The Sweating Responses of Athletes Trained on Land and in Water

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Abstract In order to examine whether different sweating responses of athletes trained on land and in water may be ascribed to changes in the central sudomotor mechanisms and/or those of the peripheral mechanisms of sweat glands, we measured the local sweating rate at the left forearm ($\dot{m}_{swf}$) and the left scapula ($\dot{m}_{sws}$), the frequency of sweat expulsion (F_{sw}) and body temperatures (mean skin temperature and rectal temperature: T_{re}) in six runners and five soccer players (R group) and six swimmers (S group) during progressive thermal stress at rest (2°C increase in ambient temperature every 15 min from 35 to 45°C RH = 30–40%). T_{re} and heart rate at the end of experiment did not differ significantly between the groups ($37.31 \pm 0.04^{\circ}\text{C}$, $74.5 \pm 7.9 \text{ beats} \cdot \text{min}^{-1}$ in the S group and $37.27 \pm 0.07^{\circ}\text{C}$, $71.1 \pm 9.0 \text{ beats} \cdot \text{min}^{-1}$ in the R group, respectively). The $\dot{m}_{sws}$ and $\dot{m}_{swf}$ at any given mean body temperature ($\bar{T}_b$) were greater in the S group than in the R group. Although the regression line showing the relationship between F_{sw} and $\bar{T}_b$ in the S group was shifted to the left of that in the R group, there was no significant difference in the slope of the lines. The $\dot{m}_{sws} \cdot F_{sw}$ or $\dot{m}_{swf} \cdot F_{sw}$ regression line was not different between the two groups. These results indicate that the higher sweating rate in the S group may be ascribed to a difference in the centrally derived sudomotor neural activity, but not to that in the peripheral mechanisms of sweat gland activity.

Key words: sweating response, frequency of sweat expulsion, centrally derived sudomotor neural activity, sweat gland activity, progressive thermal stress.

Physical training in a temperature [1, 2] or hot condition [3, 4] improves the degree of heat acclimatization with the increases in both sweat production and

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cutaneous blood flow and the initiation of sweating at lower core temperatures. A higher level of heat acclimatization is obtained with the combination of internal and external heat loads (e.g., physical training in a hot condition) [5, 6]. The effectiveness of heat dissipation via evaporation during exercise and its subsequent adaptation with chronic exercise training are dependent on the heat transfer characteristics of the environment. It is known that the training environment such as being on land or in water may influence the sweating responses to thermal stress [7–9]. However, it is unclear whether such differences of sweating responses resulting from different training environments are caused by the changes in the central sudomotor mechanisms and/or by those of the peripheral mechanisms of sweat glands.

Sweat expulsions are synchronized over the general body surface [10–12]. It has been reported that the frequency of sweat expulsions (F_{sw}) increases linearly with rise in ambient temperature (T_a) or mean body temperature ($\bar{T}_b$) at rest [10, 11, 13] and during exercise [14–16], and also a local sweating rate is linearly related to F_{sw} . Moreover, microneurography studies have revealed that the skin sympathetic nerve activity, which reflects both sudomotor and vasoconstrictor activities, shows a close quantitative and temporal correlation with F_{sw} [17, 18]. It is therefore considered that F_{sw} reflects the sudomotor nerve activity derived from the central thermoregulatory mechanism [11, 13, 19].

In the present study, we investigated 1) whether there are any differences in the sweating activity between athletes trained on land and those in water for long time (9–12 years) and, if so, 2) whether such differences are explained by changes in the central sudomotor mechanisms and/or by those of the peripheral mechanisms of sweat glands.

METHODS

Subjects. Six runners and five soccer players (R group) and six swimmers (S group) who had been active in their respective sports for 9–12 years volunteered to be subjects. Both groups had undergone physical training continuously for 3 h or more per day, 4 d or more each week. The swimmers had swum in 22–24°C water during daily exercise bouts. After a detailed explanation of the study, each subject gave their informed consent. Their physical characteristics are shown in Table 1.

Measurements. Rectal temperature (T_{re}) and skin temperatures at the left chest, forearm, thigh, and calf were recorded by copper-constantan thermocouples. The probe for T_{re} was inserted 8–10 cm beyond the anus. Mean skin temperature ($\bar{T}_{sk}$) and $\bar{T}_b$ were calculated using the formulae [20]:

$$\begin{aligned}\bar{T}_{sk} &= 0.3 \cdot \text{chest} + 0.3 \cdot \text{forearm} + 0.2 \cdot \text{thigh} + 0.2 \cdot \text{calf temperature}, \\ \bar{T}_b &= 0.8 \cdot T_{re} + 0.2 \cdot \bar{T}_{sk}.\end{aligned}$$

All temperature data were processed and stored every min using a personal computer (SORD M343SX, Japan) through a data logger (HR3087, Yokogawa,

Table 1. Physical characteristics of R and S groups.

	Age (year)	Height (cm)	Weight (kg)	body surface area (m ²)	$\dot{V}_{O_2 \max}$ (ml·kg ⁻¹ · min ⁻¹)	AT (% $\dot{V}_{O_2 \max}$)
R (n=11)	20±1	171.3±3.5	61.9±4.7*	1.74±0.07*	67.3±3.0*	78.2±2.2*
S (n=6)	19±1	174.9±4.5	71.1±4.1	1.88±0.07	60.6±4.0	74.8±3.5

R: runners/soccer players; S: swimmers. $\dot{V}_{O_2 \max}$, maximal oxygen uptake; AT, anaerobic threshold. Values are expressed as mean±SD. *Significant difference between the groups ($p < 0.05$).

Co. Ltd., Japan). The local sweating rate on the lower part of the scapula ($\dot{m}_{\text{sws}}$) and on the left forearm ($\dot{m}_{\text{swf}}$) was continuously measured by a ventilation method using a capacitance hygrometer [10, 18, 19]. A ventilated capsule was fixed on each skin area (8.8 cm²) with collodion. In the continuous records of the local sweating rate, sweat expulsions, which were synchronous at the two examined sites, were counted and the mean frequency per min (F_{sw}) was calculated.

Heart rate (HR) was measured using an electrocardiogram for every min. The maximal oxygen uptake ($\dot{V}_{O_2 \max}$) was assessed using a bicycle ergometer during incremental work tests. The anaerobic threshold (AT) was determined by previously established criteria [21].

Experimental procedures. The subjects reported to the laboratory at 08:00 A.M. without breakfast, and sat quietly on chairs in a climatic chamber (ambient temperature: $T_a = 35^\circ\text{C}$, relative humidity: RH=40%) for about 60 min. The subjects were then exposed to changes in T_a which were raised stepwise every 15 min in increments of 2°C from 35 to 45°C with RH of 30–40%. All data were taken from the measurements for the last 10 min at each T_a because it took about 5 min to reach a steady T_a . The experiments were conducted during March and April to exclude the effect of seasonal variation.

Statistical treatment. Statistical analysis of the data was performed using a two-level analysis of variance with a 5% level of significance in order to determine differences in mean values between the two groups. Analysis of covariance was used to determine differences in the regression parameters between the two groups, with the 5% significance level.

RESULTS

The HR at the start and the end of the experiment did not differ significantly between the two groups (67.1 ± 7.1 , 74.5 ± 7.9 beats·min⁻¹ (means±SE) in the S group and 65.4 ± 7.1 , 71.1 ± 9.0 beats·min⁻¹ in the R group). However, the $\dot{V}_{O_2 \max}$ and AT were significantly higher in the R group than in the S group (Table 1).

Figures 1 and 2 show the changes in body temperatures (T_{re} , $\bar{T}_{\text{sk}}$, and $\bar{T}_b$) and sweating rates ($\dot{m}_{\text{sws}}$ and $\dot{m}_{\text{swf}}$) at each T_a . T_{re} in both groups were nearly the same

Fig. 1. Changes in rectal temperature (T_{re}), mean skin temperature ($\bar{T}_{sk}$), and mean body temperature ($\bar{T}_b$) in runners/soccer players (R) and swimmers (S) during changes in ambient temperature (T_a). *Significant difference between the groups ($p < 0.05$). Each plot represents mean $\pm$ SE.

Fig. 2. Changes in local sweat rate at the left scapula ($\dot{m}_{sws}$) and at the left forearm ($\dot{m}_{swf}$) in the R and S groups during changes in ambient temperature (T_a). *Significant difference between the groups ($p < 0.05$). Each plot represents mean $\pm$ SE.

at T_a of 35–45°C. $\bar{T}_{sk}$ of the R group tended to be higher than the S group at each T_a except T_a of 45°C. The differences in $\bar{T}_{sk}$ between the two groups were significant at T_a of 35, 37, and 39°C ($p < 0.05$). Although $\bar{T}_b$ tended to be higher in the R group than in the S group at T_a of 35–41°C, the differences were not statistically significant. The $\dot{m}_{sws}$ and $\dot{m}_{swf}$ in the S group during thermal stress at each T_a tended to be higher than those in the R group except at T_a of 35°C. There was a significant

difference in $\dot{m}_{\text{sws}}$ at T_a of 39°C and in $\dot{m}_{\text{swf}}$ at T_a of 37, 39, and 41°C between the groups.

Figure 3 shows the relationships between the sweating rates ($\dot{m}_{\text{sws}}$ and $\dot{m}_{\text{swf}}$) and $\bar{T}_b$ during progressive thermal stress on the S group and the R group. There was a significant positive correlation in each relationship. Both the regression lines showing the relationship between $\dot{m}_{\text{sws}}$ and $\bar{T}_b$ and between $\dot{m}_{\text{swf}}$ and $\bar{T}_b$ in the S group are shifted to the left of those in the R group, but there was no significant difference in the slope of the lines.

Fig. 3. Regression lines relating $\dot{m}_{\text{sws}}$ to mean body temperature ($\bar{T}_b$) (upper) and $\dot{m}_{\text{swf}}$ to $\bar{T}_b$ (lower) in the R and S groups. Each plot represents mean $\pm$ SE.

Fig. 4. Regression line relating sweat expulsions (F_{sw}) to $\bar{T}_b$ in the R and S groups. Each plot represents mean $\pm$ SE.

Figure 4 shows the relationship between F_{sw} and $\bar{T}_b$ during the progressive thermal stress. It is noted that the regression line in the S group is shifted to the left of that in the R group, but there is no significant difference in the slope of the line. The relationship between the sweating rates ($\dot{m}_{sws}$ and $\dot{m}_{swf}$) and F_{sw} did not differ in the two groups (Fig. 5).

DISCUSSION

Although the HR responses during thermal stress did not differ between the R and S groups, a difference in the sweating responses between the two groups was apparent in the present study. Both the regression lines showing the relationships between $\dot{m}_{sws}$ and $\bar{T}_b$ and between $\dot{m}_{swf}$ and $\bar{T}_b$ in the S group were shifted to the left of those in the R group (Fig. 3). The sweating rate at any given $\bar{T}_b$ was greater in the S group than in the R group on the two skin sites examined. These findings suggest that the sweating response during progressive thermal stress applied in the present study was greater in the swimmers than in the runners/soccer players.

In the present study, the regression line showing the relationship between F_{sw} and $\bar{T}_b$ in the S group was shifted to the left of that in the R group with no difference in the slope (Fig. 4). However, the regression lines showing the relationship between $\dot{m}_{sws}$ or $\dot{m}_{swf}$ and F_{sw} were almost identical in the two groups (Fig. 5). These findings suggest that the higher $\dot{m}_{sws}$ and $\dot{m}_{swf}$ at any given $\bar{T}_b$ seen in the S group during progressive thermal stress may be ascribed to an increase in the central sudomotor neural activity, but not to changes in the peripheral mechanisms of sweat gland activity. The change in the central mechanisms is considered to be

Fig. 5. Regression lines relating $\dot{m}_{sws}$ to sweat expulsions (F_{sw}) (upper) and $\dot{m}_{swf}$ to F_{sw} (lower) in the R and S groups. Each plot represents mean $\pm$ SE.

such that it lowers the threshold temperature for sweating with no significant change in the gain of the central thermoregulatory mechanisms and may be attributable to environmental conditions during daily training.

In disagreement with the present findings, Henane *et al.* [7] observed that the total sweating rate during thermal stress at rest was greater in skiers than in swimmers. Moreover, the total sweating rate during exercise under 49°C environment did not significantly increase following training on land or in cool water of 20°C [9]. These earlier studies were carried out in the steady-state condition of body hyperthermia, whereas thermal transients were used in the present study.

Although the present results cannot be directly compared with the earlier studies, it is considered that there are two possibilities for the observed difference.

First, the thermal responses of sweat glands, which can be described as a function of internal and mean skin temperatures in the steady-state condition, are also modified by the rate of change in skin temperature to warm transients [22, 23]. It is therefore considered that the effect of rate of change in skin temperature on the sweating response is greater in thermal transients than in thermal steady-state conditions. If cool water (22–24°C) during daily training in the S group leads to a decrease in the thresholds of the rates of change in the cutaneous thermal receptors to induce sweating, it may be possible that a load error between the threshold temperature in the thermal receptors and $\bar{T}_{sk}$ is greater in the S group than in the R group during progressive thermal stress applied in the present study. Thus, this may be a cause of the greater sweating rate in the S group.

Another possibility for the greater sweating rate in the S group may lie in the differences of physical characteristics. Height, body weight, and $\dot{V}_{O_{2\max}}$ of subjects trained on land and in water in the earlier reports [7, 9] were nearly the same. In the present study, however, the body weight is greater in the S group than that in the R group, whereas $\dot{V}_{O_{2\max}}$ is greater in the R group than in the S group despite matching for height (Table 1). It has been reported that the sweating rate is greater in obese subjects than in lean ones [24, 25] and the sweating rate of athletes under a given passive heat is markedly higher than that of sedentary subjects [7]. Since body weight and body fat are greater in swimmers than in runners despite matching for height [26], the difference in body weight between the groups may mask the possible effects of the physical fitness level on the sweating rate.

$\bar{T}_{sk}$ was somewhat higher in the R group than that in the S group (Fig. 1). It has been reported that the forearm blood flow is lower in obese men than in lean ones during 50% $\dot{V}_{O_{2\max}}$ exercise in hot environments [27]. Therefore, the higher $\bar{T}_{sk}$ in the R group may be related to the higher skin blood flow because of the difference in physical characteristics between the two groups as mentioned above. Since sweating rates are lower in the R group than in the S group, it is also considered that the higher $\bar{T}_{sk}$ in the R group may be attributed to the lower evaporative heat loss.

In summary, the higher sweating rate at any given mean body temperature seen in the S group during progressive thermal stress may be ascribed to a greater centrally derived sudomotor neural activity, but not to a difference in the peripheral mechanisms of sweat gland activity.

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