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ORIGINAL ARTICLE

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# The critical level of water deficit causing a decrease in human exercise performance: a practical field study

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**Abstract** To analyse the critical level of water deficit which causes a decrease in aerobic and anaerobic exercise performance, a step test score (STS) and 10 s maximal anaerobic power (MAP) output during cycling exercise were measured in two experiments (Ex-1, $n=7$, and Ex-2, $n=9$), before and after baseball practice, using subjects who played regularly. The measurements in both Ex-1 and Ex-2 were repeated under four conditions of fluid ingestion (FI) (FI of 80%, 60%, 40%, and 20% of the total sweat loss) on hot summer days. The subjects were allowed free access to a sports beverage, maintained at 10–15°C, within any given FI condition during the exercise. The [mean (SEM)] duration of the exercise and the environmental conditions (wet bulb globe temperature) were similar between Ex-1 [3.52 (0.14) h and 29.2 (0.6)°C, respectively] and Ex-2 [3.82 (0.12) h and 29.2 (0.4)°C, respectively]. In both Ex-1 and Ex-2, the loss of body mass ($\Delta m_b$) increased significantly as FI decreased. In Ex-1, the STS significantly decreased ($P<0.05$) at values of $\Delta m_b$ in excess of 2.4 (0.2)% (40%FI). In Ex-2, the MAP remained unchanged at values of $\Delta m_b$ up to 2.5 (0.3)% (40%FI), while the MAP significantly decreased ($P<0.05$) at values of $\Delta m_b$ of 3.9 (0.2)% (20%FI). These results suggest that there is a critical level of water deficit at which a decrease in aerobic and anaerobic performance occurs, and that aerobic performance may be more adversely influenced by dehydration than anaerobic power output during exercise-induced dehydration.

**Keywords** Body mass loss · Total sweat loss · Step test score · Power · Rehydration

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## Introduction

Dehydration limits both the aerobic and anaerobic components of exercise performance (Sawka and Pandolf 1990), including maximal oxygen uptake (Craig and Cummings 1966), anaerobic power output (Webster et al. 1988), and physical work capacity (Nielsen et al. 1981). However, it has also been reported that there are no changes in strength, aerobic and anaerobic power output following hypohydration (Sawka and Pandolf 1990; Below et al. 1995; McConell et al. 1999). Various methods such as heat exposure, exercise, exercise during heat exposure, diuretics, and reduction of water intake have been used to induce hypohydration, and different effects of hypohydration on exercise performance would thus be expected to occur in these experiments.

Furthermore, it has been suggested that a critical level of water deficit might exist at which exercise performance would be reduced due to hypohydration (Sawka and Pandolf 1990). In a review by Sawka and Pandolf (1990), small [2% of body mass ($m_b$)] to moderate (4% of $m_b$) water deficits were reported to decrease maximal oxygen uptake in a hot environment. On the other hand, low levels of water deficits of less than 2% of $m_b$ did not influence intense exercise performed for 1 h (Below et al. 1995; McConell et al. 1999). However, it has not been confirmed experimentally whether or not there is a critical level of water deficit at which the ability to exercise aerobically and anaerobically is reduced due to hypohydration. In addition, there are few studies on the effects of hypohydration on short-term anaerobic power output (Sawka and Pandolf 1990).

It has been suggested that dehydration of 4% $m_b$ induces a greater proportion of the water loss to come from intracellular sources than does dehydration of 2% of the $m_b$ (Costill et al. 1976). The reduction of muscle water is probably accompanied by an altered electrolyte concentration (Sjøgaard 1983), which could disrupt the electrochemical potential of the cell membrane and thereby contribute to muscle fatigue (Sawka and Pandolf 1990). Furthermore, muscle glycogen content is lower and muscle lactate content higher after 2 h exercise accompanied by dehydration than when euhydrated (Hargreaves et al. 1996). During low levels of dehydration due to exercise, however, the electrolyte concentration in muscle (Costill et al. 1976), and muscle glycogen concentration (Neufer et al. 1991) were shown not to differ markedly from those measured during euhydrated conditions. Accordingly, we hypothesized that a critical level of water deficit would exist for the reduction in performance of aerobic and anaerobic exercise during exercise-induced dehydration.

To test our hypothesis, we examined the critical level of water deficit necessary to cause a decrease in step test performance and maximal anaerobic power output during cycling exercise.

During sports activities in a hot environment, greater amounts of sweating induce hypohydration if the body fluids are not sufficiently replaced; a similar situation to exercise-induced dehydration. In this practical field study, four differing levels of fluid ingestion were used to induce four levels of hypohydration during baseball practice.

## Methods

### Experiment 1

To examine the critical level of water deficit necessary to induce a decrease in aerobic exercise performance, a step test was performed before and 30 min after (recovery period) baseball practice in a hot summer climate.

#### *Subjects*

Seven male college baseball players participated in this study with the approval of the Institutional Human Subjects Committee, and after providing written informed consent. These players had been training four times a week over a period of 2 years. The [mean (SEM)] characteristics of the subjects were: age 20.7 (0.4) years, height 175 (2) cm, $m_b$ 64.3 (1.8) kg, body fat content determined by skinfold thickness (Brožek et al. 1963; Nagamine and Suzuki 1964) 10.9 (0.4)%, and fat-free mass 57.3 (1.6) kg.

#### *Protocol*

On the day of the experiment, the subjects reported to the laboratory at 1200 hours after having eaten a standard Japanese lunch (rice, egg, chicken and vegetable) and then drank 200–300 ml of water to inhibit thirst. They had refrained from heavy exercise for 24 h and from the intake of salty food, alcohol, and caffeine for 17 h before arriving at the laboratory. After a 30 min rest in the laboratory, $m_b$, tympanic temperature ($T_{tym}$), and step test performance were measured in a room maintained at 28°C (50% relative humidity) between 1300 and 1330 hours. They then took part in their usual practice sessions for the competition season (catching ball, toss batting, free batting, and fielding) in one of four conditions of hypohydration. These conditions were induced in a random order, with an interval of 5 days between the tests. To control the level of hypohydration, the quantity of fluid ingested (FI)amounted to approximately 80% (80%FI), 60% (60%FI), 40% (40%FI), or 20% (20%FI) of the total sweat loss ($m_{sw,\ tot}$) which had previously been found to occur during baseball practice in the summer. In earlier studies, we had found that subjects, who had free access to sports beverages during baseball practice in hot summer conditions, drank a total fluid intake (TFI) of 77% of $m_{sw,\ tot}$ (Nakai et al. 1994). In this way, the FI conditions were controlled at approximately one-quarter (20%FI), one-half (40%FI), and three-quarters (60%FI) of the amount of fluid drunk when given free access (80%FI) to a sports beverage (POCARI SWEAT, Otsuka Pharmaceutical Co., Ltd., Japan). This beverage was diluted with water to one half of the original concentration, and its final concentrations of carbohydrate and sodium were 3.6 $g \cdot dl^{-1}$ and 26 $mg \cdot dl^{-1}$, respectively. The beverage was maintained at 10–15°C. To provide free access to the beverage, each subject was provided with a bottle, into which the required volume had previously been measured, from which he could drink at any time during practice. To minimize the effects of high body temperatures and fatigue on the performance of the exercise tests, the measurements were made 30 min after the practice sessions. During the 30 min recovery in the laboratory after practice, the subjects had no access to any beverages. After recovering, $m_b$, $T_{tym}$, and step test performance were measured.

#### *Measurements*

The step test was a modified Harvard step test designed for Japanese adult men (40 cm bench at a rate of 30 steps a min for 3 min). The step test score (STS) was obtained from the heart rate (HR) following exercise using the equation:

$$[\text{exercise time (180s)} \times 100/(a+b+c) \times 2]$$

where, $a$, $b$, and $c$ are the HR from 1 to 1.5, 2 to 2.5, and 3 to 3.5 min after completion of exercise, respectively. The HR were measured using an HR monitor (Polar, Finland). The TFI was determined by weighing the bottles provided to each subject. The $m_b$ was measured with the players wearing only swimming trunks before and after practice, using a balance having an accuracy of 10 g (AND FW-100 k, Ishida, Kyoto), and the loss of body mass ($\Delta m_b$: presented as a percentage of initial $m_b$) was calculated from the changes in $m_b$. The $m_{sw,\ tot}$ (as a percentage of initial $m_b$) was calculated from $\Delta m_b$ after adjusting for TFI, and rehydration (TFI as a percentage of $m_{sw,\ tot}$) was also calculated from $m_{sw,\ tot}$ and TFI. Since it was not possible to determine respiratory water loss (Mitchell et al. 1972) precisely in the field, this was included in the $m_{sw,\ tot}$. The $T_{tym}$ was measured using a thermometer (Genius 3000A, Japan) before and 30 min after the practice sessions. The accuracy of Genius 3000A has been reported by several researchers (Terndrup et al. 1989; Shinozaki et al. 1988). The wet bulb (WB), dry bulb (DB), and globe temperatures (GT) were measured every 30 min during the practice, and the wet bulb globe temperature (WBGT, °C) was obtained from the equation: $0.7WB + 0.2GT + 0.1DB$ (Yaglou and Minard 1957). The mean WBGT values during each of the practice sessions were also calculated.

### Experiment 2

To analyse the critical water deficit necessary to induce a decrease in the performance of anaerobic exercise, 10 s maximal anaerobic power (MAP) output during cycling exercise was measured before and 30 min after the baseball practice sessions.

### Subjects

Nine male college baseball players participated in this study with the approval of the Institutional Human Subjects Committee, and provided written informed consent. These players had been training four times a week over a period of 2 years and three of these nine baseball players also participated in experiment 1. The characteristics of the subjects were: age 20.7 (0.4) years, height 173 (1) cm, $m_b$ 67.5 (1.8) kg, body fat content determined by skinfold thickness (Brožek et al. 1963; Nagamine and Suzuki 1964) 11.8 (0.6)%, and fat free mass 59.5 (1.5) kg.

### Protocol

The experiment protocol was the same as that employed in experiment 1, except that the subjects performed the MAP test instead of the step test.

### Measurements

An electrically controlled cycle ergometer (Power MAX VII, CONBI, Japan) was used to determine the MAP. Before experiment 2, the maximal cycling speed was measured at three loads related to $m_b$ (3, 5, 7 or 2, 4, 6 kilopond, kp), and the MAP (watts) was estimated using the load-speed equation. The 10 s MAP during cycling exercise at maximal speed was measured at a given load (kp) when the MAP (watts) was obtained. The MAP was calculated as the mean power output (watts) during 10 s for three trials performed at 30 s intervals. The $\Delta m_b$, $m_{sw, tot}$, TFI, FI, $T_{tym}$, and WBGT were also measured as in experiment 1.

### Statistical analysis

Two-way ANOVA were used to analyse the differences between before and after practice, and between FI conditions. With regard to the percentage changes in STS and MAP under the four FI conditions, one-way ANOVA were used. Newman-Kuels post-hoc tests were used to locate differences when ANOVA revealed a significant interaction. Correlations between variables were evaluated using standard linear regression analyses. In all cases, significance was accepted at $P < 0.05$.

## Results

### Experiment 1

The mean exercise time and environmental conditions (WBGT) during practice under all four FI conditions were 3.52 (0.14) h and 29.2 (0.6)°C, respectively. The practice schedules were similar for all four FI conditions. Table 1 shows the body fluid balances and the increase in $T_{tym}$ ($\Delta T_{tym}$) during practice in experiment 1. Due to the increase in TFI, a significant ($P < 0.001$) increase in rehydration and a decrease in $\Delta m_b$ were found during practice, but $m_{sw, tot}$ was similar under all four FI conditions. There was no significant difference in $\Delta T_{tym}$ between the four FI conditions.

The mean STS in subjects before practice sessions was 75.1 (4.5), and the variability (coefficient of variation, CV) of STS between FI conditions was 7.2 (0.7)%. The STS found in 40% and 20%FI after practice were significantly decreased ($P < 0.05$) compared to those before the practice sessions. The percentage changes in STS after practice found in 40% and 20%FI were significantly ($P < 0.05$) greater than those found in both the 80% and 60%FI. The STS correlated linearly with $\Delta m_b$ ($r = 0.667$, $P < 0.001$), but no significant relationships were found between $m_{sw, tot}$, $\Delta T_{tym}$, and the changes in STS in experiment 1.

### Experiment 2

The mean exercise time and environmental conditions (WBGT) during practice under all four FI conditions were 3.82 (0.12) h and 29.2 (0.4)°C, respectively. The practice schedules were similar under the four FI conditions. Table 2 shows the body fluid balance and the $\Delta T_{tym}$ during practice in experiment 2. Due to the increase in TFI, a significant ($P < 0.001$) increase in rehydration and a decrease in $\Delta m_b$ were found during practice, but $m_{sw, tot}$ was similar under the four FI conditions. The $\Delta T_{tym}$ in 20%FI was significantly ($P < 0.05$) higher than that in both the 40% and 80%FI conditions.

The mean MAP of the subjects before the practice sessions was 724 (24) watts, and the variability (CV) of MAP between FI conditions was 3.2 (0.4)%. The MAP found in 20%FI after practice was significantly decreased ($P < 0.01$) compared with that before the practice sessions. However, MAP found in 80%, 60%, and 40%FI after practice were not significantly decreased. The percentage change in MAP after practice found in 20%FI was significantly greater ($P < 0.05$) than those found in the 80%, 60%, and 40%FI. The $\Delta m_b$ was linearly correlated with change in MAP ($r = 0.657$,

**Table 1.** Body fluid balance and increase in tympanic temperature ($\Delta T_{tym}$) during exercise in four conditions of fluid ingestion (*FI*) in experiment 1 ($n = 7$). $m_{sw, tot}$, Total sweat loss, *TFI* total fluid intake, $\Delta m_b$ body mass loss, *NS* not significant. Significant differences between all of the conditions were observed in rehydration, TFI, and $\Delta m_b$. Values shown are means (SEM)

| Conditions | Rehydration TFI/$m_{sw, tot}$ % | $m_{sw, tot}$ % body mass | TFI % body mass | $\Delta m_b$ % body mass | $\Delta T_{tym}$ °C |
|---|---|---|---|---|---|
| 20%FI | 19.1 (2.7) | 3.9 (0.2) | 0.7 (0.1) | 3.1 (0.2) | 0.7 (0.2) |
| 40%FI | 39.0 (2.4) | 4.0 (0.3) | 1.6 (0.1) | 2.4 (0.2) | 0.5 (0.1) |
| 60%FI | 67.9 (3.6) | 4.2 (0.3) | 2.9 (0.3) | 1.3 (0.1) | 0.6 (0.1) |
| 80%FI | 82.6 (6.1) | 4.3 (0.2) | 3.6 (0.3) | 0.7 (0.3) | 0.6 (0.1) |
| Significance | $P < 0.001$ | NS | $P < 0.001$ | $P < 0.001$ | NS |

**Table 2.** Body fluid balance and increase in tympanic temperature ($\Delta T_{tym}$) during exercise in four conditions of fluid ingestion (*FI*) in experiment 2 ($n=9$). $m_{sw,\ tot}$ Total sweat loss, *TFI* total fluid intake, $\Delta m_b$ body mass loss, *NS* not significant, *ND* not determined. Significant difference between all of the conditions were found in rehydration, TFI, and $\Delta m_b$. In $\Delta T_{tym}$, a significant difference was observed between 20% and 40%, and between 20% and 80% FI. Values shown are means (SEM)

| Conditions | Rehydration TFI/$m_{sw,\ tot}$ | $m_{sw,\ tot}$ % body mass | TFI % body mass | $\Delta m_b$ % body mass | $\Delta T_{tym}$ °C |
|---|---|---|---|---|---|
| 20%FI | 18.9 (1.1) | 4.8 (0.3) | 0.9 (0.1) | 3.9 (0.2) | 0.8 (0.1) |
| 40%FI | 42.4 (2.4) | 4.4 (0.4) | 1.8 (0.2) | 2.5 (0.3) | 0.3 (0.1) |
| 60%FI | 62.2 (2.4) | 4.4 (0.5) | 2.8 (0.3) | 1.7 (0.2) | ND |
| 80%FI | 84.8 (6.4) | 4.6 (0.3) | 3.9 (0.3) | 0.7 (0.3) | 0.3 (0.1) |
| Significance | $P<0.001$ | NS | $P<0.001$ | $P<0.001$ | $P<0.05$ |

$P<0.001$), but no significant relationships between $m_{sw,\ tot}$, $\Delta T_{tym}$, and the changes in MAP were found in experiment 2.

## Critical level of water deficit inducing a reduction of STS and MAP

The relationship between the changes in STS and $\Delta m_b$ (A), and between the changes in MAP and $\Delta m_b$ (B) during practice under the four FI conditions is shown in Fig. 1. The STS remained unchanged at levels of dehydration up to 1.3 (0.1)% of initial $m_b$ (60%FI), but for dehydration of more than 2.4 (0.2)% of initial $m_b$ (40%FI), STS markedly decreased. On the other hand, MAP remained unchanged at levels of dehydration up to 2.5 (0.3)% of initial $m_b$ (40%FI), but was markedly decreased for dehydration of 3.9 (0.2)% of initial $m_b$ (20%FI). In this study, the FI conditions were set using previous measurements of $m_{sw,\ tot}$ in each subject during baseball practice under similar environmental conditions. Therefore, the level of rehydration (TFI as a percentage of $m_{sw,\ tot}$, Tables 1 and 2) was slightly different due to individual variability and environmental conditions. However, there were no significant differences in mean exercise time and environmental conditions (WBGT) between experiments 1 and 2.

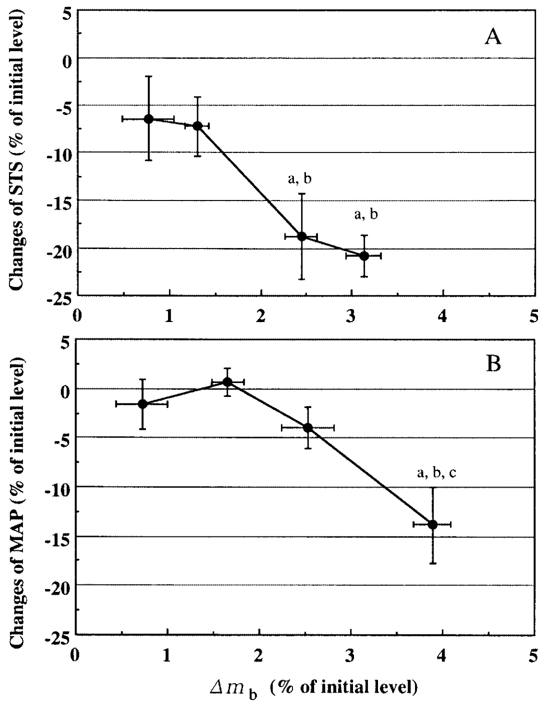


**Fig. 1.** Relationship between the changes in step test scores (*STS*, **A**), maximal anaerobic power (*MAP*, **B**) and body mass loss ($\Delta m_b$) during baseball practice under four conditions of fluid ingestion (FI). The points show means and SEM bars for the subjects. Percentage changes in STS and MAP were calculated from values obtained before and after practice. [a], [b], [c] Significant differences of MAP or STS ($P<0.05$) at 80%, 60%, and 40%FI, respectively

## Discussion

To our knowledge, this was the first study to examine the critical level of water deficit necessary to induce a decrease in the performance of aerobic and anaerobic exercise under several levels of hypohydration due to exercise-induced dehydration. It was also the first study to observe a decrease in 10 s MAP at a dehydration of 3.9% $\Delta m_b$.

The step test has been widely used to evaluate individual aerobic fitness in field studies or in studies with a large number of subjects (Åstrand and Rodahl 1977a). A lower HR during recovery is related to a high STS. In general, it has been noted that subjects having a high STS also showed better performance in many activities demanding high aerobic power, compared to those having a lower STS (Åstrand and Rodahl 1977a). Therefore, the decrease in STS indirectly indicated the decrease in aerobic performance.

The present experiment 1 demonstrated that the critical level of water deficit inducing a decrease in STS is between 1.3 (60%FI) and 2.4 (40%FI)% of initial $m_b$ under exercise-induced dehydration. Montain and Coyle (1992) reported that the magnitude of dehydration was linearly related to a decline in stroke volume and cardiac output, and that decreases in cardiac output and blood flow to exercising muscles also occur with dehydration (González et al. 1998). Furthermore, dehydration due to sweating induces a reduction of plasma volume (Costill et al. 1976; Nose et al. 1988), and the reduction of plasma and blood volume has been reported to decrease cardiac output (Krip et al. 1997). It has also been suggested that a reduction in plasma volume reduction is associated with decrements in maximal aerobic power (Yoshida et al. 1997) and rowing exercise performance (Burge et al. 1993). Therefore, aerobic exercise performance would be expected to decrease with the decline in cardiac output and blood flow in exercising muscles induced by a reduction of plasma volume due to dehydration. However, when the level of dehydration is within 2% of $m_b$, the plasma volume can recover due to a fluid shift into the plasma from the interstitial space (Nose et al. 1988). In experiment 1, the $\Delta m_b$ found under the 60% and 80%FI conditions was less than 2% and STS remained unchanged, while under the 40% and 20%FI conditions, $\Delta m_b$ was more than 2% and STS was reduced significantly. Thus, the critical level of water deficit for the decrease in STS would seem to be dehydration at a level of 2% $\Delta m_b$ under exercise-induced dehydration.

The present experiment 2 demonstrated that the critical level of water deficit inducing a decrease in MAP was between 2.5 (40%FI) and 3.9 (20%FI)% of initial $m_b$ during exercise-induced dehydration. Nielsen et al. (1981) analysed the effect of dehydration procedures on the performance of supra-maximal cycling exercise during dehydration of 3% $m_b$, and found that the reduction of performance was greater in exercise-induced dehydration than in diuretic- or sauna-induced dehydration. In our present experiments, the dehydration procedure was exercise-induced , and MAP was markedly decreased at a $\Delta m_b$ of 3.9 (0.2)% of the initial $m_b$.

Regarding the mechanisms involved in the decrease in MAP during exercise-induced dehydration, we speculate that there are three possibilities. Firstly, the reduction of muscle water content with dehydration (Costill et al. 1976) is probably accompanied by an altered electrolyte concentration (Sjøgaard 1983) which could disrupt the cell membrane electrochemical potential, thereby impairing anaerobic power (Sawka and Pandolf 1990). Secondly, enhancement of sympathetic nerve activity (SNA) due to dehydration (Chen 1996; Nakajima et al. 1998) may be related to muscle glycogen utilization (Febbraio et al.1998). Thirdly, an accumulation of muscle lactate and a reduction in muscle blood flow have been observed during exercise with dehydration of 3.9% $m_b$ (González et al. 1999).

Furthermore, an effect of muscle temperature on short-term (20 s) power output has been observed in humans (Sargeant 1987), and extremely high muscle temperatures may impair anaerobic performance (Sawka and Pandolf 1990). On the other hand, an increase in body temperature of about 1°C induces a 13% increase in the metabolic rate of the cell (Åstrand and Rodahl 1977b), and conditions of work and heat have been judged to be "easy" when the rectal temperature does not exceed 38°C (Wyndham et al. 1965). In the present study, although $\Delta T_{tym}$ at 20%FI in experiment 2 was higher than under other conditions, the difference of $\Delta T_{tym}$ between conditions was only 0.5°C. In addition, measurements of STS and MAP following the practice session were performed after a 30 min recovery in a room maintained at 28°C, suggesting that any increase in core temperature due to exercise would have returned to nearly pre-exercise levels (Saltin and Hermansen 1966; Yoshida et al. 1997). However, temperature-related factors cannot be ruled out completely as contributing to a reduced MAP.

In the present study, $\Delta T_{tym}$ at 20%FI in experiment 2 was significantly higher than that under other conditions while there was no significant difference in $\Delta T_{tym}$ between conditions in experiment 1. The difference of $\Delta T_{tym}$ in each FI condition between experiments 1 and 2 ranged from 0.1 to 0.3°C, suggesting that different subjects might show different responses of $T_{tym}$ between experiments. In addition, since dehydration induces an increase in body temperature during exercise in hot environments (Adolf 1947), the higher $\Delta T_{tym}$ observed at 20%FI in experiment 2 might be attributable to the greater dehydration of 3.9% of $\Delta m_b$ (Table 2).

It has been shown that the ingestion of a carbohydrate (CHO) beverage enhances the performance of endurance exercise (Davis et al. 1988; Mitchell et al. 1989). Fritzsche et al. (2000) also reported that intake of 3.39 l of a solution containing 204 g CHO during 2 h of cycling exercise attenuated a reduction in 4 s maximal neuromuscular power. However, it has also been reported that an intake of less than 37.1 g $CHO\cdot h^{-1}$ did not significantly enhance exercise performance (Davis et al. 1988; Mitchell et al. 1989). Even an intake of 74 g $CHO\cdot h^{-1}$ did not alter glycogen usage or depletion patterns during long-term or intermittent exercise (Mitchell et al. 1989). The sports beverage used in the present two experiments contained 3.6 $g\cdot dl^{-1}$ of CHO, and the highest fluid intakes under the 80%FI condition in experiments 1 and 2 represented the consumption of approximately 23.3 $g\cdot h^{-1}$ and 24.7 $g\cdot h^{-1}$ of CHO, respectively. These values are similar to those shown in CHO ingestion studies, which showed no significant enhancement of exercise performance (Davis et al. 1988; Mitchell et al. 1989).

In summary, the STS decreased when the $\Delta m_b$ exceeded 2.4% of the initial $m_b$, while the MAP decreased at a $\Delta m_b$ of 3.9% of the initial $m_b$. These results suggest that a critical level of water deficit inducing a decrease in aerobic and anaerobic exercise performance does exist during exercise-induced dehydration. Although we could not compare statistically the levels of water deficit between STS and MAP because of the use of different subjects in the two experiments, the present results indicate that the critical level of water deficit inducing a decrease in STS may be smaller than that for MAP. The mechanisms of the reduction in MAP with dehydration are still not clear, and further investigations are needed.

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