NUTRITIONAL, PHYSIOLOGICAL, AND PERCEPTUAL RESPONSES DURING A SUMMER ULTRAENDURANCE CYCLING EVENT

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ABSTRACT

Armstrong, LE, Casa, DJ, Emmanuel, H, Ganio, MS, Klau, JF, Lee, EC, Maresh, CM, McDermott, BP, Stearns, RL, Vingren, JL, Wingo, JE, Williamson, KH, and Yamamoto, LM. Nutritional, physiological, and perceptual responses during a summer ultraendurance cycling event. *J Strength Cond Res* 26(2): 307–318, 2012—Despite the rapid growth of mass participation road cycling, little is known about the dietary, metabolic, and behavioral responses of ultraendurance cyclists. This investigation describes physiological responses, perceptual ratings, energy balance, and macronutrient intake of 42 men (mean ± *SD*; age, 38 ± 6 years; height, 179.7 ± 7.1 cm; body mass, 85.85 ± 14.79 kg) and 6 women (age, 41 ± 4 years; height, 168.0 ± 2.9 cm; body mass, 67.32 ± 7.21 kg) during a summer 164-km road cycling event. Measurements were recorded 1 day before, and on the Event Day (10.5 hours) at the start (0 km), at 2 aid stations (52 and 97 km), and at the finish line (164 km). The ambient temperature was >39.0° C during the final 2 hours of exercise. The mean finish times for men (9.1 ± 1.2 hours) and women (9.0 ± 0.2 hours) were similar, as were mean gastrointestinal temperature (T_{GI}), 4 hydration biomarkers, and 5 perceptual (e.g., thermal, thirst, pain) ratings. Male cyclists consumed enough fluids on the Event Day (5.91 ± 2.38 L; 49% water) to maintain body mass within 0.76 kg, start to finish, despite a sweat loss of 1.13 ± 0.54 $L \cdot h^{-1}$ and calculated energy expenditure of 3,115 $kcal \cdot 10.5 \cdot h^{-1}$. However, men voluntarily underconsumed food energy (deficit of 2,594 kcal, 10.9 MJ) and specific macronutrients (carbohydrates, 106 ± 48 g; protein, 8 ± 7 g; and sodium, 852 ± 531 mg) between 0530 and 1400 hours. Also, a few men exhibited extreme final values (i.e., urine specific gravity of 1.035–1.038, $n = 5$; body mass loss >4 kg, $n = 2$; T_{GI}, 39.4 and 40.2°C). We concluded that these findings provide information regarding energy consumption, macronutrient intake, hydration status, and the physiological stresses that are unique to ultraendurance exercise in a hot environment.

KEY WORDS fluids, electrolytes, urine, sport nutrition, thermoregulation, energy expenditure

INTRODUCTION

The foods and fluids consumed by endurance road cyclists are related to both performance and well-being. Before, during, and after competition, dietary strategies can reduce fatigue and the risk of illness and enhance recovery and optimize physiological adaptations (9). Thus, several previous publications have evaluated the dietary intakes of collegiate and Olympic cyclists relative to the metabolic requirements imposed by elite competition (9,15,26). These publications focused on carbohydrate intake before and during exercise because hypoglycemia influences central fatigue (6), endurance is enhanced by preexercise glycogen levels, and because exhaustion from glycogen depletion can be postponed by carbohydrate feeding during exercise (19). A large body of information also indicates that dehydration can degrade endurance exercise performance when >2% of body mass is lost (12,28). That is, when dehydration exceeds 3–5% of body mass, both sweat rate and skin blood flow decrease, and the risk of exertional heat illness increases (2). Further, human hyperthermia and high ambient temperature potentiate the interactions between exercise metabolism, exercise performance, hydration state, and health.

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Although few core body temperature measurements in cyclists have been published, we know that marathon runners experience rectal temperatures of 39.0–41.7° C after running in mild (7–18° C) environments (21,22). Unfortunately, the scientific literature is limited as to how well nonelite cyclists maintain carbohydrate intake, fluid balance, and body temperature during ultraendurance events.

During the past decade, the popularity of mass participation endurance cycling events has grown rapidly in many countries. The U.S.A. Cycling, the official governing body for all disciplines of competitive cycling in the United States, reported 66,844 licensed members in 2009 and sanctioned 2,638 events (31). That year, the Hotter 'n Hell Hundred (HHH) was the largest single-day 100-mile (164-km) event in the U.S.A. Our research team recognized that this endurance event presented unique nutritional, physiological, and behavioral stresses to entrants and difficult clinical care challenges to medical personnel, which have not been described for nonelite cyclists.

Therefore, the purpose of this investigation was to describe the physiological and metabolic responses, perceptual ratings, energy balance, and macronutrient intake of 48 recreational endurance cyclists during a 164-km event conducted in a mean ambient temperature of 34.4 ± 4.9° C. We hypothesized that these men and women would not maintain thermal, fluid, and energy balance during this 9-hour effort and that behavioral and physiological measures would indicate great stress. We anticipated that the findings of this research would provide information to dietitians, clinicians, coaches, and race directors regarding energy consumption, macronutrient intake, hydration status, and the physiological stresses that are unique to ultraendurance exercise in a hot environment.

METHODS

Experimental Approach to the Problem

This summer field investigation involved nonelite cyclists (42 male and 6 female) who were observed before, twice during, and after a 164-km outdoor cycling event, commonly referred to as a Century Ride. The participants were free to (a) select and consume food and fluids ad libitum and (b) choose their own pace strategies. Thermal, circulatory, metabolic, macronutrient, fluid electrolyte, and perceptual variables were measured. These variables were selected because they are relevant to sport dietitians, coaches, race directors, and clinicians who advise and provide therapy to ultraendurance cyclists.

Subjects

With the approval of the event directors, investigators recruited cyclists as they attended the registration and prerace exposition of the HHH event (day −1). This event occurred in Texas during the month of August. Before giving informed written 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. The subjects were not paid, but they received an explanation of their own data.

The subjects completed a medical history questionnaire and a 28-day exercise history, which subsequently was screened by the race medical director and the responsible investigator. Exclusionary criteria included inadequacy of recent training, present musculoskeletal injury, and a history of either exertional heatstroke, exercise-heat intolerance, disease of the gastrointestinal tract (e.g., diverticulitis, hypomotility, inflammatory bowel disease), or gastrointestinal surgery. All the test participants had previously completed at least one 160-km cycling event and were aged 19–49 years.

Investigators did not provide food or water to the participants. The investigators also did not offer advice or instructions to the participants about planning or execution of race strategies, or about food and fluid intake.

Physiological Variables

On day −1, the height of each test subject was measured by standing against a tape measure, attached to a wall. Body mass was measured with a floor scale, accurate to ±100 g. Body mass index (BMI) was calculated as body mass (kilograms) divided by height^2 (meter squared). Age was recorded to the nearest year. The characteristics (mean ± *SD*, range) of 42 men were as follows: age, 38 ± 6 (20–50) years; height, 179.7 ± 7.1 (163.4–194.0) cm; body mass, 85.85 ± 14.79 (57.6–115.7) kg; BMI, 26.4 ± 4.0 (19.4–37.4). The characteristics of 6 women were as follows: age, 41 ± 4 (36–48) years; height, 168.0 ± 2.9 (164.5–171.3) cm; body mass, 67.32 ± 7.21 kg (58.0–77.6); BMI, 23.8 ± 2.3 (20.9–26.9).

Heart rate ($n = 16$ men, $n = 3$ women) and gastrointestinal temperature (T_{GI}; $n = 12$ men, $n = 3$ women) were measured in a subset of participants who were identified at the test subject information meeting. The heart rate was assessed via a wrist cardiotachometer that read heart rhythm from a chest strap. Gastrointestinal temperature (T_{GI}) was measured via an ingestible thermistor (CorTemp®, HQ Inc., Palmetto, FL, USA), which was swallowed by each volunteer at 2100 hours on the night before the event; ingestion was verified by a telephone call from an investigator. By the next morning, this temperature sensor had moved into the digestive tract via peristalsis. The T_{GI} was measured with a hand-held digital thermometer (±0.1° C), positioned near the posterior lumbar curve.

Two days before the Event Day, a subset of 10 men were identified for a preliminary procedure that allowed the calculation of sweat rate (liters per minute). This procedure has been described in detail elsewhere (1); it involved 41 ± 7 minutes of outdoor exercise in a hot environment, preexercise and postexercise body mass measurements, and corrections for the volume of sweat trapped in clothing, and the mass of urine excreted. No fluid or food was consumed during this procedure.

Sweat rate also was assessed in 20 men on the Event Day; these individuals were selected from a larger sample of riders

Table 1. Mean (±*SD*) elapsed time, gastrointestinal temperature, and heart rate measured before the start, at 2 aid stations, and at the finish line.

Variable	Group (*n*)	Prerace (0 km)	Aid station (52 km)	Aid station (97 km)	Finish (164 km)
Elapsed time (h)*	Men ($n = 33$)	0.0	1.8 ± 0.3	3.7 ± 0.5	9.1 ± 1.2
	Women ($n = 5$)†	0.0	1.8 ± 0.2	3.8 ± 0.2	9.0 ± 0.2
Cumulative ground Speed (km·h^{-1})	Men ($n = 33$)	0.0	29.5 ± 4.7	26.6 ± 3.8‡	17.9 ± 2.4§
	Women ($n = 5$)†	0.0	29.3 ± 3.7	25.8 ± 1.2	17.8 ± 0.4
Gastrointestinal temperature (°C)	Men ($n = 12$)	36.86 ± 0.38	38.14 ± 0.46‖	38.16 ± 0.21‖	38.50 ± 0.39¶
	Women ($n = 3$)†	37.02 ± 0.09	38.26 ± 0.32	38.24 ± 0.52	38.10 ± 0.28
Heart rate (b·min^{-1})	Men ($n = 16$)	#	149 ± 9	155 ± 7‡	161 ± 12§
	Women ($n = 3$) †	#	140 ± 24	151 ± 12	149 ± 14

*Subjects stopped for approximately 5–10 minutes at 2 aid stations for research measurements, elimination, drinking, and eating.

†No statistical comparison was performed across time for women, because of small sample size and incomplete data sets; this applies to all ensuing tables and figures.

‡Significantly different from 52 km ($p < 0.001$) and 164 km ($p < 0.025$) values for men.

§Significantly different from 52 km ($p < 0.001$) values for men.

‖Significantly different from 0 km ($p < 0.001$) values for men.

¶Significantly different ($p < 0.05$–0.001) from all other means for men.

#Not measured.

because they volitionally consumed no solid food, up to the 52-km point. This calculation involved the body mass difference (0–52 km) with corrections for the mass of fluids consumed, as reported in diet records written at the 52-km aid station.

Energy expenditure during exercise was calculated using an overground cycling method (29) that incorporated the ground speed and body mass of each cyclist to derive the rate of oxygen consumption (liters per minute). Considering the elapsed time, oxygen consumption was converted to kilocalories. Metabolic water production, an additional component of total body water balance, was calculated with the method of Hoyt and Honig (17). This technique used total energy expenditure (kilocalories·24 h^{-1}) including exercise, sleep, and other daily activities.

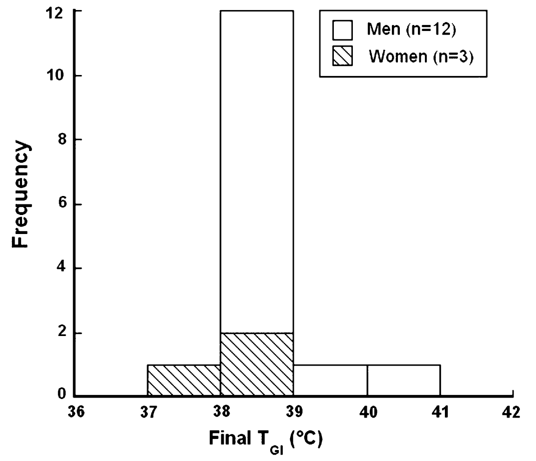

Figure 1. Gastrointestinal temperature (T_{GI}) at the end of the 164-km cycling event, measured in a subset of participants.

Perceptual Ratings

Five rating scales, all relevant to prolonged endurance exercise in a hot environment, were recorded for men and women at the starting line, at 2 aid stations, and at the finish line. First, the rating of thermal sensation (32) included 17 categories of thermal comfort, ranging from 0.0 ("unbearably cold") to 8.0 ("unbearably hot"), in increments of 0.5 units. Secondly, a rating of thirst (13) included 9 categories ranging from 1 ("not thirsty at all") to 9 ("very, very thirsty"). Third, a 6- to 20-point rating of perceived exertion (5) was presented to each cyclist after exercise, at the 2 aid stations and at the finish line; the extreme category terms ranged from "very, very light" to "very, very hard." Cyclists also responded to the statement "I have a muscle cramp" by selecting one of the following options: not at all, a little, somewhat, moderate, a lot, extreme; these options were scored 1–6, for statistical analysis. Finally, the pain rating scale (11) involved 12 categories, with extreme ratings of 0 ("no pain at all") to 10 ("Extremely intense pain, almost unbearable").

Diet Records

During the 24 hours before this event (day −1), the cyclists recorded all food and fluid that they consumed during meals and snacks. These records followed written and verbal instructions, provided by an investigator at the preparticipation

TABLE 2. Mean (±*SD*) changes of body mass and 2 urinary indices of hydration for men ($n = 42$) and women ($n = 6$), measured at 4 locations.

Variable	Group	Prerace (0 km)	Aid station (52 km)	Aid station (97 km)	Finish (164 km)
Body mass (kg)	Men	85.85 ± 14.79	84.82 ± 14.55	85.77 ± 14.78	85.09 ± 14.47
	Women	67.32 ± 7.21	66.31 ± 7.06	67.48 ± 7.49	67.25 ± 7.48
Body mass change (kg)	Men	0.0	−1.03 ± 0.98	−0.08 ± 1.27	−0.76 ± 1.82
	Women	0.0	−1.00 ± 0.54	+ 0.17 ± 0.79	−0.07 ± 0.94
Urine specific gravity	Men	1.019 ± 0.008	1.016 ± 0.010	1.018 ± 0.010	1.023 ± 0.008*
	Women	1.018 ± 0.001	1.017 ± 0.006	1.022 ± 0.005	1.023 ± 0.004
Urine color	Men	4 ± 2	4 ± 2	5 ± 2†	6 ± 1‡
	Women	4 ± 1	5 ± 1	5 ± 2	6 ± 1

*Significantly greater ($p < 0.001$) than all other time points for men, as determined by analysis of variance.
†Significantly greater ($p < 0.05$) than 0 km for men.
‡Significantly greater ($p < 0.001$) than all other time points for men.

briefing meeting. The cyclists recorded details such as the number, volume, size, brand, manufacturer, and method of preparation; nutrition labels and packages were submitted, when possible. The day −1 diet records were reviewed for completeness by an investigator, in the presence of each cyclist, on the morning of the HHH.

Diet records also were maintained on the event day; these included the morning meal, snacks and all food-fluid items consumed during the event. At 2 aid stations (52 and 97 km) and at the finish line (164 km), an investigator examined diet records for completeness, verified individual items, and reminded cyclists to record all items, which had been consumed.

Dietary records from day −1 and the Event Day were analyzed by selecting individual food items from a commercial data base (Nutritionist Pro™, version 1.2, N-Squared Computing, Salem, OR, USA). Computed outputs included the macronutrients and fluids that appear below.

Data Measurement Sites

On day −1, each participant received written and verbal instructions regarding the procedures and measurements that would occur at 4 data collection points. Measurements were taken at the same 4 locations for all cyclists: at the main medical tent (0 km, before the event), at 2 aid stations on the course (52 and at 97 km), and at the finish line (164 km) within

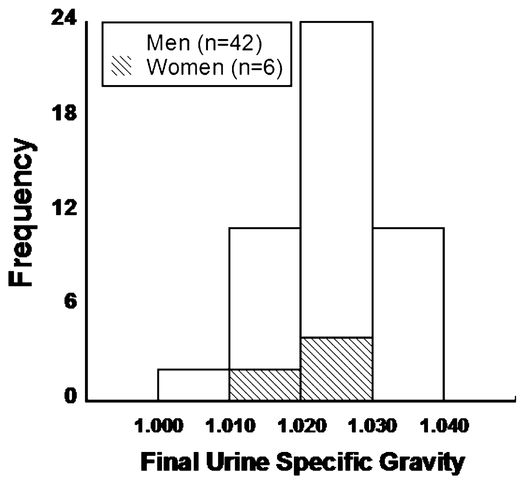

Figure 2. Distribution of urine specific gravity values for men and women, measured at the end of 9.0–9.1 hours of exercise.

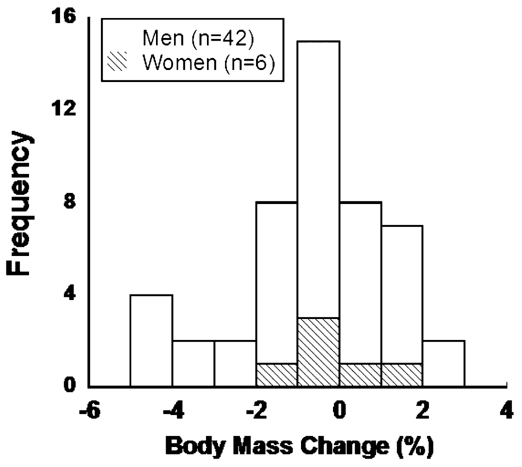

Figure 3. Frequency distribution of percent change of body mass, from preexercise (0 km) to postexercise (164 km).

Table 3. Serum osmolality and electrolytes (mean ± *SD*) measured before and after exercise.

Constituent	Group*	Preexercise (0 km)	Finish (164 km)
Osmolality ($mOsm \cdot kg^{-1}$)	Men	291 ± 4	292 ± 6
	Women	291 ± 3	289 ± 4
Sodium ($mEq \cdot L^{-1}$)	Men	141 ± 1	141 ± 3
	Women	141 ± 1	140 ± 3
Chloride ($mEq \cdot L^{-1}$)	Men	102 ± 2	102 ± 4
	Women	104 ± 1	104 ± 4
Potassium ($mEq \cdot L^{-1}$)	Men	4.1 ± 0.3	4.5 ± 0.5†
	Women	4.4 ± 0.5	5.0 ± 0.5

*Blood was sampled from 33 men and 5 women.

†Significantly greater ($p < 0.001$) than preexercise for men, as determined by Student's *t*-test.

the same medical tent used before the race start. Data sheets and rating scales were identical at all sites.

On the Event Day before the 0700-hour start, the subjects reported to a medical tent near the starting line, located in the center of Wichita Falls, TX. Baseline measurements of body mass and perceptual ratings were recorded. Floor scales (Ohaus, model DS44L, Florham Park, NJ, USA) were calibrated to a tolerance of ±100 g. An investigator verified reception of a signal from the transmitter thermistor that had been swallowed on the previous night, and the initial preexercise T_{GI} was measured. A urine sample was collected and analyzed for urine specific gravity (hand-held refractometer; model 300CL; Atago Co., Tokyo, Japan) and urine color (3). A single blood sample was collected from an antecubital vein, centrifuged, and analyzed in triplicate for osmolality with a freezing point osmometer (Advanced Instruments, Needham Heights, MA, USA, model 3250). An aliquot of blood was frozen for later analysis in triplicate of the serum electrolytes sodium, chloride, and potassium (ion selective electrodes; Medica Corp., Bedford, MA, USA). Both the osmometer and the electrolyte analyzer were calibrated using standard solutions and methods provided by the manufacturer. An investigator then gave the participants a verbal description of the physiological and perceptual measurements that would be taken that day at each data collection site.

At the aid stations (52 and 97 km, located on rural roads surrounding Wichita Falls, TX, USA), heart rate and T_{GI} were recorded for selected cyclists, immediately after exercise. For all the participants, body mass (wearing the same clothing worn at the starting line), urine specific gravity, urine color, and 5 perceptual ratings were measured. Body weight scales at all the locations were newly purchased and manufactured by the same company. All the scales were calibrated before the event, using weights of known mass. Identical refractometers were used at each site; each was

Table 4. Perceptual ratings* (mean ± *SD*) for male ($n = 40$) and female ($n = 6$) cyclists, during the 164-km mass participation event.

Sensation	Group	Preexercise (0 km)	Aid station (52 km)	Aid station (97 km)	Finish (164 km)
Thermal	Men	4.0 ± 0.6	4.7 ± 0.6†	5.2 ± 0.7†‡	5.8 ± 1.0§
	Women	4.1 ± 0.2	4.1 ± 0.2	5.2 ± 0.3	5.5 ± 1.1
Thirst	Men	2.2 ± 1.1	2.9 ± 1.1†	3.6 ± 1.4†‡	5.0 ± 1.7§
	Women	3.8 ± 1.3	3.8 ± 1.7	4.7 ± 1.6	5.8 ± 1.8
Perceived exertion	Men	‖	13 ± 2	14 ± 1‡	15 ± 2§
	Women	‖	12 ± 1	13 ± 2	14 ± 4
Pain	Men	0.1 ± 0.2	0.5 ± 0.8†	1.6 ± 1.1†‡	2.6 ± 1.5§
	Women	0.0 ± 0.0	0.1 ± 0.2	1.5 ± 1.4	1.8 ± 1.9
Muscle cramp	Men	0.0 ± 0.2	0.2 ± 0.4	0.4 ± 0.6†‡	1.2 ± 1.3§
	Women	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.5	0.7 ± 0.8

*Perceptual rating scales are described in the Methods section; the numerical ranges for each measurement appear in the Results section.

†Significantly greater ($p < 0.001$) than 0 km for men, as determined by analysis of variance.

‡Significantly greater ($p < 0.025$–0.001) than 52 km for men.

§Significantly greater ($p < 0.001$) than all other time points for men.

‖Rated only at aid stations and the finish line.

calibrated before the event, using distilled water, per manufacturer instructions.

Cyclists were asked to remember all food and fluid that they consumed during the next event stage, immediately before they mounted bicycles and proceeded toward the next data collection site.

After completing the entire 164-km distance, the cyclists reported to the medical tent near the finish line. The heart rates and T_{GI} of selected subjects were measured immediately after exercise. Blood and urine were sampled and analyzed as described above. All the other physiological and perceptual variables that had been measured previously at the starting line (see above), including diet records, were repeated.

Statistical Analyses

All data are presented as mean ± *SD*. Repeated measure analysis of variance were applied to all variables that were measured at the starting line, the 52-km aid station, the 97-km aid station, and finish line. A *t*-test for paired samples was used to compare Preevent and Postevent means, and day −1 and Event Day means, Although the authors believe that separating the data on the basis of sex is informative and unique, no statistical comparisons of male and female data (across time or between sexes) were performed because of the small number of women who participated.

The number of test subjects varies in the following tables and figures, for the following reasons: The investigators could not locate all the subjects at field measurement sites because thousands of cyclists participated, test subjects chose not to not report certain findings, and test subject attrition.

RESULTS

Environmental conditions on the Event Day were recorded each hour, from 0800 to 1500 hours. The mean (±*SD*) dry bulb temperature was 34.4 ± 5.0° C, ranging from 24.4 (0800 hours) to 39.5° C (1400 hours). The relative humidity was 53 ± 14%; it ranged from 40 (1400 hours) to 83% (0800 hours). The wet blub globe temperature was 30.8 ± 3.5° C and ranged from 22.8 (0800 hours) to 33.6° C (1400 hours). Cloud cover throughout the Event Day was minimal or nonexistent.

Registered entrants included 704 men and women and 96.2% finished the entire 164-km distance. The mean finish time for men and women was similar (Table 1); also, the times to reach the 52- and 97-km aid stations were similar. We estimated that these times included 10 minutes for rest, rehydration, and data collection at each aid station. The average finishing times of men (9.1 hours) and women (9.0 hours) demonstrate that the subjects were not elite competitors, in that the times of the fastest finishers were as follows: men, 93 cyclists finished in <5 hours, 194 cyclists finished between 5 and 6 hours, and 163 cyclists finished between 6 and 7 hours; women, 5 cyclists finished in <5 hours, 10 cyclists finished between 5 and 6 hours, and 24 cyclists

TABLE 5. Calculated energy expenditure and metabolic water production (mean ± *SD*) of men (n = 33) and women (n = 5) on event day.

Cyclists	9-h Energy expenditure (cycling)*		15-h energy expenditure (sleep + activities)†		24-h total energy expenditure‡		9 h (Cycling) metabolic water production (ml)§	24-h total metabolic water production (ml)§
	MJ	kcal	MJ	kcal	MJ	kcal		
Men	12.3 ± 1.8	2,950 ± 436	6.9 ± 1.0	1,652 ± 248	19.2 ± 2.3	4,602 ± 538	349 ± 52	545 ± 64
Women	11.6 ± 0.5	2,764 ± 123	5.6 ± 0.6	1,328 ± 149	17.1 ± 1.1	4,092 ± 266	327 ± 15	485 ± 32

*Column 2 calculations used the overground cycling method of Swain et al. (29). Oxygen consumption was calculated from the ground speed and body mass of each rider and was then converted to energy expenditure (kilocalories = liter per minute × 5) by considering total exercise time of each subject.

†Column 3 calculations used the method of Saris et al. (26). Fifteen hours daily resting energy expenditure = 7-hour sleep (estimated as 0.074 kJ·min^{-1}·kg^{-1}) + 8 hours of other nonexercise activities (estimated as 0.111 kJ·min^{-1}·kg^{-1}).

‡Column 4 = column 2 + column 3.

§Column 5 and 6 calculations involved the method of Hoyt and Honig (17): metabolic water (milliliters) = (0.119 × EE) − 2.25, where EE is energy expenditure.

Table 6. Total energy and fluid intake (mean ± *SD*) of cyclists on day −1 and event day. *

			Day before event (day −1)‡		Event day‡	
Variable	Group†	Units	Mean ± *SD*	Range	Mean ± *SD*	Range
Dietary energy intake	Men	MJ	11.1 ± 3.5	7.2–21.4	2.2 ± 0.9	0.4–4.1
		kcal	2,648 ± 837	581–5,049	521 ± 224	84–967
	Women	MJ	7.8 ± 2.7	5.6–11.4	2.4 ± 1.5	1.0–4.7
		kcal	1,865 ± 639	1,352–2,725	570 ± 347	247–1,123
Dietary energy intake	Men	kJ·kg^{-1}	132.7 ± 46.0	34.6–249.6	26.6 ± 12.0	4.1–52.4
		kcal·kg^{-1}	31.7 ± 11.0	8.3–59.6	6.4 ± 2.9	1.0–12.0
	Women	kJ·kg^{-1}	115.0 ± 34.0	84.2–168.1	35.9 ± 22.3	17.0–69.3
		kcal·kg^{-1}	27.5 ± 8.1	20.1–40.1	8.6 ± 5.3	4.1–16.5
Fluid consumed in all beverages	Men	L	2.17 ± 1.64	0.33–6.03	5.91 ± 2.38	1.89–10.88
	Women	L	1.28 ± 1.53	0.12–4.02	4.68 ± 1.66	2.78–6.83
Fluid consumed in all beverages §	Men	ml·kg^{-1}	25.6 ± 19.2	5.0–78.2	70.6 ± 28.1	22.1–138.0
	Women	ml·kg^{-1}	19.1 ± 22.7	1.9–60.5	71.1 ± 29.6	38.2–117.8

*Consumed in fluids and solid foods.

†Men, $n = 33$; women, $n = 5$.

‡Day −1 occurred on Friday and the event occurred on Saturday; values for day −1 represent 24 hours; Event Day values represent the morning meal plus food intake during the event (~10.5 hours) but include no food after the event; thus, no between-day statistical comparisons were made.

§Fluid varieties appear in Figure 4.

finished between 6 and 7 hours. The range of speeds and finish times were 14.3–22.7 km·h^{-1} and 7.1–11.3 hours for men, and 17.5–18.5 km·h^{-1} and 8.7–9.2 hours for women.

The mean final heart rate for men significantly increased ($p < 0.001$) between the 52-km mark and the finish line (Table 1). The mean (±*SD*) gastrointestinal temperature (Table 1) increased significantly ($p <$ 0.05–0.001) in 12 men to 38.5° C; it increased to 38.1° C in women ($n = 3$). These mean values suggest only mild hyperthermia. However, the frequency distribution of T_{GI} (Figure 1) shows that

Table 7. Consumption of selected macronutrients by men ($n = 33$) and women ($n = 5$) on day −1 and event day.

		Day before event (day −1)†		Event day†	
Macronutrient*	Group	Mean ± *SD*	Range	Mean ± *SD*	Range
Carbohydrate (g)	Men	368 ± 130	116–722	106 ± 48	17–207
	Women	236 ± 112	135–304	116 ± 80	52–243
Carbohydrate (% of total MJ)	Men	56.7 ± 11.4	33.4–79.6	81.6 ± 12.3	47.8–100.0
	Women	49.3 ± 9.5	40.1–64.6	79.1 ± 10.4	61.2–86.5
Protein (g)	Men	93 ± 40	46–167	8 ± 7	0–29
	Women	92 ± 34	64–139	7 ± 3	3–12
Protein (g·kg body mass^{-1})	Men	1.1 ± 0.5	0.4–2.1	0.1 ± 0.1	0.0–0.3
	Women	1.4 ± 0.4	0.9–2.1	0.1 ± 0.1	0.1–0.2
Protein (% of total MJ)	Men	13.8 ± 3.7	8.2–22.7	6.6 ± 4.3	0.4–16.9
	Women	19.6 ± 1.3	17.5–20.6	5.9 ± 3.2	3.3–11.3
Sodium (mg)	Men	4,475 ± 2,072	1,156–11,285	852 ± 531	124–2,352
	Women	3,453 ± 2,134	1,809–6,351	911 ± 562	413–1,940
Potassium (mg)	Men	2,255 ± 1,256	535–5,668	434 ± 221	59–935
	Women	2,292 ± 1,255	1,297–4,774	442 ± 240	149–773

*Consumed in fluids and sold food.

†See footnote ‡ from Table 6.

considerable variability existed and that 3 cyclists experienced a T_{GI} increase of >2.0° C.

Unexpectedly, 5 men reported to investigators, before starting their 164-km ride, with early morning urine specific gravities of 1.030–1.037, indicating frank dehydration. As anticipated, both mean urine specific gravity and mean urine color indicated progressive dehydration during the event (Table 2), but the final (164 km) mean values represented a wide range of hydration categories (4). For example, the frequency distribution of final urine specific gravities (Figure 2) showed that 11 men experienced a final urine specific gravity >1.030, and that 2 finished the event with <1.010. Urine color was strongly and positively correlated with urine specific gravity ($r^2 = 0.86$; $p < 0.0001$), verifying previously published findings (3), and suggesting a simple option for personal hydration assessment.

As noted above, sweat rate was measured on 2 different occasions. Two days before the Event Day (Thursday), a mean sweat rate of 1.41 ± 0.51 $L \cdot h^{-1}$ (41 minutes of exercise) was measured for a group of 10 men. On the Event Day (Saturday), the mean sweat rate was 1.13 ± 0.54 $L \cdot h^{-1}$ for 20 men during the first 52 km (elapsed time, 1.8 hours; mean T_{GI}, 38.14° C) of the event. Our casual observations suggested that exercise intensity on Thursday was uniformly greater than on Event Day and that air temperatures were similar; this likely explained the difference in sweat rate. Although few field measurements of sweat rate have been reported for cyclists who exercise in hot environments, these values are comparable with male sweat rates recorded during summer training sessions for soccer and rowing (28).

Mean data in Table 2 suggest that both men and women maintained body mass well during the 164-km ride. Men lost an average of 0.76 kg (0.9% of body mass), and women lost only 0.07 kg (0.1% of body mass). Because it was logistically impossible to measure the mass of food items (i.e., with cyclists moving independently along a 164-km course), we could not determine the extent to which body mass was offset by solid foods; this is acknowledged as a limitation of body mass data. However, the frequency distribution of body mass change (Figure 3) shows that considerable variability existed, and that 2 men finished the event with a loss of >4.0 kg; this represents a considerable dehydration. Seventeen cyclists gained body mass (0.1–3.0%; Figure 3), but we do not know if this was because of solid food or fluid retention.

Mean serum osmolality and serum concentrations of sodium and chloride (Table 3) were statistically similar, before and after exercise. Serum potassium increased significantly in men ($p < 0.001$) during 9 hours of exercise; this likely was because of the release of intramuscular potassium into the circulation. The range of serum values at the finish line (164 km) for men ($n = 33$) was as follows: osmolality, 280–304 $mOsm \cdot kg^{-1}$; sodium, 134–148 $mEq \cdot L^{-1}$; chloride, 94–109 $mEq \cdot L^{-1}$; and potassium, 3.6–5.5 $mEq \cdot L^{-1}$. These ranges are similar to published clinical norms of a large sample of healthy individuals (18): osmolality, 285–295 $mOsm \cdot kg^{-1}$; sodium, 136–145 $mEq \cdot L^{-1}$; chloride, 98–106 $mEq \cdot L^{-1}$; and potassium, 3.5–5.0 $mEq \cdot L^{-1}$.

Five perceptual ratings, all relevant to endurance exercise, are reported in Table 4. Similar to the physiological responses above, the mean perceptual ratings indicated mild-to-moderate strain. As anticipated, thermal sensations, thirst, perceived exertion, pain, and sensation of muscle cramping increased significantly ($p < 0.025 = 0.001$) from the start (0 km) to the finish (164 km), but the mean values

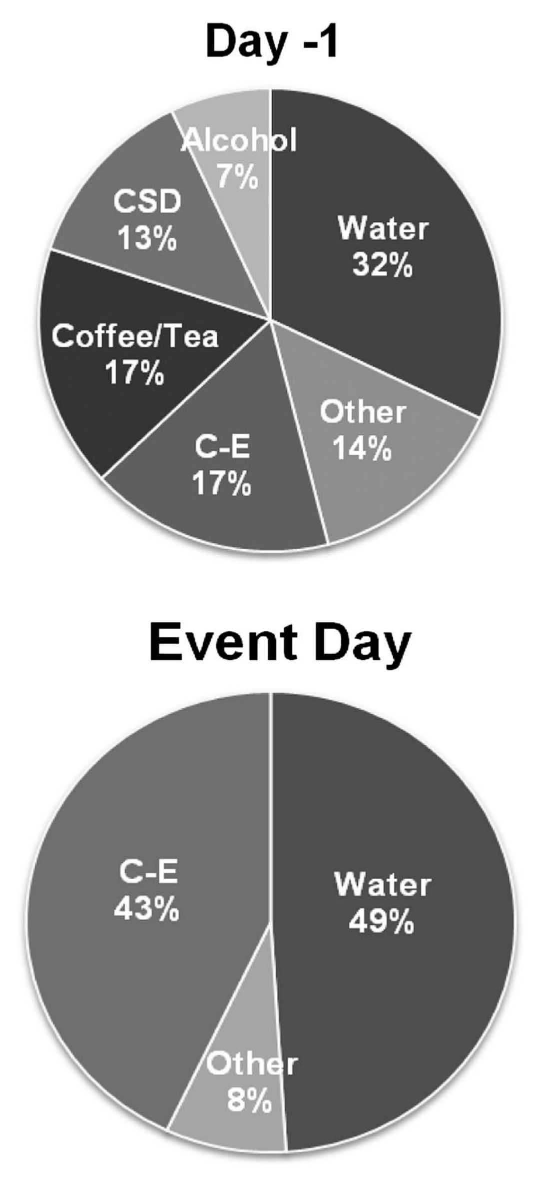

Figure 4. Types of fluids consumed by men ($n = 31$). On day −1, the other category consisted of 5% fruit juice, 3% pickle juice, and 2% milk. On the Event Day, the other category consisted of 6% pickle juice and 1% milk. C–E = carbohydrate-electrolyte replacement fluid; CSD = carbonated soft drink.

demonstrated relatively small changes. The range of perceptual ratings for men at the finish line (164 km) were as follows: thermal, 2.5–7.5; thirst, 1–8; perceived exertion; 12–19; pain, 0–7; and muscle cramp, 0–4.

Table 5 presents energy expenditure values for the Event Day. These calculations involve the 9-hour cycling event, energy expenditure during the remainder of the day (15 hours of sleep + activities), and the sum of these 2 quantities. Based on this total daily energy expenditure (column 4), metabolic water production was calculated as an adjunct to the body mass change data (Table 2) and the fluid consumption data (Table 6).

Tables 6 and 7 present dietary intakes of male and female cyclists, on the day before the event (day -1) and on the Event Day. These values include the total dietary fluid volume, energy (kilocalories), and selected macronutrients. Figure 4 depicts the types of fluids that were consumed by men on day -1 and on the Event Day.

DISCUSSION

This 164-km cycling event, conducted in Texas during the month of August, proved to be challenging for the cyclists because the ambient temperature, with minimal cloud cover, exceeded 39.0° C during the final 2 hours of exercise. This event also proved to be logistically challenging for investigators at distant data measurements sites because (a) it was difficult to identify test participants among thousands of riders and (b) the temporal difference between the first and last test participants was 4.2 hours, a road distance of approximately 61 km. Interestingly, the mean physiological and perceptual responses of women and men were similar, except the variables that were related to body size and energy-metabolic requirements. Although we did not test for significant differences between men and women, because of the small number of women who enrolled ($n = 6$), we include women's data because few previous studies have examined competitive female cyclists (9).

We initially hypothesized that cyclists would not maintain thermal, fluid, and energy balance and that physiological measures would indicate great stress. However, the average completion time was 9.0–9.1 hours, and cyclists maintained an overall ground speed of 17.8–17.9 $\text{km}\cdot\text{h}^{-1}$ (Table 1), the mean values indicated mild-to-moderate thermal and cardiovascular strain. Also interesting are the mean values for body mass change, urine specific gravity, urine color, serum osmolality, and serum electrolytes (Tables 2 and 3), which show that cyclists maintained fluid-electrolyte balance during this event. But there were exceptions. Those who responded at the extremes of the frequency distributions (Figures 1–3) were the cyclists whose homeostasis was perturbed most and who had the greatest risk of exertional heat illness. For example, the 2 greatest T_{GI} values at the finish line were 39.4 and 40.2° C (Figure 1), meaning that 13% (2/15) of the cyclists in this subsample were hyperthermic, at the threshold of exertional heatstroke (2), but had no signs or symptoms of heat illness. Eleven participants exhibited urine specific gravity values $\geq$1.030, indicating frank dehydration (28). In fact, the 6 greatest values for urine specific gravity (range, 1.034–1.038; Figure 2) were extraordinarily high, well outside the 95% confidence limits published previously for young men during daily activities (4). The frequency distribution in Figure 3 also is interesting because it demonstrates that 4 cyclists lost >4% body mass during this event. This level of dehydration is widely recognized as one that degrades endurance exercise performance (28).

Numerous studies have been published regarding renal function after a marathon and crosscountry skiing but, because little is known about the physiological effects or fluid-electrolyte balance during ultraendurance cycling (23), we present the following findings regarding renal function and fluid-electrolyte balance. First, sweat rate on the Event Day was 1.13 ± 0.54 $\text{L}\cdot\text{h}^{-1}$, in a subset of 20 men during the first 52 km. Extrapolating this sweat loss to 164 km, we calculated that the total mean sweat loss was 3.56 L. Second, the male cyclists consumed 5.91 L of fluid during this event (Table 6). Third, because we were unable to measure the mass of consumed solid food, urine volume, and fecal mass, we assumed that the solid food mass gain and the fecal mass loss were approximately equal (0.5 kg) across 9 hours (7) and assumed that respiratory water loss and metabolic water production (0.35 kg; Table 5) were approximately equal (1). Considering a net body mass change of -0.76 kg (Table 2), we then calculated that mean urine excretion during exercise was 3.1 L ($-3.56 + 5.91 - \text{urine} = -0.76$). This rate of urine production ($\sim$300 $\text{ml}\cdot\text{h}^{-1}$) suggests that 9 hours of exercise in the heat of Texas did not pose a threat to renal health, in agreement with the findings of Neumayr et al. (23), who concluded that ultramarathon cycling was "harmless" to the renal function of 16 men who raced across the Alps in 26.4 hours, in ambient temperatures ranging from -1 to 20° C. Yet, although an average of 0.8% of the body mass was lost during the HHH (Table 2), Figure 2 suggests that considerable renal concentrating stress existed in 26% of the male cyclists, in that they experienced a urine specific gravity $\geq$1.030. This phenomenon, resulting from exercise-heat stress, deserves further study.

Although little is known about changes that occur in athlete perceptions during ultraendurance cycling in a hot environment, the ratings in Table 4 provide several insights into nonelite cyclists. As hypothesized, perceptual ratings increased significantly ($p < 0.025$–0.001) from the start (0 km) to the finish (164 km). However, although the mean values indicated only mild-to-moderate strain, the range of values was large for each rating. For example, thermal stress at the finish line ranged from "cool" to "very hot"; thirst, from "not thirsty at all" to "very thirsty"; perceived exertion, from "somewhat hard" to "very, very hard"; and pain intensity, from "no pain at all" to "very strong pain". In combination with cumulative ground speed (Table 1), the perceptual ratings in Table 4 provide a consistent picture of the HHH experience of nonelite cyclists.

That is, as their ground speed declined between aid stations (0–52, 52–97, 97–164 km), they encountered greater pain and muscle cramps; they also felt hotter, thirstier, and more fatigued. Every rider covered the final stage of the course (97–164 km) slower than the previous 2 stages (0–52 and 52–97 km) partly because of an air temperature exceeding 39° C during the final 2 hours of the event.

Observations of professional cyclists during the Tour de France (26) indicated that their average daily energy expenditure exceeded 5,736 $\text{kcal}\cdot24\cdot\text{h}^{-1}$ (24 $\text{MJ}\cdot24\cdot\text{h}^{-1}$). Using methods that were developed by other research teams (17,26,29), Table 5 describes the following components of energy expenditure on the Event Day: cycling (9 hours), sleep + nonexercise daily activities (15 hours), and 24 hours total energy expenditure. The data for 33 men show that 64.1% (2,950/4,602 = 0.641) of energy expenditure on the Event Day was expended during 9 hours of cycling exercise, on the164-km course. The average energy expenditure for men on the Event Day was 328 $\text{kcal}\cdot\text{h}^{-1}$ during 9 hours of cycling, and 110 $\text{kcal}\cdot\text{h}^{-1}$ during 15 hours of nonexercising daily activities; the former was almost 3 times greater than the latter. During the event, the energy expended (at a mean ground speed of 17.9 $\text{km}\cdot\text{h}^{-1}$) was equivalent to 18.3 $\text{kcal}\cdot\text{km}^{-1}$ (29.5 $\text{kcal}\cdot\text{min}^{-1}$). Assuming that these cyclists (Table 5) awoke at 0530 hours and began exercise at 0700 hours (race start time), we calculated that their energy expenditure for all activities was 3,115 kcal (13.0 MJ) up to the race finish at 1600 hours. In comparison, these men consumed only 521 kcal (2.2 MJ) up to 1600 hours (Table 6), in fluids and solid foods. This means that they consumed only 16.7% of the energy they expended (i.e., an energy deficit of 2,594 kcal, 10.9 MJ), supporting the previously described phenomenon of voluntary energy depletion during endurance cycling (7). Brouns et al. (8) provided 2 theoretical explanations for such voluntary energy depletion: (a) the amount of feces produced from a normal diet would require competitors to defecate several times during the day, consequently interrupting exercise; and (b) a large volume of solid food may interfere with fluid intake, which is important on hot days to replace large sweat losses. In a related study (7), they concluded that cyclists may not be able to eat enough food to compensate for the extremely high energy expenditure of ultraendurance competition, even though they are well aware of the importance of adequate energy intake.

Although we have no data to indicate which foods or fluids were consumed after the HHH event (Tables 6 and 7), Brouns et al. (7,8) provide a plausible scenario. They observed the dietary intakes of 13 highly trained males (age, 20 ± 2 years; body mass, 73.3 ± 1.7 kg; height, 180 ± 2 cm) who consumed a diet high in carbohydrates on 2 baselines days. On 2 subsequent days of simulated Tour de France competition (50–90% $\dot{V}O_2$max, intermittent, 6.5 $\text{h}\cdot\text{d}^{-1}$), these cyclists experienced energy deficits of 10 and 8 $\text{MJ}\cdot24\cdot\text{h}^{-1}$. On the single recovery day, which followed these prolonged exercise simulations, investigators measured a mean excess energy intake of approximately 2 $\text{MJ}\cdot24\cdot\text{h}^{-1}$ and concluded that energy intake increased in proportion to the energy deficit.

Carbohydrate intake represents the most striking feature of the macronutrient analysis presented in Table 7. Eighty-four percent of dietary energy on the Event Day (vs. 55.2% on day −1) was consumed in the form of carbohydrates. However, all other macronutrients were considerably underconsumed by men on the Event Day. For example, the large percentage of dietary carbohydrate on the Event Day was consumed at the expense of protein (Table 7). Mean protein consumption between 0530 and 1600 hours was only 0.1 g per kilogram of body mass (8 g total), which was well below the 1.2–1.4 $\text{g}\cdot\text{kg}^{-1}\cdot\text{d}^{-1}$ recommended by Lemon (20) and Tarnopolsky et al. (30) but similar to that of male professional cyclists during the Tour of Spain (167 $\text{km}\cdot\text{d}^{-1}$, 2 mountain stages [15]). Considering that postexercise protein intake has been associated with reduced postexercise muscle soreness (14) and decreased postexercise skeletal muscle damage (27), we recommend that dietitians and sport nutritionists counsel recreational cyclists to consume protein preferentially, after ultraendurance events such as the HHH. Our recommendation is supported by the suggestion that elite competitors have better nutrition knowledge and superior on-course nutritional provisions, than slower recreational cyclists (25).

Two other observations regarding carbohydrates are noteworthy. First, Coyle (12) and the American College of Sports Medicine (28) recommend that cyclists consume 30–60 $\text{g}\cdot\text{h}^{-1}$ carbohydrate during competition, to maintain blood glucose and sustain exercise performance. If cyclists had complied with this recommendation, their carbohydrate intake would have been 270–540 g on the Event Day. The fact that no cyclist consumed this amount of carbohydrate (range of intakes, 17–207 $\text{g}\cdot10.5\cdot\text{h}^{-1}$; Table 7) may explain, in part, why the ground speed decreased during each successive segment (0–52 km, 29.7 ± 4.3 $\text{km}\cdot\text{h}^{-1}$; 52–97 km, 24.1 ± 4.1 $\text{km}\cdot\text{h}^{-1}$; 97–164 km, 12.7 ± 1.8 $\text{km}\cdot\text{h}^{-1}$; mean ± *SD*). Second, only 43% of fluids consumed on the Event Day (Figure 4) were carbohydrate-electrolyte replacement beverages (C–E), and 49% were water. This low C–E intake by cyclists does not follow the widely accepted sport nutrition principles that (a) hypoglycemia influences central fatigue (6), (b) endurance is enhanced by preexercise glycogen levels (19), and (c) exhaustion from hypoglycemia (6) and glycogen depletion (19) can be postponed by carbohydrate feeding during exercise. Also, contrary to these principles, the cyclist who consumed the smallest amount of carbohydrate on the Event Day (17 g in 10.5 hours) crossed the finish line 1 hour ahead of the closest male study participant (range of 41 other men, 17–207 g protein; Table 7). He also consumed little food before and during the event (82 kcal total, 81% carbohydrate), as opposed to day −1 (2,074 kcal, 69% carbohydrate). We interpret this case to mean that carbohydrate intake is only 1 factor that influences exercise performance. This is acknowledged as a limitation of this study and may explain why the statistical correlation between carbohydrate intake (Event Day, $n = 27$) and finish time was weak and nonsignificant, for the 164-km total time ($r^2 = 0.02$; $p = 0.44$) and for the time to complete the final 97 km ($r^2 = 0.02$; $p = 0.49$).

The mean volume of fluid that men consumed on day −1 was 2.17 ± 1.64 $\text{L}\cdot 24\cdot\text{h}^{-1}$ (Table 6), considerably different from that of 10 male professional cyclists (15). The latter consumed only an average of 1.26 L of fluid during 3 days of competition; water, which comprised 82% of their total fluid volume while covering 167 $\text{km}\cdot\text{h}^{-1}$. However, the mean volume of fluid consumed on the Event Day (Table 6; 5.91 ± 2.38 $\text{L}\cdot 10.5\cdot\text{h}^{-1}$) was 2.7 times greater than day −1. This is reasonable, considering the 3.56 L sweat loss (see above) that men experienced during the 164-km ride and explains the maintenance of body mass throughout the HHH (Table 2). The fluid intake of women on the Event Day, expressed per kilogram of body mass, was nearly identical to that of men (71 $\text{ml}\cdot\text{kg}^{-1}$, Table 6). This supports the observations of marathon runners (16) in which 54 women drank virtually the same amount of water as 63 men (22.9 and 22.3 cups, respectively) during a 42.1-km footrace.

It also is important to note that the fluids that men consumed on day −1 (Figure 4) consisted of 8 varieties, whereas C–E and water comprised 92% of the fluids consumed on the Event Day. Figure 4, which shows the ratio of water (49%) to C–E beverages (43%) consumed during the HHH event, stands in contrast to the findings of García-Rovés et al. (15), who reported that 10 elite competitors drank considerably more water (82%) than C–E (18%) during 3 consecutive days of the Tour of Spain. This may be because of the greater consumption of solid foods by elite cyclists. These findings (i.e., regarding relatively large percentages of water) deserve further study, because numerous experiments have reported that blood glucose concentration is lower during water (control) experiments than during C–E trials (6).

In recent years, it has become customary for race directors to provide sodium supplements (i.e., salt capsules) at the aid stations of ultraendurance events (24). This practice is based, in part, on the importance of sodium in the maintenance of extracellular volume, and the relationship between whole-body sodium imbalance, heat exhaustion, and heat cramps (2). Some sport nutrition authorities recommend that athletes who compete in events longer than 6–8 hours should consume sodium at a rate of approximately 1,000 $\text{mg}\cdot\text{h}^{-1}$, in either C–E or foods (10). The data in Table 7 demonstrate that the mean dietary sodium intake of men on the Event Day was low (852 ± 531 mg total), only 19% of day −1. However, despite a total sweat loss of 3.56 L (see above), we have no evidence to indicate that this deficit was detrimental to health or performance. For example, the mean serum sodium level at the finish line (Table 3, 141 ± 3 $\text{mEq}\cdot\text{L}^{-1}$) was well within the normal range. Second, the rating of muscle cramp severity (Table 4) at the finish line was weakly and nonsignificantly correlated with the amount of sodium consumed (Table 7; $r^2 = 0.03$), the total volume of fluid consumed (all varieties; Table 6; $r^2 = 0.02$), and the total volume of water consumed ($r^2 = 0.01$). We interpret these observations to mean that the whole-body sodium imbalance was not great enough to result in clinical signs or symptoms of heat cramps or heat exhaustion (2).

PRACTICAL APPLICATIONS

The participants in this study were considered to be nonelite cyclists, on the basis of their average performance time (9.0 and 9.1 hours) and ground speed (17.9 and 17.8 $\text{km}\cdot\text{h}^{-1}$). We recommend that dietitians, sport nutritionists, and clinicians counsel recreational ultraendurance cyclists to emphasize the following: (a) Unrecognized under consumption of energy occurs. In the present 164-km event, an energy deficit of 2,594 kcal, (10.9 MJ) was measured. Cyclists should consume considerably more energy during the event, to maintain exercise performance (12). (b) Protein is under-consumed on the Event Day. During 2–4 postevent meals, protein should be emphasized by consuming at least 1.2–1.4 g per kilogram of body mass.

Further, we remind clinicians, coaches, and athletes that a minority of cyclists in ultraendurance events experience extreme final values (i.e., urine specific gravity of 1.035–1.038, body mass loss >4 kg, and T_{GI} of 39.4 and 40.2° C). These levels of renal and thermal stress reemphasize the widely recognized principles of (a) maintaining adequate fluid intake to avoid severe dehydration, as guided by multiple observations of urine color or urine specific gravity (4,28); (b) learning and watching for the signs and symptoms of the exertional heat exhaustion and exertional heatstroke (2); and (c) participating with a companion who will share the responsibility of monitoring health and nutrition, during and after the event (2,10).

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