Endurance Running Performance after 48 h of Restricted Fluid and/or Energy Intake

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ABSTRACT

OLIVER, S. J., S. J. LAING, S. WILSON, J. L. BILZON, and N. WALSH. Endurance Running Performance after 48 h of Restricted Fluid and/or Energy Intake. *Med. Sci. Sports Exerc.*, Vol. 39, No. 2, pp. 316–322, 2007. **Purpose:** To determine the effect of a 48-h period of either fluid restriction (FR), energy restriction (ER), or fluid and energy restriction (F + ER) on 30-min treadmill time trial (TT) performance in temperate conditions. **Methods:** Thirteen males participated in four randomized 48-h trials (mean ± SD: age, 21 ± 3 yr; $\dot{V}O_{2max}$ 50.9 ± 4.3 mL·kg^{-1}·min^{-1}). Control (CON) participants received their estimated energy (2903 ± 199 kcal·d^{-1}) and water (3912 ± 500 mL·d^{-1}) requirements. For FR, participants received their energy requirements and 193 ± 50 mL·d^{-1} water to drink, and for ER, participants received their water requirements and 290 ± 20 kcal·d^{-1}. F + ER was a combination of FR and ER. After 48 h, participants performed a 30-min treadmill TT in temperate conditions (19.7 ± 0.6°C). A separate investigation (N = 10) showed the TT to be highly reproducible (CV 1.6%). **Results:** Body mass loss (BML) was 0.6 ± 0.4% (CON), 3.2 ± 0.5% (FR), 3.4 ± 0.3% (ER), and 3.6 ± 0.3% (F + ER). Compared with CON (6295 ± 513 m), less distance was completed on ER (10.3%) and F + ER (15.0%: P < 0.01). Although less distance was completed on FR (2.8%), this was not significantly different from CON. **Conclusions:** These results show a detrimental effect of a 48-h period of ER but no significant effect of FR on 30-min treadmill TT performance in temperate conditions. Therefore, these results do not support the popular contention that modest hypohydration (2–3% BML) significantly impairs endurance performance in temperate conditions. **Key Words:** DIET, DEHYDRATION, TIME TRIAL, REPRODUCIBILITY

Episodes of forced or voluntary fluid restriction (FR) and energy restriction (ER), often lasting for a number of days, frequently occur in occupational and athletic settings (e.g., military recruits on field exercise (5,22), athletes with eating disorders (3) and athletes making weight for competition (7)). It is commonly believed that modest hypohydration equal to 2–3% body mass loss (BML) has a detrimental effect on endurance performance (11,24). However, the research investigating the effects of modest levels of hypohydration on endurance performance in temperate conditions remains equivocal. One widely cited paper reports significant 7% increases in time to complete 5000- and 10,000-m track races when athletes were hypohydrated to approximately 2% BML using the diuretic furosemide (2). Another study shows that a 3% BML evoked by heat exposure decreases work completed on a cycle ergometer by 8% in a 30-min period (10). In contrast, similar BML evoked using a combination of exercise and FR had no significant effect on work completed on a cycle ergometer in a 15-min period (20) or distance completed on a treadmill in a 30-min period (13). The different methods used to evoke hypohydration (process termed "dehydration") and distribution of losses from different fluid compartments may account for the equivocal findings regarding the effects of modest hypohydration on endurance performance (11). In line with this, endurance performance was compromised when hypohydration was evoked by diuretic administration (2) and heat exposure (10) but not when similar BML was achieved using a combination of exercise and FR (13,20). From a practical perspective, an advantage of the latter two studies (13,20) is that a combination of exercise and FR represents the type of dehydration commonly occurring in military personnel and athletes performing in temperate conditions. Unfortunately, all of the aforementioned studies induced hypohydration over a short time period (≤5 h). Therefore, little information is available about the effects of more prolonged dehydration, similar to that encountered in many occupational and athletic settings, on endurance performance.

Time to exhaustion (TTE) at intensities ranging from 50 to 100% $\dot{V}O_{2max}$ is widely reported to decrease after ER lasting 23–36 h (15,19,21,29). However, TTE protocols have been criticized for having poor test–retest reliability with mean CV ranging from 20 to 27% (17,18) compared with mean CV of < 5% for time trial (TT) protocols (17,25). Poor reproducibility in TTE protocols might be explained by psychological factors (e.g., motivation and boredom), which may be more variable in an open versus a known end-point test (17). Variability of this magnitude causes difficulty in identifying the proportion of change in individual performance attributable to the intervention and not to measurement error. Although numerous investigations have examined the effects

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of ER on TTE, the independent and combined effects of fluid and energy restriction (F + ER) on endurance performance assessed using a TT have not been examined. Therefore, the aim of the present study was to examine the independent and combined effects of prolonged (48 h) F + ER on 30-min treadmill TT performance in temperate conditions. We hypothesized that FR or ER would decrease TT performance and that the effects of F + ER would be additive.

METHODS

Participants

Thirteen recreationally active healthy males (mean ± SD: age, 21 ± 3 yr; height, 179 ± 6 cm; body mass, 74.7 ± 7.9 kg; body fat 16.8 ± 5.2%; $\dot{V}O_{2max}$ 50.9 ± 4.3 mL·kg^{-1}·min^{-1}; HR_{max} 199 ± 7 bpm) volunteered to participate in the study. All participants gave written informed consent before the study, which received local ethics committee approval.

Preliminary Measurements

Before the experimental trials, maximal oxygen uptake ($\dot{V}O_{2max}$) was measured by means of a continuous incremental exercise test on a treadmill. Criteria for attaining $\dot{V}O_{2max}$ included the participant reaching volitional exhaustion, an HR within 10 bpm of age-predicted HR_{max}, and a respiratory exchange ratio = 1.15 (4). From the $\dot{V}O_2$–work rate relationship, the work rate equivalent to 50% $\dot{V}O_{2max}$ was estimated and was used for submaximal exercise during the experimental trials. On a separate day, 7–10 d before beginning the experimental trials, participants returned to the laboratory for individual energy expenditure estimation and familiarization. Participants arrived euhydrated at 08:00 h after an overnight fast, having consumed water equal to 40 mL·kg^{-1} of body mass the previous day. On arrival and after voiding, anthropometric measurements of height and nude body mass (NBM) were collected. After these measurements, body composition was estimated using whole-body dual-energy x-ray absorptiometry (DEXA; Hologic, QDR1500, software version V5.72, Bedford, MA), and resting metabolic rate was estimated using a portable breath-by-breath system (Metamax 3B, Biophysik, Leipzig, Germany). After breakfast, participants performed a 1.5-h treadmill walk at 50% $\dot{V}O_{2max}$, during which energy expenditure was estimated (Cortex Metalyser 3B, Biophysik, Leipzig, Germany). For short periods during the day, participants wore the portable breath-by-breath system (Metamax 3B, Biophysik, Leipzig, Germany) to estimate the energy expenditure incurred during habitual living in the laboratory environment. These additional energy expenditure data were used, along with the RMR data, to estimate the energy intake required for the experimental trials. Additionally, during this 24-h period, fluid requirements were estimated by assessing changes in body mass at hourly intervals. Physical activity was standardized throughout the familiarization and all experimental trials by recording 24-h step counts with pedometers (Digi-walker SW-200, Yamax, Tokyo, Japan). Lunch and evening meals were provided between 13:30–14:00 and 17:30–18:00 h, respectively. The following morning, participants performed a 30-min treadmill TT familiarization.

Experimental Trials

Participants were required to complete four experimental trials separated by 7–10 d, in a random order (Table 1). Each experimental trial consisted of a 48-h period of dietary intervention, followed by a 30-min TT and a 6-h recovery period. The four dietary interventions included a control trial (CON), an FR trial, an ER trial, and an F + ER trial.

BASIC SCIENCES

Experimental Procedures

On the day before the experimental trial, to control nutritional and hydration status, participants were provided with their estimated energy requirements (2710 ± 170 kcal·d^{-1}, of which 49, 36, and 15% were carbohydrate, fat and, protein, respectively) and water equal to 40 mL·kg^{-1} of body mass. Participants were also instructed to refrain from exercise. Participants arrived at the laboratory at 22:00 h the evening before beginning each trial (Fig. 1). The intervention began at 08:30 h after participants had voided and an NBM had been obtained. Thereafter, NBM was recorded every 2 h during wakefulness. Euhydration was verified by ensuring that all participants' urine specific gravity was $<$ 1.020 g·mL^{-1}. Participants were seated for 10–15 min, after which a 0-h blood sample was collected without venestasis by venepuncture from an antecubital vein. Further urine and blood samples were collected after 24 h (08:30 h, day 2) and 48 h (08:30 h, day 3).

After breakfast on day 1 and 2, participants performed a 1.5-h treadmill walk at a set workload equivalent to

TABLE 1. Nutrient intake for a 24-h period.

	CON	FR	ER	F + ER
Fluid				
Fluid consumed (mL)	3912 ± 500	960 ± 70	3893 ± 484	962 ± 73
Water to drink (mL)	3145 ± 476	193 ± 50	3816 ± 481	885 ± 70
Water in food (mL)	767 ± 39	767 ± 39	77 ± 4	77 ± 4
Energy				
Energy consumed (kcal)	2903 ± 199	2903 ± 199	290 ± 20	290 ± 20
Carbohydrates (g)	387 ± 28	387 ± 28	39 ± 3	39 ± 3
Fat (g)	119 ± 9	119 ± 9	12 ± 1	12 ± 1
Protein (g)	104 ± 5	104 ± 5	10 ± 1	10 ± 1
Sodium (g)	3.3 ± 0.3	3.3 ± 0.3	0.3 ± 0.0	0.3 ± 0.0

Values are mean ± SD. CON, control; FR, fluid restriction; ER, energy restriction; F + ER, fluid and energy restriction. Macronutrient composition was the same across all trials and was equal to 50, 36, 14% where carbohydrate, fat, and protein, respectively.

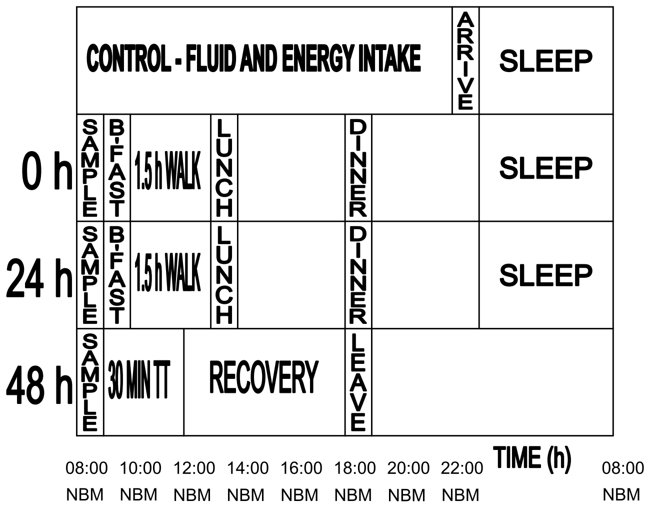

FIGURE 1—Schematic of trial events. NBM, nude body mass.

approximately 50% $\dot{V}O_{2max}$. Core temperature (T_{re}: YSI Model 4000A, Daytona, OH) and heart rate (HR: Polar Electro, Kempele, Finland) were monitored continuously. Water was consumed equal to fluid losses on the CON and ER 1.5-h walks, whereas no fluids were provided during the FR and F + ER 1.5-h walks. After lunch and evening meals, participants also completed a 20-min walk. All walks and TT were performed in an air-conditioned laboratory (19.7 ± 0.6°C, 58.8 ± 7.3% RH). After 48-h urine and blood samples, participants performed a 30-min treadmill TT (09:00–09:30 h).

Before completing the TT, participants performed a 5-min warm-up at 9 km·h^{-1}. Each TT was performed under standardized conditions in a quiet laboratory, with only information about elapsed time provided. Participants were instructed to run as far as possible in 30 min and to control the speed of the treadmill (gradient set at 1%) as and when they felt appropriate. No fluids were consumed throughout the TT. A fan was placed in front of the treadmill during each TT, with the wind speed set at 2.0 m·s^{-1}. During the TT, T_{re}, HR, and ratings of perceived exertion (RPE; (6)) were recorded at 5-min intervals. Heat storage rate (°C·km^{-1}) was estimated by dividing the change in T_{re} by distance covered. Total distance was recorded, and participants were provided with this information on completion of the study. A further urine sample, blood sample, and NBM recording were obtained immediately after TT. Participants then completed a 6-h rehydration and refeeding period before leaving the laboratory.

Reproducibility of the 30-min Treadmill TT

The reproducibility of the TT was determined in a separate investigation. Ten males (age, 22 ± 3 yr; height, 179 ± 9 cm; body mass, 74.2 ± 9.1 kg; $\dot{V}O_{2max}$ 54.8 ± 7.5 mL·kg^{-1}·min^{-1}) performed four TT comprising a familiarization and three further TT evenly spaced across a 2-wk period. Within-subject variation was minimized by testing at a similar time of day. In addition, on the day before each TT, participants refrained from exercise and consumed a similar diet and water equal to 40 mL·kg^{-1} of body mass. To minimize heteroscedasticity, reproducibility was derived from log-transformed final distances (16). Typical error of the measurement, expressed as an absolute value (SEM) and CV, were obtained as described elsewhere (16). Allowing for a familiarization trial, the SEM and CV between trials 1–2 and 2–3 were 106 m and 114 m and 1.5% and 1.6%, respectively. A CV of 3.8% was noted between the familiarization and trial 1, highlighting the importance of allowing participants a single familiarization session. In addition, no order or learning effect was identified, with analysis of variance (ANOVA) revealing no significant differences between trials 1, 2, and 3 ($F_{(2, 18)} = 0.55$, $P = 0.59$). The CV of 1.6% is much smaller than the CV reported for the more traditional TTE protocols and compares favorably with that reported previously in endurance-trained runners for a 1-h TT (CV = 2.7%, (25)).

Analytical Methods

Blood samples were collected into two separate vacutainer tubes (Becton Dickinson, Oxford, UK), one containing K_3EDTA and one containing lithium heparin. Blood in the tube containing K_3EDTA was used to determine hemoglobin concentration in triplicate using a hematology analyzer (Beckman Coulter Gen S, Fullerton, CA). Hematocrit (heparinized blood) was determined in triplicate using the capillary method, and plasma volume changes were estimated (14). The remaining blood in the K_3EDTA tube and the lithium heparin tube were centrifuged (1500*g* for 10 min at 5°C). Plasma was aspirated and then stored at −80°C for further analysis. Plasma concentrations of free fatty acids (FFA: K_3EDTA plasma), glucose, and lactate (heparinized plasma) were determined using spectrophotometric kits (Randox, County Antrim, UK). Urine samples were collected midflow into universal containers, and the remaining urine volume was pooled for 24-h volume determination. Urine specific gravity was measured using a handheld refractometer (Atago Uricon-Ne, NSG Precision Cells, NY).

Statistical Analysis

A one-way repeated-measure ANOVA with *post hoc* Bonferroni corrected *t*-tests was used to determine the effects of dietary restriction on TT performance. In addition,

TABLE 2. The effects of a 48-h period of fluid (FR), energy (ER), or combined fluid and energy (F + ER) restriction and a 30-min treadmill time trial on urine specific gravity (g·mL^{-1}).

	CON	FR	ER	F + ER
0 h	1.015 ± 0.004	1.014 ± 0.002	1.014 ± 0.002	1.015 ± 0.003
24 h	1.015 ± 0.003	1.028 ± 0.002^{a,b,*}	1.015 ± 0.004	1.029 ± 0.003^{a,b,*}
48 h	1.017 ± 0.003	1.030 ± 0.003^{a,b,*}	1.017 ± 0.004	1.032 ± 0.002^{a,b,*}
After time trial	1.021 ± 0.004$^{*,\#}$	1.028 ± 0.002^{a,b,*}	1.023 ± 0.003$^{*,\#}$	1.030 ± 0.6^{a,b,*}

Values are mean ± SD. CON, control; FR, fluid restriction; ER, energy restriction; F + ER, fluid and energy restriction. ^{a} vs CON; ^{b} vs ER; * vs 0 h; $^{\#}$ vs 48 h; $P < 0.01$.

TABLE 3. The effects of a 48-h period of fluid (FR), energy (ER), or combined fluid and energy (F + ER) restriction on 30-min treadmill time trial performance.

Participant	CON	FR	ER	F + ER
1	6351	5770	5366	4903
2	6302	6389	6054	5843
3	7220	6667	6233	5967
4	6245	5990	5252	5002
5	6393	6146	5101	4624
6	6299	6219	5723	4334
7	6843	6733	6661	6202
8	5489	5530	4973	4701
9	6471	5963	5888	5577
10	5968	6205	5300	5277
11	5382	5525	4906	5099
12	6029	5718	5814	5793
13	6842	6538	6124	6089
Mean	6295	6107	5646[a,b]	5339[a,b]
SD	513	405	541	613

Values are distance completed (m). CON, control; FR, fluid restriction; ER, energy restriction; F + ER, fluid and energy restriction. [a] vs CON; [b] vs FR; $P < 0.01$.

the number of participants whose performance on FR, ER, and F + ER decreased or increased by more than 2 SEM versus CON was also recorded. Two-way fully repeated ANOVA were performed on physiological indices, RPE, urine specific gravity, plasma volume change, and metabolite concentrations. Appropriate adjustments to the degrees of freedom were made in cases where the assumptions of sphericity and normality were violated. *Post hoc* Tukey HSD and Bonferroni adjusted *t*-tests were used where appropriate. Significance was accepted at $P < 0.05$.

RESULTS

BML, Urine Specific Gravity, Urine Volume, and Plasma Volume Change

The 48-h period on FR, ER, and F + ER evoked linear BML that was significantly different from CON by 24 h ($P < 0.01$). At 48 h, before beginning the TT, BML was 0.6 ± 0.4% (CON), 3.2 ± 0.5% (FR), 3.4 ± 0.3% (ER), and 3.6 ± 0.3% (F + ER). BML was greater on F + ER than FR at 48 h ($P < 0.01$). Urine specific gravity remained unchanged on CON and ER during the 48-h period (Table 2). In contrast, urine specific gravity increased on FR and F + ER, reaching a plateau by 24 h ($P < 0.01$). Compared with 48 h, urine specific gravity increased after the TT on CON and ER only ($P < 0.01$). Urine volume was lower on FR and F + ER (1597 ± 174 and 1196 ± 141 mL) and higher on ER (6457 ± 747 mL) compared with CON (4804 ± 77 mL, $P < 0.01$) during the 48-h period. At 48 h, plasma volume was unaltered on CON and FR (−1.4 ± 5.7 and −0.9 ± 4.9%, $P > 0.05$) and decreased on ER and F + ER (−5.2 ± 3.2 and −5.1 ± 4.5%, $P < 0.05$). Compared with 48 h, plasma volume decreased as a result of the TT, although this only reached significance on FR (CON: −5.8 ± 3.9; FR: −6.3 ± 3.5 ($P < 0.05$); ER: −4.9 ± 4.6; F + ER: −4.8 ± 3.7%).

TT Performance

There was a significant difference for distance completed, with less distance covered on ER and F + ER compared with CON and FR ($F_{(3, 36)} = 29.7$, $P < 0.01$; Table 3). Although less distance was covered on FR compared with CON and on F + ER compared with ER, these differences were not significant. The mean percentage change in distance completed compared with CON was larger on ER (−10.3%; 95 CI, −7.2 to −13.4%) and F + ER (−15.0%; 95 CI, −10.0 to −20.1%) than on FR (−2.8%; 95 CI, −0.3 to −5.3%). The addition of 95% confidence limits to the mean identifies the likely range of the true differences between the restrictions and CON. Individual assessment revealed that all 13 participants on ER and F + ER completed less distance compared with CON. Additionally, compared with CON, the differences were greater than 2 SEM in 11 of 13 participants on ER and in all 13 participants on F + ER. On FR, 9 of 13 participants covered less distance compared with CON. The decrease in distance completed on FR compared with CON was greater than 2 SEM in only 7 of 13 participants.

Thermoregulatory and Cardiovascular Responses to the TT

T_{re}, HR, and RPE increased throughout the TT (main effect of time, $P < 0.05$). There was a significant interaction ($F_{(3, 24)} = 15.3$, $P < 0.01$), where higher peak T_{re} found on FR compared with CON, and lower peak T_{re} found on F + ER compared with CON ($P < 0.05$; Table 4). Peak T_{re} for ER and F + ER was also significantly lower than FR ($P < 0.05$). Heat storage was significantly greater on FR (0.37°C·km^{-1}) compared with CON, ER, and F + ER (0.32°C·km^{-1}; $F_{(3, 24)} = 5.4$, $P < 0.01$). HR and RPE were not different between the four trials. NBM change (sweat loss) during the TT was greater for CON compared with FR, ER, and F + ER ($F_{(3, 36)} = 8.6$, $P < 0.01$).

Plasma FFA, Glucose, and Lactate Responses

Plasma FFA concentration increased on ER trials by 24 h (ER and F + ER: $P > 0.05$: Table 5) and was significantly greater than CON and FR from this point onwards ($P < 0.05$). Plasma FFA concentration did not alter significantly during the 48 h on CON and FR. Plasma glucose concentration decreased on ER by 24 h and F + ER by 48 h ($P < 0.05$) and was significantly lower than CON from

TABLE 4. Final exercising T_{re}, HR, RPE, and nude body-mass change (NBMΔ) after a 30-min treadmill time trial after a 48-h period of fluid (FR), energy (ER), or combined fluid and energy (F + ER) restriction.

	CON	FR	ER	F + ER
T_{re} (°C)	39.10 ± 0.26	39.33 ± 0.35[a]	38.91 ± 0.36[b]	38.84 ± 0.25[a,b]
HR (bpm)	194 ± 9	197 ± 7	192 ± 12	191 ± 14
RPE	18.6 ± 0.8	18.8 ± 1.0	18.4 ± 1.0	18.4 ± 0.9
NBMΔ (%)	1.2 ± 0.3	0.9 ± 0.3[a]	0.9 ± 0.2[a]	0.8 ± 0.1[a]

Values are mean ± SD. RPE, rating of perceived exertion; CON, control. [a] vs CON; [b] vs FR; $P < 0.05$.

TABLE 5. The effects of a 48-h period of fluid (FR), energy (ER), or combined fluid and energy (F + ER) restriction and a 30-min treadmill time trial on plasma free fatty acid (FFA), glucose, and lactate concentration.

	CON	FR	ER	F + ER
FFA (mmol·L^{-1})				
0 h	0.4 ± 0.1	0.4 ± 0.2	0.3 ± 0.2	0.4 ± 0.2
24 h	0.6 ± 0.2	0.5 ± 0.1	1.6 ± 0.7^{a,b,*}	1.7 ± 0.5^{a,b,*}
48 h	0.6 ± 0.2	0.6 ± 0.2	1.8 ± 0.6^{a,b,*}	2.0 ± 0.7^{a,b,*}
After time trial	1.1 ± 0.3$^{*,\#}$	1.1 ± 0.3$^{*,\#}$	2.2 ± 0.4^{a,b,*}	2.4 ± 0.6^{a,b,*}
Glucose (mmol·L^{-1})				
0 h	5.1 ± 0.6	5.0 ± 0.6	5.3 ± 0.5	5.1 ± 0.8
24 h	5.3 ± 0.6	5.4 ± 0.6	4.4 ± 0.7^{b,*}	4.4 ± 0.8^{b}
48 h	5.4 ± 0.6	5.5 ± 0.8	4.2 ± 0.8^{a,b,*}	4.1 ± 0.6^{a,b,*}
After time trial	8.2 ± 2.3$^{*,\#}$	7.9 ± 1.7$^{*,\#}$	4.5 ± 1.1^{a,b,*}	4.4 ± 0.8^{a,b,*}
Lactate (mmol·L^{-1})				
0 h	1.0 ± 0.4	1.1 ± 0.4	1.1 ± 0.3	1.0 ± 0.4
24 h	1.1 ± 0.5	0.9 ± 0.4	1.2 ± 0.4	1.3 ± 0.6
48 h	1.2 ± 0.3	1.2 ± 0.5	1.3 ± 0.3	1.4 ± 0.4
After time trial	10.3 ± 2.7$^{*,\#}$	9.2 ± 2.8$^{*,\#}$	8.4 ± 2.6$^{a,*,\#}$	7.4 ± 2.3$^{a,b,*,\#}$

Values are mean ± SD. CON, control. ^{a} vs CON; ^{b} vs FR; * vs 0 h; $^{\#}$ vs 48 h; $P < 0.05$.

this point onwards on ER and F + ER ($P < 0.05$). Plasma glucose concentration did not alter significantly during the 48 h on CON and FR. Plasma lactate concentration did not alter significantly during the 48-h intervention on any trial. Plasma FFA, glucose, and lactate concentration increased after the TT compared with 0 h on all trials ($P < 0.05$). The TT evoked increases in plasma FFA and glucose concentration compared with 48 h on CON and FR ($P < 0.05$). Compared with 48 h, plasma FFA and glucose concentration did not alter significantly after the TT on ER and F + ER. The TT evoked increases in plasma lactate concentration compared with 48 h on all trials ($P < 0.05$), although plasma lactate was significantly lower on ER trials (ER and F + ER) at this time ($P < 0.05$).

DISCUSSION

These results show a detrimental effect of a 48-h period of ER (~2600 kcal deficit each day), but no significant effect of FR alone (~2.9 L fluid deficit each day) on 30-min treadmill TT performance in temperate conditions. In addition, TT performance was similar after a 48-h period of ER and after F + ER. Thus, these results do not support the popular contention that modest hypohydration (2–3% BML) significantly decreases endurance performance in temperate conditions.

To our knowledge, this is the first study to investigate the effects of a prolonged period of FR on endurance performance. The 48-h period of FR in this study evoked similar BML (3.2%) to heat exposure (3%) (10) and larger BML than the diuretic furosemide (~2%) (2) in studies reporting an approximately 8% decrease in endurance performance after acute dehydration (≤5 h). However, prolonged FR in this study did not significantly effect endurance performance (−2.8% vs CON). The findings of the present study do agree with others showing no significant decrease in TT performance when approximately 2% BML was evoked by a combination of acute exercise and FR lasting less than 2 h (13,20). The contradictory findings may be attributable to the different methods of dehydration (e.g., diuretics, exercise, and sauna) (11) or duration of dehydration (acute vs prolonged) used in studies: it is conceivable that these factors might alter the distribution of fluid losses from different fluid compartments. For example, during an incremental cycle test to exhaustion (albeit lasting only 10–12 min), peak power output was better preserved when approximately 4% BML was evoked by exercise with F + ER (−7 W) than when approximately 4% BML was evoked by diuretic (−21 W) or sauna exposure (−23 W) (8). Impaired endurance performance after a period of dehydration is commonly attributed to a combination of increased cardiovascular and thermoregulatory strain (11,24). Typically, dehydration lowers blood volume (hypovolemia), which subsequently causes a reduction in cardiac output via reduced stroke volume (24). In addition, hypovolemia may decrease heat dissipation via reduced cutaneous blood flow (dry heat loss) and possibly also via reduced sweat rates (evaporative heat loss), which may further contribute to impaired exercise performance (24). In line with this, exercise performance (5000- and 10,000-m track race) decreased when sizeable reductions in plasma volume (10–12%) occurred after diuretic treatment 5 h before exercise (2) but was better maintained when plasma volume did not alter significantly (<1%) after similar BML was evoked using a combination of exercise with F + ER for a 48-h period (8). The present results and those previously (8) indicate that, in contrast with acute dehydration (≤5 h), a more prolonged period of dehydration (48 h) evoked by bouts of exercise and restricted water intake does not cause hypovolemia: this is possibly because the longer time period allows for equilibration of fluids across body water compartments. However, this contention should be verified using tracer techniques (e.g., Evans blue dye dilution) to measure blood volume as opposed to estimating changes using hemoglobin and hematocrit. Nevertheless, we might tentatively suggest that unaltered plasma volume (<1%) may account for the lack of a significant effect of hypohydration on endurance performance in the present study.

Using diuretics or heat exposure to evoke similar BML to the present study impairs exercise performance (2,8) and possibly raises the risk of heat illness (9,12). Although we did not observe a significant decrease in 30-min TT performance on the FR trial, the raised core temperature

(+0.2°C vs CON) may increase the likelihood of impaired performance and heat illness (9) when performing more prolonged exercise and/or performing in the heat: as is often the case in athletic and occupational settings. The lower sweat rate during exercise after FR (and similar work rate to CON) presumably accounts for the increased final exercising core temperature compared with CON (26). The mechanism(s) responsible for reduced exercising sweat rate during hypohydration include a possible role for hypovolemia and a more likely role for hypertonicity: the latter via osmosensitive neurons in the hypothalamus or a possible effect of high interstitial osmotic pressure inhibiting fluid availability to the sweat glands (24). These results and others (8) showing no change in plasma volume (albeit estimated) during prolonged dehydration, alongside a reported increase in serum osmolality during prolonged FR (27), support a more likely role for hypertonicity in the reduced exercising sweat rate after prolonged dehydration.

ER equal to approximately 2600 $kcal \cdot d^{-1}$ for more than 24 h caused a significant increase in plasma FFA and decrease in plasma glucose similar to those reported during a 36-h fast, where TTE at 70% $\dot{V}O_{2max}$ decreased by 36% (19). Indeed, TTE at intensities ranging from 50 to 100% $\dot{V}O_{2max}$ is widely reported to decrease after ER lasting 23–36 h (15,19,21,29). Somewhat surprisingly, conflicting evidence exists about the most likely causes of decreased TTE with short-term ER: these include a possible role for liver and muscle glycogen depletion, altered acid–base balance, central fatigue, and a possible placebo effect (1,15,19,29). To our knowledge, this is the first investigation to assess the effects of a 48-h period of ER on endurance performance using a TT. The 10% decrease in endurance performance during the ER trial in the present study is relatively modest compared with the 36% (19) and 44% (21) decreases in TTE in studies using similar energy deficits and shorter restrictions (27–36 h). The larger decrement in endurance in previous ER studies may be attributable to the lower intensity and longer duration of exercise used in the TTE protocols (mean TTE ranged 77–160 min) of those studies. The relatively modest effect of ER on work rate is reflected in lowered final exercising HR and T_{re}, although these responses were not significantly different from CON. Nevertheless, these results highlight the importance of adequate energy intake and the potential for impaired endurance performance in athletes and military personnel during relatively short periods of ER (e.g., during weight cutting and military operations).

These results also show that athletes who choose to ignore the American College of Sports Medicine's advice (23) and practice weight cutting by restricting both fluids and energy simultaneously maybe be mistaken in thinking that they will evoke much larger BML than through fluid restriction alone. Although significant, BML was only, on average, 0.4% greater after restricting fluids and energy simultaneously (mean BML: 3.6%) compared with restricting fluids alone (mean BML: 3.2%). This is particularly important when considering that endurance performance was impaired after the ER trials but not after the FR trial. We might logically have expected BML after F + ER to be the sum of BML after FR alone and ER alone. However, when FR and ER were combined (fluid intake: 0.9 $L \cdot d^{-1}$ on F + ER vs 3.9 $L \cdot d^{-1}$ on ER), we did not observe the large BML component, due to urine output that was evident on the ER trial (48-h urine volume: 1.2 L on F + ER and 6.4 L on ER). This provides an explanation for why BML after F + ER (3.6%) was not the sum of BML after FR (3.2%) plus the BML associated with the large urine output during ER (3.4%). Increased urinary sodium excretion during ER (28) and the restricted dietary sodium intake (Table 1) may account for the increased urine output during the ER trial (vs CON).

In conclusion, these results show a detrimental effect of a 48-h period of ER (~2600 kcal deficit each day) but no significant effect of FR alone (~2.9 L fluid deficit each day) on 30-min treadmill TT performance in temperate conditions. In addition, TT performance was similar after a 48-h period of ER and after F + ER. Therefore, these results do not support the popular contention that modest hypohydration (2–3% BML) significantly decreases endurance performance in temperate conditions.

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