Ultraendurance Cycling in a Hot Environment: Thirst, Fluid Consumption, and Water Balance

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Abstract

Armstrong, LE, Johnson, EC, McKenzie, AL, Ellis, LA, and Williamson, KH. Ultraendurance cycling in a hot environment: thirst, fluid consumption, and water balance. *J Strength Cond Res* 29(4): 869–876, 2015—The purpose of this field investigation was to identify and clarify factors that may be used by strength and conditioning professionals to help athletes drink adequately but not excessively during endurance exercise. A universal method to accomplish this goal does not exist because the components of water balance (i.e., sweat rate, fluid consumed) are different for each athlete and endurance events differ greatly. Twenty-six male cyclists (mean ± SD; age, 41 ± 8 years; height, 177 ± 7 cm; body mass, 81.85 ± 8.95 kg) completed a summer 164-km road cycling event in 7.0 ± 2.1 hours (range, 4.5–10.4 hours). Thirst ratings, fluid consumed, indices of hydration status, and body water balance (ingested fluid volume − [urine excreted + sweat loss]) were the primary outcome variables. Measurements were taken before the event, at designated aid stations on the course (52, 97, and 136 km), and at the finish line. Body water balance during exercise was not significantly correlated with exercise time on the course, height, body mass, or body mass index. Thirst ratings were not significantly correlated with any variable. We also observed a wide range of total sweat losses (4.9–12.7 L) and total fluid intakes (2.1–10.5 L) during this ultraendurance event. Therefore, we recommend that strength and conditioning professionals develop an individualized drinking plan for each athlete, by calculating sweat rate (milliliter per hour) on the basis of body mass change (in kilograms), during field simulations of competition.

Key Words dehydration, rehydration, exertional hyponatremia, body mass, performance

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Introduction

Professional sports medicine associations recommend that body weight loss during exercise should not exceed 2% to avert compromised exercise performance. These organizations also recommend that weight gain be avoided during prolonged exercise (11,32) because consumption of a large volume of dilute fluid, coupled with sodium losses in sweat and urine, can result in the clinical condition known as symptomatic exertional hyponatremia (EH) when body fluids become too dilute (8,14,22). In its advanced stage, this illness becomes one of the few noncongenital nontraumatic conditions that results in disorientation, nausea, vomiting, muscular twitching, grand mal seizure, pulmonary or cerebral edema, coma, or sudden death (4,8,9,35). Thus, long-duration physical activity in a hot environment (2) presents a challenge: drinking enough to promote optimal exercise performance, while avoiding the dangers of overdrinking. Even more challenging, a universal method to accomplish this goal (i.e., drinking adequately but not excessively) does not exist because the components of body water balance (e.g., sweat rate, total fluid intake [TFI], urine volume) are different for each athlete, and endurance events vary greatly (e.g., duration, sport, environmental temperature, terrain) (5).

A few authors (12,24,27) have proposed a simple solution: drink only when thirsty. This approach to rehydration is reasonable, but the brain's regulation of thirst is complex (1,16), and little is known about thirst during ultraendurance events, or if drinking to thirst prevents EH. Therefore, the first purpose of this field investigation was to determine if any variables predict and are significantly correlated with thirst during a prolonged endurance event. If thirst was strongly correlated with variables such as TFI or body mass change, strength and conditioning professionals could use these factors to predict drinking behavior during training and competition. We hypothesized that thirst would predict both TFI and body mass change.

Exercise duration also has been proposed as a predisposing factor for EH because most cases occur during endurance cycling (12), running events that are 42.2 km or longer (26,34), triathlons that last 7–17 hours (33,34), repeated days

of military training (35), and long hikes (9). Some authorities (17,23,25,32) have suggested that slower athletes (e.g., 4–5 hours marathon runners) are at greater risk for EH than faster athletes because they stop at more aid stations along the course and drink a greater volume at each opportunity. However, our previous research at this event (2) did not systematically evaluate the relationship between time on course and the total volume of fluid consumed or body water balance. We hypothesized that these relationships would be statistically significant; if this were verified, sports medicine organizations could revise present fluid replacement guidelines (i.e., focusing on newly discovered factors) to reduce the risk for EH, and strength and conditioning professionals could design more effective drinking schedules for training and competition. Therefore, the second purpose of this field investigation was to determine if measured variables (e.g., time on course, ground speed, body mass change) predicted the TFI or body water balance of ultraendurance cyclists during a 164-km summer road cycling event. Total fluid intake and body water balance were selected as primary variables of interest because they represent weight gain, fluid retention, and increased risk for EH (23,32). Total fluid intake also is the single aspect of body water balance that athletes can readily control (i.e., with bottles attached to the bicycle frame or held in jersey pockets) during endurance cycling.

Methods

Experimental Approach to the Problem

We selected the Hotter'N Hell Hundred event (HHH) in Wichita Falls, TX, because it is one of the largest single-day cycling event in America and because it presents severe prolonged exercise-heat stress to entrants, as reported in this journal previously (2). Investigators recruited cyclists as they visited the Exposition Center, 1–2 days before the HHH event, during the month of August, 2011. Although this investigation was part of field research that resulted in 3 previous publications (2,5,6), none of the data here have been published previously.

Subjects

The 26 experienced male cyclists, who served as test participants in this field investigation, had previously completed at least one 160-km cycling event. Their training preparation during the 30 days before this 2011 HHH event involved 8 ± 4 h·wk^{-1} of cycling and 3 ± 1 rides per week (mean ± SD). These men exhibited the following personal characteristics before exercise on the morning of the event: age, 41 ± 8 (range, 20–52) years; height, 177 ± 7 (range, 164–188) cm; body mass, 81.85 ± 8.95 (range, 63.10–101.95) kg; and body mass index, 25.8 ± 2.3 (range, 22.4–29.5) kg·m^{-2}.

Before giving written informed consent, each cyclist received a written and verbal description of all procedures, measurements, time commitment, benefits, and risks, as approved by the University Institutional Review Board for Human Studies. Each man completed a medical history questionnaire, which subsequently was reviewed by the event medical director and the responsible investigator before Event Day. Exclusionary criteria included inadequacy of recent training, present musculoskeletal injury, and a history of either exertional heatstroke or exercise-heat intolerance. The subjects were not paid, but they received an explanation of their own data.

Procedures

On the day before this event, age was recorded to the nearest year. The height of each participant was measured by standing without shoes, against a tape measure that was attached to a wall. Body mass was measured with a floor scale (model DS44L; Ohaus, Florham Park, NJ), accurate to ±100 g. Body mass index was calculated as body mass (in kilograms) divided by height^2 (in square meters). Because 18 participants stopped at 3 aid stations (52, 97, and 136 km) along the course, the calculations for their exercise time on the course (in hours; official event time) and ground speed (in kilometers per hour; 164 km per official event time) incorporated an estimated 10 minutes for rehydration and data collection at 3 aid stations on the course. The exceptions to this correction for time involved the fastest 8 cyclists, who finished in 5 hours or less and rode as part of a "pace group" because they did not stop at any aid station.

Table 1. Exercise performance and fluid balance responses of 26 males recorded during the 164-km cycling event.

Variables	Mean ± SD	Range
Exercise time on the course (h)	7.0 ± 2.1	4.5 to 10.4
Ground speed (km·h^{-1})	25.4 ± 7.2	15.8 to 36.5
Total fluid intake (L·164 km^{-1})	4.9 ± 2.0	2.1 to 10.5
Rate of fluid intake (L·h^{-1})	0.7 ± 0.2	0.3 to 1.2
Urine volume (L·164 km^{-1})	0.8 ± 0.5	0.3 to 2.4
Total sweat loss (L·164 km^{-1})	7.3 ± 1.8	4.9 to 12.7
Sweat rate (L·h^{-1})	1.1 ± 0.4	0.5 to 1.9
Body mass change (kg)*	−2.2 ± 1.4	+0.6 to −4.8
Body mass change (%)	−2.7 ± 1.8	+0.7 to −6.5
Body water balance (L·164 km^{-1})†	−3.2 ± 1.4	−0.3 to −5.4

*Measured by floor scale accurate to ±100 g.
†Body water balance = (ingested fluid volume) − (urine excreted + sweat loss).

On Event Day before the 0700 hours start, subjects reported to a medical tent near the starting line, located in the center of Wichita Falls, TX,

Table 2. Hydration-relevant variables, measured before the event and at the finish line medical tent.

Variables	Pre-event (0 km)	Finish (164 km)	Change
Urine-specific gravity	1.019 ± 0.007	1.022 ± 0.008*	+0.003 ± 0.009
Urine color	4 ± 1	6 ± 1†	+2 ± 2
Thirst rating	2 ± 1	6 ± 2†	+4 ± 2

*Did not change during the event ($p > 0.05$).
†Significantly different from pre-event value ($p < 0.00001$, $n = 26$).

where investigators recorded baseline measurements of body mass and a perceptual rating of thirst. Cyclists rated thirst sensation by selecting a number between 1 and 9; the odd numbers were anchored as follows: 1 (not thirsty at all), 3 (a little thirsty), 5 (moderately thirsty), 7 (very thirsty), and 9 (very, very thirsty). A urine sample was collected in a clean transparent sample cup and analyzed for urine-specific gravity (handheld refractometer, model 300CL; Atago Co., Tokyo, Japan) and urine color (i.e., the sample was held over a sheet of white paper and was compared with a validated color chart) (7). Refractometers were calibrated before the event, using distilled water, as per manufacturer's instructions. All cyclists began riding at 0700 hours. After completing the entire 164-km distance, cyclists reported to the medical tent near the finish line. All variables that had been measured previously at the starting line (see the first sentence of this paragraph) were repeated, including diet records.

Investigators did not offer advice/instructions to participants about planning or execution of event strategies. Cyclists were free to consume food and fluids according to their usual practices. On Event Day, cyclists recorded all food and fluid that was consumed during meals and snacks, according to written and verbal instructions that a registered dietitian provided at the preparticipation briefing meeting. Cyclists recorded food details such as the number, volume, size, brand, manufacturer, and method of preparation; they submitted nutrition labels and packages, when possible. Investigators provided all cyclists with 2 identical plastic bottles (known capacity of 592 mL each), which were prelabeled with external volume demarcation lines. During the event, at the 3 designated aid stations (52, 97, and 136 km) and at the finish line (164 km), an investigator interviewed each cyclist to verify individual foods and fluids consumed between aid stations. When a cyclist arrived at each of the 3 aid stations, plastic bottles were visually examined for the amount that had been consumed to the nearest 3 mL (0.1 oz). An investigator then recorded this volume, refilled each bottle to capacity with plain water, and returned it to the cyclist. Immediately before they mounted bicycles and proceeded toward the next data collection site, cyclists were instructed to remember all food and fluid that they consumed during the next event stage. The 8 cyclists who finished 164 km in 5 hours or less (see above) were exceptions to diet interviews and bottle inspection procedures, in that they did not stop at the 3 designated aid stations on the course; thus, they reported food and fluid intake only after finishing the event.

The total volume of sweat lost by each participant was calculated using the following formula: sweat loss = (ΔMb) + (ingested fluid mass) + (ingested solid food mass) + (water generated during substrate oxidation) − (mass loss due to substrate oxidation) − (urine excreted). This calculation modified the method described by King et al. (19) by correcting for (a) solid food

Table 3. Statistical correlations* between total fluid intake (in liters), postevent thirst rating, change of thirst rating, and selected variables.

Variables evaluated on event day	r^2	p
Total fluid intake ($L \cdot 164\ km^{-1}$) versus pre-event thirst rating	0.00	0.97
Total fluid intake versus postevent thirst rating	0.00	0.81
Total fluid intake versus change of thirst rating	0.00	0.83
Total fluid intake versus pre-exercise body mass (kg)	0.02	0.53
Total fluid intake ($L \cdot 164\ km^{-1}$) versus height (cm)	0.00	0.85
Total fluid intake versus body mass index ($kg \cdot m^{-2}$)	0.05	0.26
Total fluid intake versus body water balance ($L \cdot 164\ km^{-1}$)	0.08	0.18
Postevent thirst rating versus pre-event body mass (kg)	0.03	0.39
Postevent thirst rating versus change of body mass (kg)	0.01	0.56
Postevent thirst rating versus height (cm)	0.06	0.22
Postevent thirst rating versus body mass index ($kg \cdot m^{-2}$)	0.04	0.36
Postevent thirst rating versus ground speed ($km \cdot h^{-1}$)	0.14†	0.06†
Postevent thirst rating versus body water balance ($L \cdot 164\ km^{-1}$)	0.00	0.70
Change of thirst rating versus change of body mass (kg)	0.00	0.99
Change of thirst rating versus ground speed ($km \cdot h^{-1}$)	0.00†	0.70†
Change of thirst rating versus body water balance ($L \cdot 164\ km^{-1}$)	0.00	0.97

*Determined by linear regression analyses ($n = 26$).
†r^2 and p values for ground speed are identical to exercise time on the course values.

mass, determined from computerized analyses of all food items consumed during exercise and (b) volume of urine excreted (i.e., not produced and held in the bladder). Body water balance during exercise was represented by the following formula: body water balance = (ingested fluid volume) − (urine excreted + sweat loss). To estimate urine volume, cyclists counted the duration in seconds (i.e., required to completely empty the bladder), each time they urinated; this method was developed by Peterson and Webster (28).

Statistical Analyses

Sample size was calculated before the study on the basis of the variability in body mass loss. We conservatively estimated that the variation in body mass loss was ~10%, and that the day-to-day between-subject variation was ~50%. Subsequently, the retest correlation (r) or reliability of our outcome measure was calculated as: $50^2 - 10^2/50^2 = 2500 - 100/2500 = 0.96$. For this analysis, which involves a pre-event and post-event measurement for each subject, the minimal sample size to detect a significant difference at a 0.05 α level was calculated as 8 subjects, using the following equation: $n = (1 - r)\ N/2$ or $n = (1 - 0.96)\ 400/2 = 8$, where $N = (32/\mathrm{ES}^2)/2$, and effect size was 0.2. Thus, the present sample of 26 men exceeded the minimal sample size to detect a significant difference ($p \leq 0.05$).

Descriptive statistics for time on the course, ground speed, fluid intake, urine volume, sweat loss, body mass change, and body water balance are presented with the associated standard deviation (±SD). Pre-event and post-event mean values for urine-specific gravity, urine color, and rating of

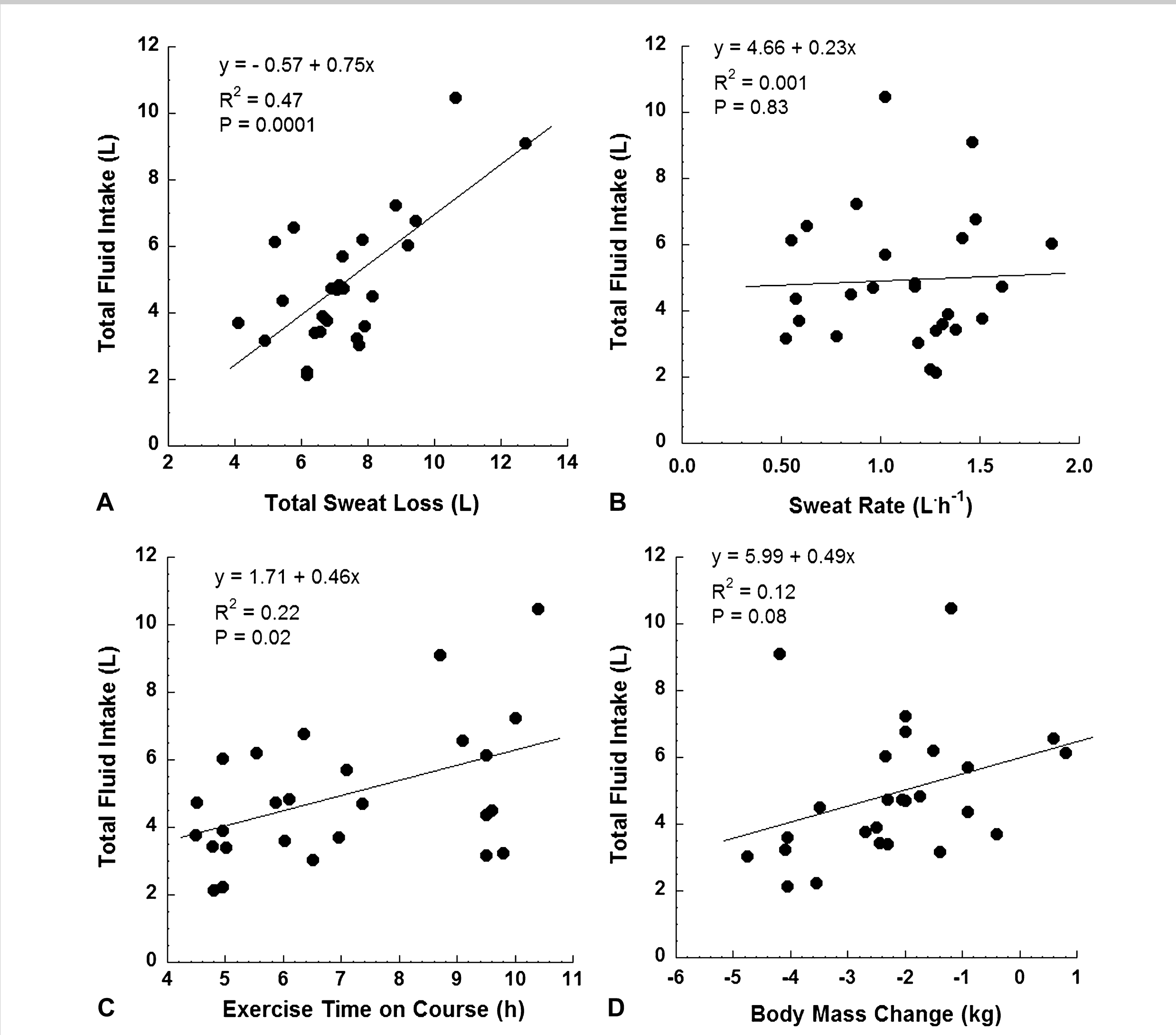

Figure 1. Relationships between total fluid intake (y axes) during the 164-km ride and 4 relevant variables (x axes): A, total sweat loss; B, sweat rate; C, exercise time on the course; and D, body mass change.

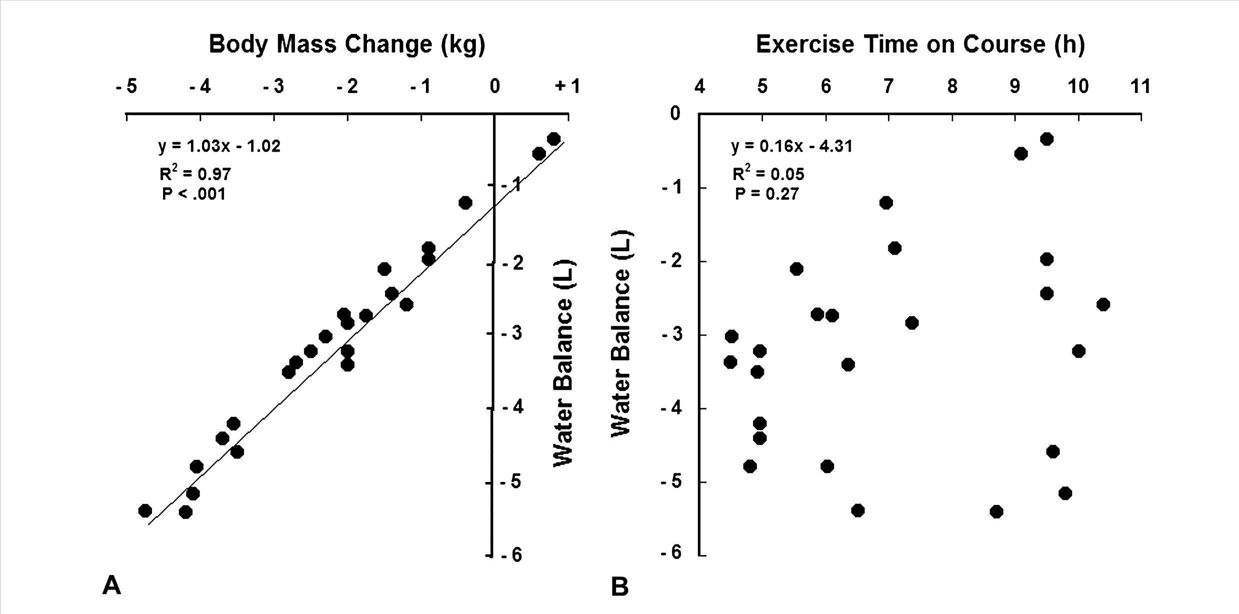

Figure 2. Relationships between body water balance (ingested fluid volume − [urine excreted + sweat loss]): (A) body mass change and (B) exercise time on the course.

thirst were compared by paired sample *t*-tests. The relationship between TFI, thirst ratings, and selected variables (postevent and change, $n = 26$) were evaluated by linear regression analyses to determine r^2 and probability values. Linear regression analyses also were conducted to evaluate potential predictors (e.g., body mass, height, body mass index, body water balance, ground speed, exercise time on the course) of TFI and water balance and then were presented in graphic format.

Results

Environmental conditions on Event Day were recorded from 0700 to 1700 hours at the local meteorological station in Wichita Falls, TX. The mean dry bulb temperature was 35.5 ± 6.5° C, and ranged from 25.6 (0700 hours) to 42.2° C (1700 hours). Mean wet bulb globe temperature was 30.8 ± 1.9° C (range, 27.8° C at 0700 hours to 32.7° C at 1200 hours). Cloud cover throughout Event Day was 0–5%. The mean relative humidity was 29 ± 16%, and ranged from 17 (1500 hours) to 58% (0800 hours).

The exercise performance and fluid balance responses of the 26 male cyclists appear in Table 1. The mean times to complete 164 km (7.0 ± 2.1 hours) on this relatively flat paved course indicate that these participants were endurance trained. The range of finish times (4.5–10.4 hours) represented an array of competitive abilities. Table 1 also demonstrates that the range of body mass change (in kilograms) was +0.6 to −4.8 kg (+0.7 to −6.5%), whereas the range of body water balance was −0.3 to −5.4 L. This emphasizes that body mass change is different from body water balance.

The range of solid food mass (i.e., determined from computerized analyses of all food and fluid items consumed during exercise) was 180–930 g, with a mean of 390 ± 150 g. This mass of solid food consumed during this cycling event (not shown in Table 1) influenced body mass change but influenced body water balance insignificantly because virtually all solid food contained little or no water.

Hydration variables (i.e., pre-event, post-event, and change) are presented in Table 2. As anticipated, urine color and thirst increased significantly ($p < 0.00001$) during the 164-km ride (Table 2). However, urine-specific gravity did not change significantly during this ultraendurance cycling event ($p > 0.05$).

Neither TFI nor thirst ratings (i.e., postevent, change) were significantly correlated with any variable in Table 3, including body water balance ($L \cdot 164\ km^{-1}$).

Figure 1 depicts the relationships between TFI (in liters) and 4 variables during the 164-km cycling event. Total fluid intake was significantly correlated with total sweat loss ($r^2 = 0.47, p = 0.0001$) and exercise time on the course ($r^2 = 0.22, p = 0.02$). However, total sweat loss ($L \cdot 164\ km^{-1}$) and exercise time on the course were not significantly intercorrelated ($r^2 = 0.02$, $p = 0.47$). Thirst was not significantly correlated with any measured variable (Table 3). Figure 2 demonstrates that exercise time on the course (i.e., the counterpart to ground speed) was not related to body water balance.

Discussion

Previous outdoor studies have demonstrated reduced cycling and running performance in association with mild

dehydration, involving body mass losses of only 1.0–1.8% (3,10,20). In concert with these findings, professional sports medicine organizations (11,32) recommend that athletes drink adequately (i.e., avoiding a body weight loss >2%, which degrades endurance performance) without gaining weight (i.e., suggesting excessive fluid retention and increased risk for symptomatic EH). However, no universal method exists to accomplish these recommendations because (a) the components of body water balance (e.g., sweat secretion, fluid consumption, urine excretion) are different for each athlete and (b) endurance events vary greatly in duration, mode (e.g., cycling, running, swimming), environmental temperature, and terrain. This study attempted to identify and clarify factors that may be used by strength and conditioning professionals to help athletes adequately but not excessively hydrate during endurance exercise. We hypothesized that thirst would predict both TFI and body mass change, but this hypothesis was not supported. We also hypothesized that the time on course would predict the total volume of fluid consumed and body water balance; the former prediction was supported, but the latter was not.

This was an observational field investigation, which did not control independent variables such as exercise intensity or the type/amount of fluids and solid foods that were consumed. As such, causality cannot be implied. Nevertheless, statistically significant relationships were identified, which clarify the complex interactions of factors that influence drinking and body water balance during prolonged cycling exercise. For example, Figure 1 illustrates that TFI was significantly correlated with exercise time on the course (in hours) and total sweat loss (in liters) but not sweat rate (in liters per hour) or body mass change (in kilograms). Contrary to Figure 1, net body water balance (in liters) was not significantly correlated with exercise time on the course (Figure 2), serving as a reminder that fluid intake is only one component of water turnover (body water balance = [ingested fluid volume] − [urine excreted + sweat loss]).

Similarly, no measured variable was significantly correlated with ratings of thirst (Table 3). This suggests that (a) cyclists in this investigation did not rely on thirst to guide their drinking during exercise and that (b) thirst is idiosyncratic and difficult to predict on the basis of other variables. Although we did not survey planned drinking or individual motivation to drink, published evidence suggests that preconceived notions predispose some individuals to consume an excessive volume of fluid during prolonged exercise in a hot environment (4,8). Furthermore, drinking behavior (i.e., volume consumed) is a complex entity (13,29,31), which is influenced by learned preferences, cultural influences, learned behaviors, fluid characteristics, distance to the source, and environmental conditions (6,15).

As noted above, professional sports medicine organizations (11,32) recommend that athletes avoid gaining weight during endurance events because it represents excessive fluid retention and increased risk for EH (22). However, net body mass change involves different factors than body water balance (see Methods). This explains why the range of body mass change (in kilograms) was +0.6 to −4.8 kg (+0.7 to −6.5%), whereas the range of body water balance was −0.3 to −5.4 L (Table 1). Furthermore, body mass change underestimated body water balance (i.e., true water loss) by 0.91 L during 7 hours of cycling exercise, although these factors were strongly correlated ($r^2 = 0.97$, $p < 0.0001$; Figure 2).

In this field study, the following 2 limitations are acknowledged. First, advanced age may influence the sensitivity of thirst, as observed in adults who are older than 65 years (18). Although it is unlikely that participants in this study (mean age, 41 ± 8 years) experienced age-related deficits of thirst or renal regulation of body water balance (21), the present findings may not be relevant to older or very young athletes. Second, all participants in this investigation were men. A few publications suggest that the drinking behavior of women differs from that of men in subtle ways (30,32), in part due to differences of reproductive hormones (33,36). However, because few previous studies have focused on women during ultraendurance exercise (35), the influence of gender is unknown and worthy of future research.

Practical Applications

Field observations of 26 endurance cyclists produced 3 primary insights that strength and conditioning professionals can use. First, although cyclists had continuous access to bottled fluids, they experienced an average body mass loss of 2.7% (Table 1) and increased thirst ($p < 0.00001$; Table 2); drinking according to their usual practices did not maintain body mass loss within published guidelines of <2% (11,32) for 17 of the 26 cyclists (65%). This is meaningful because a body mass loss of only 1.0–1.8 % has been associated with decrements of cycling (10) and running (3,20) performance in controlled field studies. Furthermore, those cyclists who maintained a body mass loss of <2% during exercise (Figure 1, panel D) exhibited a wide range of total sweat losses (4.9–12.7 L), TFI (2.1–10.5 $L \cdot 164\ km^{-1}$), and rates of fluid intake (0.3–1.2 $L \cdot hour^{-1}$). These observations suggest that no single rehydration recommendation (i.e., to drink a specific volume per hour) is appropriate for all athletes. Second, neither height, body mass, nor body mass index were significantly correlated with thirst ratings, TFI, or body water balance (Table 3); this means that physical characteristics should not be used to generalize drinking recommendations, such as “a larger athlete should consume more water.” Third, body water balance was not significantly correlated with exercise time on the course (Figure 2), although TFI was significantly correlated (Figure 1). This opposes the concept that slower cyclists (e.g., 7–10 hours of finish time) are at greater risk for EH (i.e., excessive fluid retention) than faster cyclists simply because they consume more fluid during the event (4,17,23,25,32); fluid intake is only one component of body water balance. However, because cyclists have continuous access to bottles in their jersey pockets and

on their bicycle frame, this finding should not be generalized to other endurance sports.

These 3 primary insights suggest that each athlete requires an individualized drinking plan, based on field measurements, which simulate competition and training. The strength and conditioning professional can accomplish this with 1 instrument: a digital floor scale that is precise to 0.1 kg (0.2 lb) (11). The athlete first voids the bowel and bladder, measures body weight nude (or wearing undergarments), exercises for 1 hour, and repeats the body weight measurement. If this field simulation mimics race conditions closely (i.e., matching the exercise intensity and environmental conditions), the calculated sweat rate will closely approximate the athlete's sweat rate during competition. If this field simulation is conducted within 1 week of an impending competition, it is unlikely that changes of aerobic capacity and heat acclimatization status will diminish the accuracy of calculated sweat rate. A simple formula is used: sweat rate (in milliliters per hour) = (body weight before) − (body weight after), where 1 kg equals 1 L of body water and 1 g equals 1 mL of body water. After calculating an athlete's sweat rate (in milliliters per hour), the strength and conditioning professional can design a drinking schedule that will avoid a body weight loss of more than 2%. Because body weight loss underestimates body water loss by approximately 30% (Table 1; Figure 2, panel A), the use of calculated sweat rate to design a drinking plan also minimizes the likelihood of consuming excess fluid and the risk for EH.

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