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original research

Influence of Hydration on Physiological Function and Performance During Trail Running in the Heat

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Context: Authors of most field studies have not observed decrements in physiologic function and performance with increases in dehydration, although authors of well-controlled laboratory studies have consistently reported this relationship. Investigators in these field studies did not control exercise intensity, a known modulator of body core temperature.

Objective: To directly examine the effect of moderate water deficit on the physiologic responses to various exercise intensities in a warm outdoor setting.

Design: Semirandomized, crossover design.

Setting: Field setting.

Patients or Other Participants: Seventeen distance runners (9 men, 8 women; age = 27 ± 7 years, height = 171 ± 9 cm, mass = 64.2 ± 9.0 kg, body fat = 14.6% ± 5.5%).

Intervention(s): Participants completed four 12-km runs (consisting of three 4-km loops) in the heat (average wet bulb globe temperature = 26.5°C): (1) a hydrated, race trial (HYR), (2) a dehydrated, race trial (DYR), (3) a hydrated, submaximal trial (HYS), and (4) a dehydrated, submaximal trial (DYS).

Main Outcome Measure(s): For DYR and DYS trials, dehydration was measured by body mass loss. In the submaximal trials, participants ran at a moderate pace that was matched by having them speed up or slow down based on pace feedback provided by researchers. Intestinal temperature was recorded using ingestible thermistors, and participants wore heart rate monitors to measure heart rate.

Results: Body mass loss in relation to a 3-day baseline was greater for the DYR (−4.30% ± 1.25%) and DYS trials (−4.59% ± 1.32%) than for the HYR (−2.05% ± 1.09%) and HYS (−2.0% ± 1.24%) trials postrun ($P < .001$). Participants ran faster for the HYR (53.15 ± 6.05 minutes) than for the DYR (55.7 ± 7.45 minutes; $P < .01$), but speed was similar for HYS (59.57 ± 5.31 minutes) and DYS (59.44 ± 5.44 minutes; $P > .05$). Intestinal temperature immediately postrun was greater for DYR than for HYR ($P < .05$), the only significant difference. Intestinal temperature was greater for DYS than for HYS postloop 2, postrun, and at 10 and 20 minutes postrun (all: $P < .001$). Intestinal temperature and heart rate were 0.22°C and 6 beats/min higher, respectively, for every additional 1% body mass loss during the DYS trial compared with the HYS trial.

Conclusions: A small decrement in hydration status impaired physiologic function and performance while trail running in the heat.

Key Words: environmental physiology, dehydration, rehydration, core temperature, heart rate

Key Points

- The physiologic and performance decrements associated with dehydration that exist in laboratory settings also exist in field settings.
- Methodologic challenges in the field setting make isolating these effects difficult.

In laboratory settings, when athletes perform intense aerobic exercise in the heat and become hypohydrated to a level of 2% body mass loss or greater, or when they start to exercise at this level, physiologic strain increases predictably and performance decreases.[1–4] For example, during exercise in the heat, core body temperature and heart rate (HR) increase by 0.12°C to 0.25°C and 3 to 5 beats/min, respectively, for every 1% of body mass lost.[1–4] This graded core temperature increase with increasing water deficit indicates that physiologic adjustments are both necessary and effective for maintaining heat loss when sweat rate and skin blood flow are reduced. Dehydration reduces the overall water volume in the body, resulting in a reduction in central blood volume and, therefore, skin blood flow.[1] Dehydration initiates a cascade of events in which blood volume decreases, causing a compensatory increase in HR, followed by a decrease in stroke volume due to the increased heart rate and decreased filling time for the heart.[5] Evidence for greater physiologic strain and resultant compromised performance includes increased HR, decreased stroke volume, thermoregulatory strain (or the physiologic response to excessive heat production and storage in the absence of heat dissipation), stress response, perception of effort and anticipatory regulation of pace, hypovolemia, hyperosmolality, and a decrease in percentage of total work completed, among other factors.[1,6–12]

Because exercise intensity is the single greatest influence on the rate of core temperature rise in the heat,[13–15] authors of many of these laboratory studies control intensity. Also regulated in well-controlled studies are other variables that could compromise consistency among trials, including ambient temperature, humidity, length of exercise, time of day, nutritional intake, clothing, airflow, and heat acclimatization status. Only when these variables are controlled can the influence of hydration status be isolated.[16]

In recent field studies, investigators have examined the influence of hydration status on numerous physiologic and performance outcomes, notably core body temperature and finishing time. Many of these researchers[17–21] reported findings inconsistent with previous laboratory studies, in that body temperature did not increase with dehydration. Moreover, other performance outcomes were not related to hydration status, and in some cases, greater dehydration was associated with better performance.[21,22]

A plausible cause of these different findings is variable intensity of exercise in field studies, rather than a lack of research quality or the inability to control or monitor exercise intensity. Athletes who are allowed to perform an exercise task unsupervised may manipulate intensity based on physiologic and psychological feedback. Thus, a dehydrated person may actually have a lower body core temperature because intensity has decreased.[23] Similarly, a euhydrated person can perform at a higher intensity for a longer period of time and, ironically, may have a higher body core temperature than a dehydrated counterpart.[14] Both scenarios are possible in a field setting when intensity is not controlled. Therefore, the premise that certain physiologic responses (eg, body core temperature) are not influenced by hydration status may, in fact, reflect uncontrolled intensity and not hydration status itself. Comparing field and laboratory findings has been made even more difficult by other methodologic considerations, such as the lack of crossover, within-subjects comparisons, and uncontrolled weather conditions (eg, temperature, humidity, sun, wind). Given that a lack of controlled intensity is the only consistent factor permeating all the field studies in which hydration did not contribute to physiologic strain, we felt this was a worthy factor to examine further in the field setting.

The purpose of our study was to determine the role of hydration status with regard to physiologic function and performance in a field setting, using both controlled and uncontrolled exercise intensities. We controlled absolute intensity (ie, finishing time) in 2 submaximal trials by providing verbal feedback to the volunteers. We hypothesized that when finishing time was consistent, physiologic responses would be due to differences in hydration status, similar to those previously noted in laboratory studies. When intensity was not consistent, as in a race, we expected to observe performance decrements, but not necessarily more exaggerated physiologic responses, when athletes were more dehydrated.

METHODS

Participants

Seventeen heat-acclimatized, experienced, well-trained runners volunteered (race trials: 9 men, 8 women; submaximal trials: 10 men, 7 women). We excluded participants for any of the following: chronic health problems; a history of cardiovascular, metabolic, or respiratory disease; fever or other current illness; age outside the range of 18 to 59 years; a condition that could cause complications from ingesting the Cor-Temp disposable temperature sensor (HQ, Inc, Palmetto, FL); a history of exertional heat stroke or heat exhaustion within the last 3 years; a musculoskeletal injury during the time of the running trials; and any woman who was pregnant, attempting to become pregnant, or thought she might be pregnant. We also excluded individuals whose exercise or physical activity consisted of less than 30 minutes per day, 4 times per week, at a moderate intensity for the past 3 months. Participants completed a running history questionnaire and a medical history questionnaire before enrolling in the study. Some level of heat acclimatization was assumed based on the running history questionnaire, which indicated that the participants were regularly engaged in training sessions outside in warm temperatures in the weeks leading up to data collection. The data collection took place in the middle of June. All participants read and signed a written informed consent form. This study was approved by the university's institutional review board.

Testing Protocol

Volunteers reported to a nearby state park for familiarization and baseline measurements. To familiarize themselves with the 4-km course, participants completed 2 practice runs on the course, 2 to 4 weeks before the first trial. The 4-km course consisted of 75% single-track trails typical of New England trails (occasional rocks, roots, ruts, turns, and low branches). Twenty-five percent of the course was run on a hard-packed dirt road. The course had many rolling hills and 1 brief (less than 1-minute) but steep hill climb. To gauge an individual's running ability, we instructed him or her that one of the familiarization runs must consist of running 1 loop (4 km) hard. This timed practice run was used to group participants into 3 groups of 4 and 1 group of 5 runners with similar abilities. This was done so that monetary incentives for race times (combined time for the 2 races) would be partitioned out based on performance compared with runners of similar ability. The experimental trials consisted of completing four 12-km timed trail runs on 4 separate days, as described below:

Race Trials

A. Twelve-kilometer race, beginning hydrated and receiving fluid during the race (hydrated race = HYR)
B. Twelve-kilometer race, beginning hypohydrated and not receiving fluid during the race (dehydrated race = DYR)

Submaximal Trials

A. Twelve-kilometer, submaximal run, beginning hydrated and receiving fluid during the run (hydrated submaximal = HYS)
B. Twelve-kilometer, submaximal run, beginning hypohydrated and not receiving fluid during the run (dehydrated submaximal = DYS)

Water (400 mL) was provided at the end of the first (4 km) and second loops (8 km) for the 2 hydrated trials. Data collection always preceded fluid replacement for these trials. The 4 trials took place across a 14-day period. Days 1 and 14 were ''all-out'' races (HYR and DYR). Days 4 and 7 were submaximal runs (HYS and DYS). All participants were randomly assigned to either a hydrated or a hypohydrated protocol for each trial; approximately half were randomly assigned to HYR and the others to DYR. They then followed the opposite hydration protocol for the second race. The submaximal trial followed the same procedure. All volunteers received a calibrated scale (model BWB-800 A; Tanita Corporation, Tokyo, Japan) to record body mass measurements for 17 consecutive days. They took their own nude body mass measures each morning for the 3 days before the first trial, which served as a baseline weight, and every day until the last trial. For the submaximal effort, we explained to the participants that we wanted them to run a pace they considered ''moderate'' effort. They knew this would be at an intensity that was not maximal and something they could match again a few days later in the other submaximal trial. We informed participants that the key component of the submaximal trials was an attempt to match finishing time for both trials.

The day before each trial, all individuals were randomly assigned to either the hydrated or hypohydrated group and were informed of their assignment. Those in the hypohydrated groups (DYR and DYS) were instructed to start fluid restriction 22 hours before their individual start times (start times were approximately 1:00 PM). Those in the hydrated groups (HYR and HYS) were allowed to consume fluids ad libitum. All participants performed a typical easy training run (60-minute run or 90 minutes of jogging and walking/hiking) after 3:00 PM the day before the trial. All consumed the same dinner the night before each trial and the same breakfast and snack each morning of the 4 testing days. They ingested an ingestible thermistor before breakfast, which was 5 hours, on average, before testing began. Those in the hypohydrated groups (DYR and DYS) drank 200 mL of water when consuming the ingestible thermistor.

Before the start of each trial, participants completed the Profile of Mood States (POMS) questionnaire[24] and a 56-question Environmental Symptoms Questionnaire (ESQ)[25] while sitting in the shade. We then took the following baseline measurements: body mass, body temperature (T_{GI}), HR, rating of perceived exertion (RPE), urine color, urine specific gravity (U_{SG}), urine osmolality (U_{osm}), perceived thirst,[26] and perceived thermal sensations.[27] After baseline measurements, volunteers began trail runs individually, with 4-minute intervals separating start times. Each participant's start time was consistent for the first 3 trials. Start times for the fourth trial were advanced by 1 hour because of predicted higher temperatures for the day; however, the separations between start times remained the same. After running 4 km and 8 km (loops 1 and 2), participants had a mandatory 4-minute break, during which T_{GI}, HR, RPE, perceived thirst, and perceived thermal sensations were measured. To replicate the pace performed during the first submaximal trial on the second submaximal trial, we provided feedback at 4 evenly spaced points (every 1 km) along each loop. If at any point during a trial an individual needed to urinate, urine was collected in a jug, measured, and calculated into the participant's body mass loss and sweat rate. At the conclusion of each trial, immediate postrun measurements consisted of body mass, T_{GI}, HR, perceived thirst, perceived thermal sensation, and blood lactate. Ten minutes after the run, HR and T_{GI} were measured and the POMS and ESQ were completed. Twenty minutes after the run, T_{GI}, HR, perceived thirst, and perceived thermal sensation were measured. Participants in the hypohydrated trials remained on site until they were rehydrated to within 2% of baseline body mass measures. All volunteers received monetary compensation for their participation, and a portion of the payment was an incentive based on performance, as noted above.

Instrumentation

The wet bulb globe temperature was measured every 20 minutes. The value for each individual's trial was calculated using the wet bulb globe temperature measured during that time. The average value for each person's trial was then compared with other trials to identify differences.

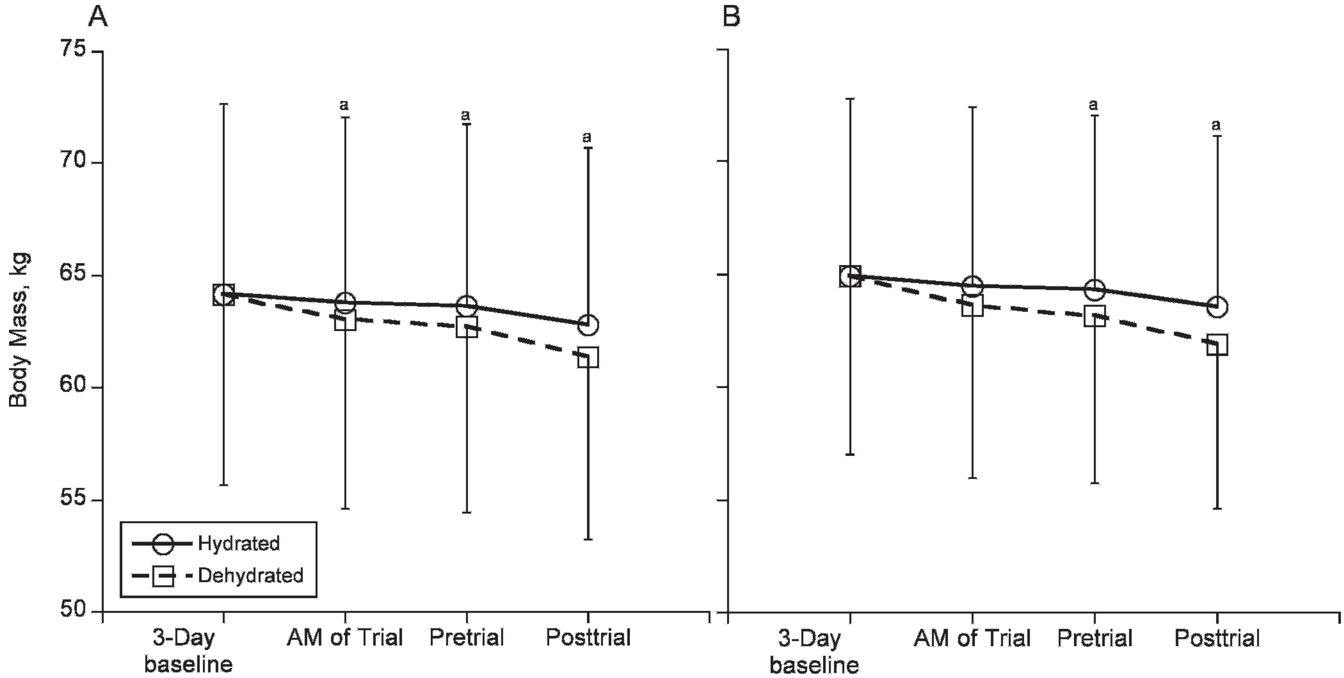
Each participant's percentage of body fat was calculated using 3-site skin-fold measurements (following rehydration after the last trial).[28] Duplicate measures (U_{osm}, blood lactate) were averaged. Percentage of dehydration at each time point was calculated by subtracting weight from the 3-day average baseline weight and dividing by the 3-day baseline and multiplying by 100. Sweat rate was calculated by the following formula: [(pretest body mass − posttest body mass) + fluid consumed − urine output]/time. The HR was measured using monitors (model E40; Polar Electro, Lake Success, NY). Urine color was determined by a urine color chart.[29] Urine osmolality was determined via freezing-point depression using an osmometer (model 3DII; Advanced Instruments, Inc, Needham Heights, MA). Blood lactate was measured using a lancet device (Accu-Chek Softclix, F. Hoffmann-LaRoche Ltd, Basel, Switzerland) and a portable lactate analyzer (Accutrend Lactate, Sports Resource Group, Inc, Hawthorne, NY).

Profile of Mood States scores were calculated by entering participants' responses into an electronic POMS scoring system (version 6.6; Education and Industrial Testing Service, Massachusetts Institute of Technology, Cambridge, MA). Changes in POMS scores were calculated by subtracting the pretest value from the posttest value.

Statistical Analysis

Montain and Coyle[1] demonstrated an increase of 0.15°C for every additional 1% level of dehydration. Based on our prediction of a 4% difference in dehydration at the end of the race, the difference would be about 0.6°C. According to our experience in previous studies, predicted mean core temperatures of 38.6°C and 39.2°C, with an α level of .05 and a power of 0.8, would require a minimum sample size of 16.

Race and submaximal trials were analyzed as separate data sets. A 2-way, repeated-measures analysis of variance (hydration status × time) was used to test for differences between trials and across time. Greenhouse-Geisser corrections were conducted when the assumption of sphericity was violated. We used a Bonferroni correction with post hoc *t* tests to determine pairwise differences in the event of



Race Trial	Pretrial	Posttrial	Δ (Posttrial-pretrial)	Submaximal Trial	Pretrial	Posttrial	Δ (Posttrial-pretrial)
Hydrated	-0.79 ± 0.95%	-2.05 ± 1.09%	-1.26 ± 0.50%	Hydrated	-0.89 ± 1.19%	-2.03 ± 1.24%	-1.14 ± 0.45%
Dehydrated	-2.27 ± 1.24%[a]	-4.3 ± 1.25%[a]	-2.04 ± 0.27%[a]	Dehydrated	-2.02 ± 1.27%	-4.59 ± 1.32%[a]	-2.57 ± 0.69%[a]

Figure 1. Body mass (mean ± SD) throughout the race (A) and submaximal (B) trials, with associated percentage of body mass lost compared with baseline. [a] $P \leq .05$ for the same time point between hydration states. Figure 1A reprinted with permission of the National Strength and Conditioning Association, Colorado Springs, CO, from Stearns RL, Casa DJ, Lopez RM, et al.[49]

a significant F ratio. Statistical analysis for pretest and posttest values during trials was performed using a paired-samples t test with a Bonferroni correction. The effect of hydration status on body core temperature and HR immediately postrun and 10 minutes postrun was calculated by the following formula:

[(Absolute difference in HR) or
(core temperature difference between hydrated and dehydrated trials)]
÷ (Absolute difference in dehydration level between hydrated and dehydrated trials)
= (Change in HR or core temperature for each 1% body mass loss)

An α level of .05 was used to determine statistical significance. All data analyses were performed using SPSS (version 10.0; SPSS Inc, Chicago, IL).

RESULTS

Participant Characteristics

The 18 participants had the following characteristics: age = 27 ± 7 years, height = 171 ± 9 cm, mass = 64.2 ± 9.0 kg, and body composition = 14.6% ± 5.5% fat, based on 3-site skin-fold caliper measurements. Because of external constraints, 17 volunteers completed the submaximal exercise trials (10 men, 7 women) and 17 completed the race trials (9 men, 8 women). A total of 16 participants completed both submaximal and race trials. Preliminary statistics revealed no differences between the sexes in terms of the main outcome variables. Therefore, the data for men and women were combined.

Environmental Conditions

The wet bulb globe temperatures for the 2 race trials (HYR: 25.3 ± 2.1°C; DYR: 27.0 ± 1.5°C) were similar ($P > .05$). Dry bulb and wet bulb temperatures for the HYR were 26.29 ± 2.83°C and 23.99 ± 2.94°C, and dry bulb and wet bulb temperatures for the DYR were 28.01 ± 2.83°C and 22.79 ± 0.76°C. The differences between the wet bulb and dry bulb temperatures were not significant for either trial (HYR or DYR). Similarly, the wet bulb globe temperatures for the 2 submaximal trials (HYS: 27.1 ± 1.6°C; DYS: 26.9 ± 1.5°C) were not different ($P > .05$). Dry bulb and wet bulb temperatures for the HYS were 28.25 ± 2.13°C and 22.50 ± 1.63°C, and dry bulb and wet bulb temperatures for the DYS were 27.85 ± 2.21°C, and 22.23 ± 1.62°C ($P > .05$).

Body Mass Changes

Between-trials comparisons (HYR versus DYR and HYS versus DYS) demonstrated differences in body mass at the prerun and postrun time points (all comparisons: P

Table 1. Urine Osmolality, Urine Color, Urine Specific Gravity, and Blood Lactate Level (Mean ± SD)

Trial	Hydration State	Urine Osmolality		Urine Color		Urine Specific Gravity		Lactate, mmol/L
		Pretrial	Posttrial	Pretrial	Posttrial	Pretrial	Posttrial	Posttrial
Race								
	Hydrated	324 ± 252	410 ± 244	3 ± 2	5 ± 2	1.009 ± 0.006	1.012 ± 0.006	5.0 ± 1.2
	Dehydrated	1002 ± 106[a]	820 ± 154[a]	6 ± 1[a]	6 ± 1[a]	1.027 ± 0.004[a]	1.020 ± 0.004[a]	4.6 ± 1.4
Submaximal								
	Hydrated	296 ± 254	371 ± 216	2 ± 2	5 ± 3	1.008 ± 0.007	1.013 ± 0.007	2.8 ± 0.7
	Dehydrated[a]	995 ± 112	929 ± 103	6 ± 1	7 ± 1	1.026 ± 0.003	1.026 ± 0.003	3.9 ± 2.2

[a] $P < .05$ between hydrated and dehydrated trials at the corresponding time points.

< .001). Dehydrated participants (DYR and DYS) had reductions in body mass compared with their 3-day baselines for the morning of, immediately before, and after all dehydrated trials (all comparisons: $P < .001$; Figure 1). Volunteers in the DYR lost an average of 1.5 kg before the start and finished with an average loss of 2.8 kg, whereas those in the HYR started at an average of 0.54 kg less than their baselines and lost an average of 1.37 kg. The percentage of dehydration calculated pre-exercise via body mass losses was supported by urine hydration markers (Table 1).

Core Body Temperature

Hydration status before all trials did not influence core body temperature leading up to the start of each run between HYR and DYR or HYS and DYS ($P > .05$). However, postrun, core body temperature in DYR was greater (39.49 ± 0.37°C) than in HYR (39.18 ± 0.47°C, $P = .038$; Figure 2A). Core body temperature for HYR versus DYR at loop 2 (39.12 ± 0.68°C versus 39.37 ± 0.45°C) and at 10 minutes (38.87 ± 0.59°C versus 38.99 ± 0.56°C) and 20 minutes postrun (38.25 ± 0.62°C versus 38.45 ± 0.53°C) was not different. For DYS, core body temperature was greater than for HYS after the second loop (39.04 ± 0.33°C versus 38.75 ± 0.39°C, $P = .009$), postrun ($P < .001$), and 10 minutes ($P = .001$) and 20 minutes postrun ($P = .001$; Figure 2B). Core body temperature immediately postrun for HYS was 38.62 ± 0.33°C, whereas for DYS, it was 39.17 ± 0.42°C. Comparing the submaximal trials at the immediately postexercise time point, body core temperature increased 0.22°C for every additional 1% of body mass loss (Figure 2).

Sweat Rate

Sweat rates for the HYR and DYR were 1.57 ± 0.44 L/h and 1.45 ± 0.39 L/h, respectively. The 8% difference in sweat rates between the HYR and DYR was not significant ($P > .05$). Sweat rates for the HYS and DYS were 1.41 ± 0.31 L/h and 1.32 ± 0.28 L/h, respectively. The 6% difference in sweat rates between the HYS and DYS was not significant ($P > .05$).

Heart Rate

Hydration status before all trials did not influence pretrial HR between hydrated and dehydrated races or submaximal trials (both comparisons: $P > .05$). The HR for DYR was greater ($P \leq .05$) than that for HYR at 10 minutes postrun (132 ± 18 beats/min versus 118 ± 10 beats/min, $P = .003$) and 20 minutes postrun (114 ± 16 beats/min versus 103 ± 12 beats/min, $P = .009$; Figure 2A). The HR for DYS was greater ($P \leq .05$) than that for HYS after the second loop (175 ± 10 beats/min versus 167 ± 9 beats/min, $P = .016$), postrun (179 ± 11 beats/min versus 164 ± 10 beats/min, $P < .001$), and at

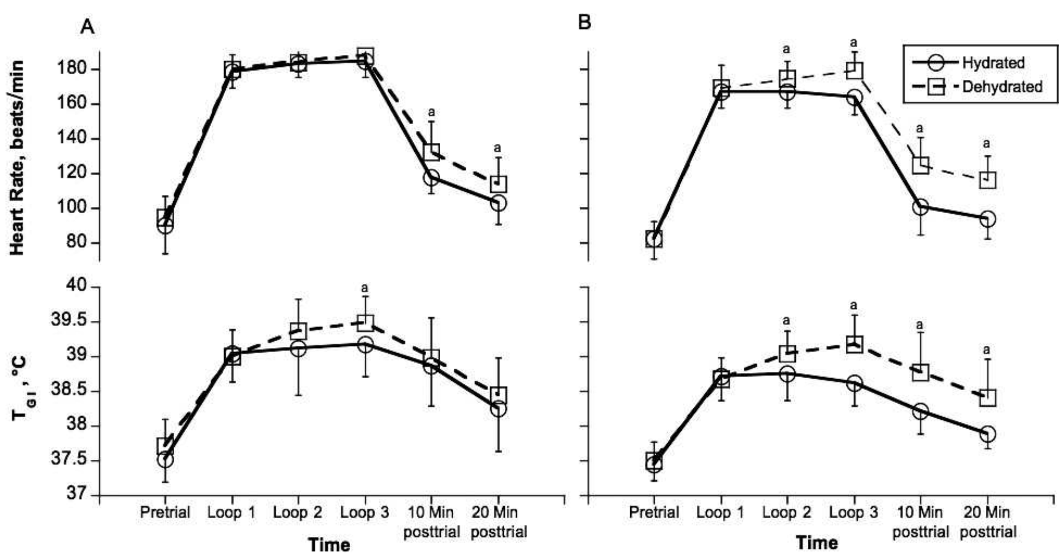


Figure 2. Heart rate and core body temperature (mean ± SD) throughout race (A) and submaximal (B) trials. [a] $P \leq .05$ for the same time point between hydration states.

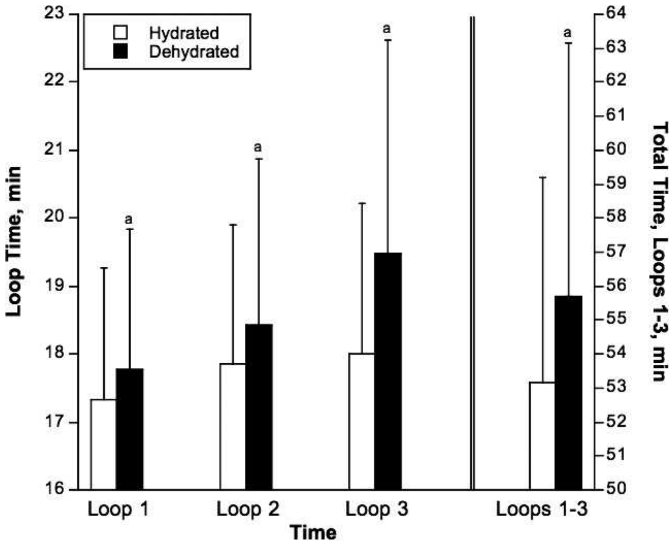


Figure 3. Race trial performance times (mean ± SD) [a] $P \leq .05$ for the same time point between hydration states. Reprinted with permission of the National Strength and Conditioning Association, Colorado Springs, CO, from Stearns RL, Casa DJ, Lopez RM, et al.[49]

10 minutes postrun (125 ± 16 beats/min versus 101 ± 16 beats/min, $P < .001$) and 20 minutes postrun (116 ± 145 beats/min versus 94 ± 12 beats/min, $P < .001$; Figure 2B). Comparing the submaximal trials at the immediately postexercise time point, a 6-beats/min increase in HR occurred for every additional 1% of body mass loss. Additionally, HR was 10 beats/min higher at 10 minutes postexercise for every additional 1% of body mass loss (Figure 2).

Performance

We closely monitored HYS and DYS loop time and provided feedback to attempt to keep finishing times consistent. Total times to complete HYS and DYS were not different (59.57 ± 5.31 minutes and 59.44 ± 5.44 minutes, respectively; $P > .05$). However, time for loop 1 was faster during DYS (19.37 ± 1.58 minutes) than for HYS (19.48 ± 1.65 minutes, $P = .033$). Times for loop 2 (19.85 ± 1.80 minutes and 19.97 ± 1.97 minutes, respectively) and loop 3 (20.23 ± 2.03 minutes and 20.25 ± 1.98 minutes, respectively) were not different between HYS and DYS ($P > .05$). For the race, HYR was faster than DYR for loops 1 (17.32 ± 1.94 minutes versus 17.77 ± 2.06 minutes, $P = .028$), 2 (17.85 ± 2.05 minutes versus 18.42 ± 2.46 minutes, $P = .010$), and 3 (18.01 ± 2.20 minutes versus 19.47 ± 3.16 minutes, $P = .003$) and for total time (53.15 ± 6.05 minutes versus 55.70 ± 7.45 minutes, $P = .001$; Figure 3).

Perceptual Responses

Perceived thirst was greater in DYS versus HYS prerun (6.0 ± 1.0 versus 2.0 ± 1.0), postloop 1 (7.0 ± 1.0 versus 3.0 ± 1.0), postloop 2 (7.0 ± 1.0 versus 4.0 ± 1.0), postrun (9.0 ± 1.0 versus 6.0 ± 2.0), and 20 minutes postrun (8.0 ± 1.0 versus 3.0 ± 1.0) (all comparisons: $P < .001$; Figure 4). Thermal sensation was greater in DYS versus HYS postloop 2 (6.5 ± 1.0 versus 5.5 ± 1.0, $P = .035$), postrun (6.0 ± 1.00 versus 5.5 ± 1.0, $P = .003$), and 20 minutes postrun (5.0 ± 1.0 versus 4.0 ± 0.5) (all comparisons: $P < .001$). Rating of perceived exertion was greater in DYS versus HYS postloop 1 (14.0 ± 2.0 versus 12.0 ± 2.0, $P = .002$), postloop 2 (15.0 ± 2.0 versus 12.0 ± 2.0, $P = .001$), and postrun (16.00 ± 2.0 versus 13.0 ± 2.0, $P < .001$).

Thirst was greater in DYR versus HYR prerun (6.0 ± 1.0 versus 2.0 ± 1.0), postloop 1 (7.0 ± 1.0 versus 5.0 ± 1.0), postloop 2 (8.0 ± 1.0 versus 5.0 ± 2.0), postrun (8.0 ± 1.0 versus 3.0 ± 2.0), and 20 minutes postrun (8.0 ± 1.0 versus 4.0 ± 2.0) (all comparisons: $P < .001$). Thermal sensation was greater in DYR versus HYR postloop 2 (7.0 ± 0.5 versus 6.5 ± 0.5, $P = .027$) and 20 minutes postrun (5.0 ± 1.0 versus 4.5 ± 1.0, $P = .018$). The RPE was greater in DYR versus HYR postloop 2 (18.0 ± 1.0 versus 17.0 ± 2.0, $P = .044$), postrun (19.0 ± 1.0 versus 18.0 ± 1.0, $P = .037$), and 20 minutes postrun (8.0 ± 2.0 versus 6.0 ± 1.0, $P = .028$).

Environmental Symptoms Questionnaire. Changes in the ESQ, measured by assessing the change from prerun to postrun, were greater in DYR versus HYR (26 ± 21 versus 12 ± 12, $P = .007$). No differences were noted between prerun and postrun scores in HYS and DHS (7 ± 10 versus 15 ± 19, $P = .104$).

Profile of Mood States. From prerun to postrun, *Tension/Anxiety* decreased to a greater extent in DYS versus HYS ($P = .03$). *Fatigue/Inertia* ($P = .021$) and *Total Mood Disturbances* ($P = .028$) increased more from prerun to postrun in DYS than in HYS (Table 2).

DISCUSSION

Our primary purpose was to evaluate the influence of hydration status on physiologic strain and performance at various exercise intensities in a field setting. The research questions were as follows: (1) When finishing time remains constant (as a result of pace feedback), how does dehydration influence physiologic function?; and (2) How does an athlete's maximal-intensity exertion while hydrated or dehydrated influence physiologic function and performance?

Submaximal Running (HYS and DYS)

When finishing time was held constant (absolute intensity consistent between trials), physiologic responses were notably influenced when body mass loss differences were 2.56% (2.03% versus 4.59%). When dehydration increased, postrun body core temperature and HR were approximately 0.5°C and 15 beats/min higher, respectively (Figure 2), even though intensity was moderate, finishing times were the same, environmental conditions were not extreme, and differences in hydration status were just 2.5% (Figure 1). These results are similar to those of previous laboratory[1–3,9,30] and field[31–33] studies but contrast with those of some previous field studies[17–21] in which body core temperature was not influenced by hydration. We examined a realistic athletic model,[34] in which a slight fluid deficit is carried forward from the previous day and increased during an acute bout of activity.

In previous laboratory studies,[1–4,9] exercise in warm or hot conditions resulted in 0.12°C to 0.25°C and 3 to 5 beats/min increases in body core temperature and HR, respectively, for every additional 1% of body mass lost. We

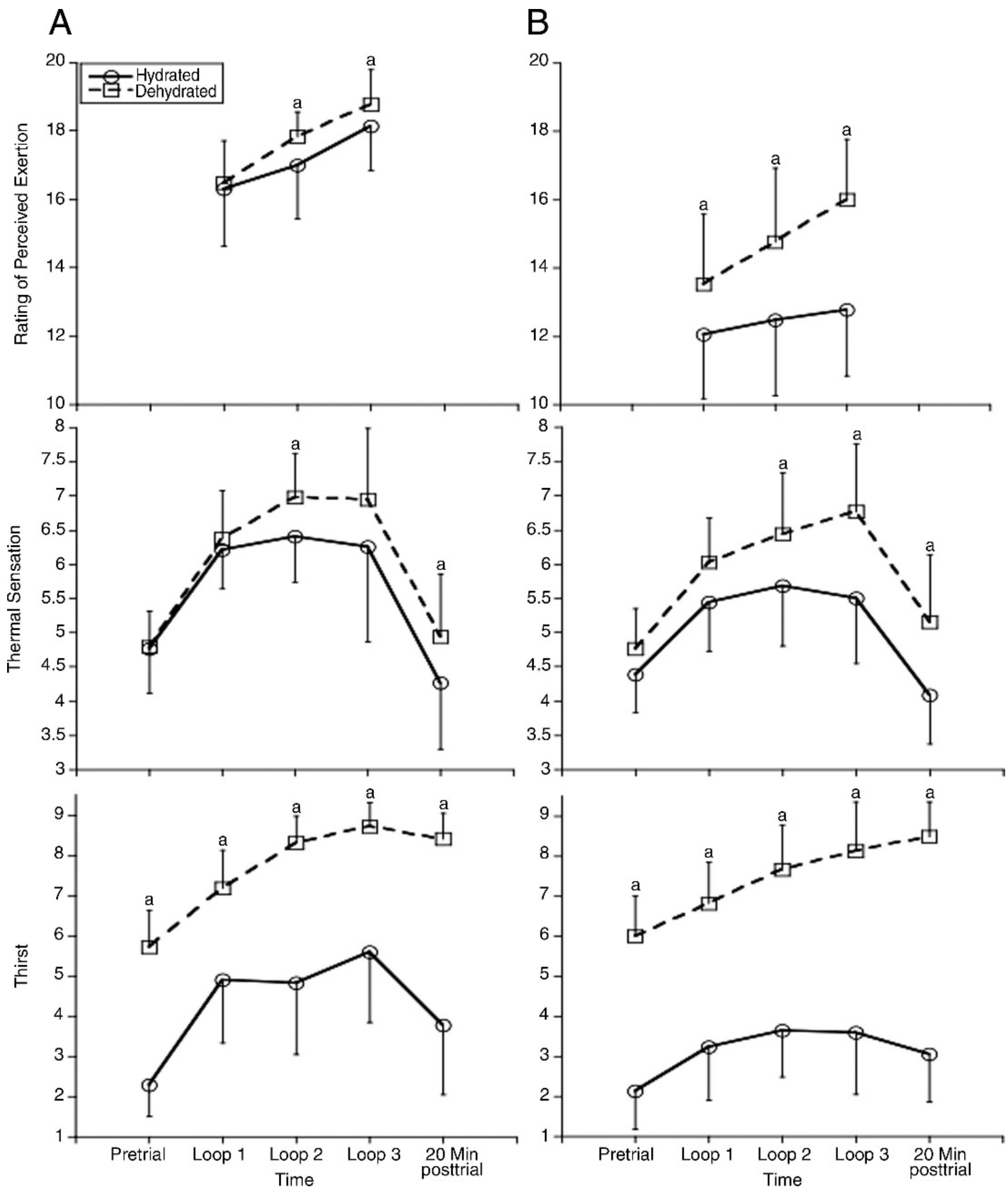


Figure 4. Rating of perceived exertion (RPE), thermal sensation, and thirst (mean ± SD) throughout the race (A) and submaximal (B) trials. [a] $P \leq .05$ for the same time point between hydration states.

noted 0.22°C and 6-beats/min increases in body core temperature and HR, respectively, for every additional 1% of body mass lost (Figure 2). Also, HR was 10 beats/min higher at 10 minutes postrun for every additional 1% of body mass lost (Figure 2). Thus, dehydration may exacerbate physiologic strain even more during the recovery from exercise, a concept with ramifications for interval training and sports with work and rest periods.

Table 2. Changes in Profile of Mood States Scores for Race and Submaximal Trials (Mean ± SD)

		Changes in Profile of Mood States Scores (Postrun − Prerun)						
Trial	Hydration State	Tension-Anxiety	Depression-Dejection	Anger-Hostility	Vigor-Activity	Fatigue-Inertia	Confusion-Bewilderment	Total Mood Disturbance
Race								
	Hydrated	4 ± 2	0 ± 0	0 ± 0	4 ± 0	−7 ± 1	0 ± 1	−7 ± 5
	Dehydrated	−3 ± 1	1 ± 3	−2 ± 6	−4 ± 3	9 ± 6	1 ± 3	7 ± 3
Submaximal								
	Hydrated	−2 ± 2	0 ± 1	−2 ± 5	−3 ± 1	2 ± 2	0 ± 1	0 ± 8
	Dehydrated	0 ± 1[a]	1 ± 1	2 ± 3	−5 ± 1	6 ± 2[a]	2 ± 1	15 ± 5[a]

[a] $P < .05$ between hydrated and dehydrated trials at the corresponding time points.

Our findings likely differed from those of previous field studies because both trials (HYS and DYS) required participants to finish in approximately the same time. Dehydrated runners (2.53% additional body mass loss at the end of the run) experienced greater physiologic strain attaining the designated finishing time, as indicated by multiple exaggerated postrun responses (including T_{GI}, HR, thermal sensation, RPE, POMS, and plasma lactate level; Figures 2 and 4; Tables 1 and 2). The effort was perceived to be greater, indicating that the psychological response paralleled the exaggerated physiologic responses.[8,35–38] Put simply, dehydrated runners had to work harder (and knew it) to accomplish a task that was easier when they were less dehydrated.

These deficits associated with running in a slightly more dehydrated condition reflect combined psychologically and physiologically mediated responses. But one could argue, given the data, that the response is not entirely psychological. Athletes would likely reduce running pace if they sensed a fluid deficit,[11,12,37,39] but in our study, pace remained constant as part of the research design. So, while perceptual measures (RPE, thermal sensation, thirst, POMS) were exaggerated during and after the run, physiologic measures clearly indicated that hydration status altered the thermoregulatory response when finishing time was controlled. The magnitude of the HR differences (nearly 20 beats/min higher for DYS versus HYS) at the end of the run and after 10 minutes of recovery reminds us of the effects of hydration status on cardiovascular function. Additionally, the 0.22°C rise in body temperature for every additional 1% of body mass loss confirms that in field studies, when an athlete is not given the opportunity to decrease pace, the difference in hydration status affects thermoregulatory function. Although this finding has long been shown in laboratory studies,[1–4,30,33] some authors[17–22,40,41] have strongly speculated that this physiologic response does not occur in field studies. Our results show that hydration status and core temperature were not related in previous studies because participants could decrease pace as a protective or necessary response to hyperthermia or fatigue. When a critical factor that mediates body core temperature is controlled (eg, finishing time), the relationship between hydration status and body core temperature is apparent.

Additionally, wind velocity is another factor to consider. Laboratory studies have been criticized[42] as exaggerating the physiologic strain attributed to dehydration due to a lack of sufficient wind velocity. Differences in cooling as a result of varying wind velocities have been demonstrated in a laboratory setting[43]; however, Dugas et al[44] showed that very high wind speeds (>20 m/s) could offset dehydration levels of approximately 4%. An examination of the effect of wind velocity in a warm environment had never been performed with participants who were dehydrated up to approximately 4% in the field. Our results reveal that when wind velocity at least equaled running velocity, it was insufficient to counter the levels of dehydration and resulting performance decrements that occurred.

The 6 greatest benefits of enhanced hydration status in a submaximal scenario (body mass loss of 2.0% versus 4.59% at the finish) were (1) lower core temperature during the effort, upon finishing, and for the 20 minutes of recovery; (2) decreased cardiovascular strain during the effort, upon finishing, and for the 20 minutes of recovery; (3) decreased perceptions of warmth and exertion; (4) decreased thirst level, which may have psychological ramifications[40,41]; (5) decreased perturbations of psychological state, as indicated by numerous responses in the POMS; and (6) decreased blood lactate level.

Maximal Running (HYR and DYR)

We examined the effect of hydration status (body mass loss of 0.8% versus 2.3% immediately before the race and of 2.05% versus 4.3% at the end of the race) on performance and physiologic function while running in warm conditions. Previous authors[19–21] have shown that when relationships between hydration status and some element of performance (eg, finishing time) are assessed, increasing dehydration often does not degrade performance. In fact, quite the opposite was true: the fastest runners seemed to be the most dehydrated.[22,40] Reasonable explanations for this phenomenon include less weight to carry (a greater benefit in events such as distance running, because less energy is required to maintain and produce forward movement) and less time needed to stop or slow down and rehydrate. Past examinations begged the following question: If the same runner undertook the same activity and maintained a better hydration status, would he or she perform better? Without a control group, there was no way of knowing. Therefore, we sought to examine this question directly by asking runners to race at maximal effort on 2 occasions at 2 hydration levels.

Finishing body core temperature was lower in the hydrated runners, even though they were running at a faster pace (Figure 2). This finding is surprising, because exercise intensity plays such an important role in the rate of body core temperature rise.[13,14,23] The additional thermoregulatory strain imposed by exercising while more dehydrated may have exerted a greater influence than the magnitude of temperature change imposed by the faster pace attained when racing in a less dehydrated condition. So each group had a physiologic explanation for a high body temperature while racing in the heat. The hydrated group would have a high core body temperature because of greater intensity, as supported by the previous literature,[13,14,23] and the dehydrated group would also have a high core temperature because of greater thermoregulatory strain (as shown by the submaximal temperature response when finishing times were the same). For most of the race (postloops 1 and 2) these contributors (intensity versus dehydration) of a rapid rise in core temperature provided similar magnitudes of response. However, by the end of the race, the greater level of dehydration coupled with a slightly greater exercise duration drove temperature significantly higher, trumping the higher intensity experienced by the hydrated group. The self-imposed (or actual physiologic) constraints that caused a decrease in pace, while seemingly protective, could not completely offset rising temperature. The dehydrated runners ran slower and at a lower intensity but reached a core body temperature that was higher than that of the same runner at a higher intensity but in a less dehydrated state. This finding may provide a clue to the cause of heat illness in athletes. An athlete who is dehydrated but motivated to perform at a high level may have a rise in body temperature, even with a decrease in pace, which is relevant when athletes are forced to perform at maximal effort as a result of external (eg, military supervisor, coach) or internal (eg, qualifying for a team or time) influences.

As indicated by similar HRs and higher RPEs and body core temperatures, the dehydrated runners were providing maximal effort. Yet performance decreased and the perceptual environmental symptoms associated with maximal exercise (as indicated by a greater change in postrace ESQ scores) increased. Despite feeling as if they were running maximally and physiologically straining their bodies, the dehydrated runners still completed the course in slower times. The greater thirst responses in the more dehydrated group (as we found) may have provided a powerful psychological cue to reduce intensity in response to perceived compromised hydration. This response to thirst may pose a risk if pace continues at nondehydrated intensity.[22,37,40] Additionally, the participants' lack of blinding regarding hydration status may have offered psychological cues to modify pace and effort. However, even though they ran more slowly, they still had a higher finishing temperature and perceived more adverse signs and symptoms during the maximal effort. So the reduced intensity likely provided some degree of self-imposed protection against the risks of maintaining an unrealistic pace in the presence of the given hydration status. But the decreased pace could not completely protect against the increased thermoregulatory strain (demonstrated by the increase in core body temperature due to heat production and gain imposed by the greater dehydration in combination with stressful environmental factors) during maximal effort.

Dehydration linked with performance decrements occurs during endurance activity. A meta-analysis[45] of 14 such studies showed that the decrement begins at about 2% of body mass loss, especially in temperate or warm environments, a finding corroborated by others.[46] Sports medicine governing bodies[47,48] have promoted appropriate rehydration practices, encouraging athletes to rehydrate at a rate that prevents body mass loss from exceeding 2%. Such recommendations (rehydrating to keep body mass loss to less than 2%, never overhydrating, following thirst dictates for slower runners, and individualizing rehydration plans based on sweat rate for faster runners) remain wise advice.

In a race scenario, enhanced hydration status (2.05% versus 4.3% of body mass lost at the finish) resulted in (1) faster finishing time in the 7.5-mi (12-km) race, (2) lower body core temperature upon finishing, (3) fewer environmental symptom changes from prerace to postrace, (4) enhanced recovery, given the lower HR for at least 20 minutes postrun, (5) decreased feelings of warmth and exertion (even though running faster), as evidenced by decreased thermal sensation and lower RPE, respectively, (6) decreased thirst response, which may have psychological ramifications,[40,41] and (7) decreased ability to evenly pace oneself (discussed in a recent publication).[49]

In conclusion, it seems likely that the physiologic and performance decrements associated with dehydration that have been consistently shown in a laboratory setting exist when athletes perform athletic activities in a natural sport setting. The differences that have been noted between laboratory and field settings are linked to the methodologic challenges in a field setting, which make it harder to isolate the effects and are not due to the absence of the physiologic effects themselves.

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