b from pre-exercise resting values among the three conditions. It is feasible that energy expenditure is not chiefly modulated by the extent of elevation in body temperature during prolonged physical exertion. Clearly, further research is required to elucidate the underlying mechanisms.

In the present study, resting T_{sk} at WT was already elevated compared to those at both MT and CT. It has been suggested that exercise following preheating requires low oxygen uptake during exercise, but precooling demands greater energy expenditure for exercise (Kruk et al., 1990). This implies that signals from thermoreceptors in the skin to the preoptic anterior hypothalamus (POAH) initiate a metabolic response to reduce energy production in advance (Ishikawa et al., 1984; Klir & Heath, 1994; Lenzi et al., 1981). In previous animal studies, warm stimulation for POAH is suggested to contribute to the inhibition of metabolic response (Adair, 1976; Chen et al., 1998; Zhang et al., 1995). These findings support the view that stimulus to thermoreceptors in the skin itself by environmental temperature has a strong influence on the energy metabolism.

No significant differences in oxygen uptake and T_{re} were observed between MT and CT, which are

considered to be sub-thermoneutral conditions (Smolander et al., 1986). In contrast, T_{sk} and T_b at both MT and CT were influenced by changes in environmental temperature. T_{sk} at MT and CT were changed fairly low level throughout the exercise period, when compared to WT. Additionally, T_{re} at MT and CT were adequately modulated especially during the latter half of exercise, whereas that at WT was constantly increased to the end of exercise. Thus, we speculate that there are no significant differences in the effects of ambient temperature on energy expenditure between MT and CT.

Conclusion

During prolonged sub-maximal exercise, environmental temperature has an impact on the change in core temperature and thermoregulatory response in humans. The increase in energy expenditure for exercise is substantially reduced in a warm environment when compared with those in both median and cold environments. This reduction in energy expenditure may inhibit excess metabolic heat generation and consequently enable prolonged exercise in a warm environment.

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