# Dehydration Impairs Cycling Performance, Independently of Thirst: A Blinded Study

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## ABSTRACT

ADAMS, J. D., Y. SEKIGUCHI, H.-G. SUH, A. D. SEAL, C. A. SPRONG, T. W. KIRKLAND, and S. A. KAVOURAS. Dehydration Impairs Cycling Performance, Independently of Thirst: A Blinded Study. *Med. Sci. Sports Exerc.*, Vol. 50, No. 8, pp. 1697–1703, 2018. **Purpose**: The aim of the present study was to examine the effect of dehydration on exercise performance independently of thirst with subjects blinded of their hydration status. **Methods**: Seven male cyclists (weight, 72 ± 9 kg; body fat, 14% ± 6%; peak oxygen uptake, 59.4 ± 6 $\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) exercised for 2 h on a cycle ergometer at 55% peak oxygen uptake, in a hot-dry environment (35°C, 30% relative humidity), with a nasogastric tube under euhydrated–non-thirst (EUH-NT) and dehydrated–non-thirst (DEH-NT) conditions. In both trials, thirst was matched by drinking 25 mL of water every 5 min (300 $\text{mL}\cdot\text{h}^{-1}$). In the EUH-NT trial, sweat losses were fully replaced by water via the nasogastric tube (calculated from the familiarization trial). After the 2 h of steady state, the subjects completed a 5-km cycling time trial at 4% grade. **Results**: Body mass loss for the EUH-NT and DEH-NT after the 2 h was −0.2% ± 0.6% and −2.2% ± 0.4%, whereas after the 5-km time trial, it was −0.7% ± 0.5% and 2.9% ± 0.4%, respectively. Thirst (35 ± 30 vs 42 ± 31 mm) and stomach fullness (46 ± 21 vs 35 ± 20 mm) did not differ at the end of the 2 h of steady state between EUH-NT and DEH-NT trials ($P > 0.05$). Subjects cycled faster during the 5-km time trial in the EUH-NT trial compared with the DEH-NT trial (23.2 ± 1.5 vs 22.3 ± 1.8 $\text{km}\cdot\text{h}^{-1}$, $P < 0.05$), by producing higher-power output (295 ± 29 vs 276 ± 29 W, $P < 0.05$). During the 5-km time trial, core temperature was higher in the DEH-NT trial (39.2°C ± 0.7°C) compared with the EUH-NT trial (38.8°C ± 0.2°C; $P > 0.05$). **Conclusions**: These data indicated that hypohydration decreased cycling performance and impaired thermoregulation independently of thirst, while the subjects were unaware of their hydration status. **Key Words:** CORE TEMPERATURE, TIME TRIAL, DRINK, HYDRATION, HYPOHYDRATION, FLUID BALANCE

During endurance exercise, especially in the heat, maintaining adequate hydration is recommended for optimal performance (1–4). Proper fluid replacement reduces physiological strain (5) and diminishes thirst (6). Although thirst plays an integral role in water homeostasis by acting as a key signal to initiate fluid intake (6), it is suppressed by the act of drinking (7). Some scientists have argued that thirst alone, acting as part of an anticipatory regulatory system (8), could impair exercise performance in dehydrated subjects (9).

Regardless of thirst, most previous studies showing that dehydration impairs exercise performance have failed to blind their subjects to fluid intake and/or hydration state. This absence of blinding could induce a bias that might affect the results based on subjects' perceptions and expectations. Studies that manipulated hydration status through fluid ingestion are limited by the nature of drinking and its effect on thirst.

In 2015, two studies (9,10) investigated the effect of hypohydration on exercise performance in a blinded manner via intravenous infusion of isotonic saline during exercise. Although both studies reported no differences in cycling performance when subjects were dehydrated to 2%–3% body weight, higher thermoregulatory and cardiovascular strain was observed. Furthermore, both studies did not allow for the ingestion of any water during exercise.

Previous experiments have suggested that the act of swallowing reduces thirst, increases performance, and inhibits vasopressin release, via oropharyngeal stimulation (7,11–13), as opposed to mouth rinsing. Interestingly, although ingestion of small volumes of water alleviates thirst (14), drinking to thirst during exercise often leads to involuntary dehydration and might impair performance (15–17). Recently, James et al. (13) observed the effect of hypohydration on exercise performance in a blinded manner using nasogastric tubes to insure blinding. Although James et al. found differences in performance, the dehydrated trial led to a greater thirst rating.

Therefore, the aim of the present study was to investigate the effect of dehydration on a 5-km cycling time-trial performance independently of thirst with subjects blinded to their hydration status.

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## METHODS

### Participants

Twenty-nine cyclists signed informed consent forms to participate in the study. Twenty-one withdrew due to the discomfort associated with the nasogastric tube insertion, whereas one subject dropped out after the first trial. Seven male cyclists (height, 1.78 ± 0.1 m; weight, 72 ± 9 kg; body fat, 14% ± 6%; peak oxygen uptake ($\dot{V}O_{2peak}$), 59.4 ± 6 $mL \cdot kg^{-1} \cdot min^{-1}$) that completed the entire protocol were included in the analysis. All cyclists had extensive racing experience and competed regularly at USA Cycling category 3 or higher races. Eligibility criteria for participation included other than competitive cycling status, absence of any metabolic, cardiovascular, and renal diseases, as well as history of heat stroke. The study was approved by the university's institutional review board and participants gave their written consent before enrolment.

### Preliminary Screening

During the preliminary screening, anthropometric characteristics were recorded during the first visit at the laboratory. Weight (Health-O-Meter Professional, 349 KLX, McCook, IL) and height (Seca, Model 700, Hamburg, Germany) were measured without shoes and with minimal clothing to the nearest 0.1 kg and 0.005 m, respectively. Body composition was determined via dual-energy x-ray absorptiometry (General Electric, Lunar Prodigy Promo, Chicago, IL). $\dot{V}O_{2peak}$ test was performed on an electronically braked cycle ergometer (Velotron, Racermate, Seattle, WA). After standardized warm-up at 100 W, power increased by 40 W every 2 min until volitional exhaustion. During the test, expiratory gasses were analyzed via an online gas analyzer (Parvo Medics TrueOne 2400, Sandy, UT). At least three of the four following criteria were used to verify attainment of $\dot{V}O_{2peak}$: 1) oxygen uptake plateau with increased workload, 2) respiratory exchange ratio greater than 1.1, 3) heart rate (HR) greater than 90% of age-predicted maximal value (220 − age), and 4) perceived exertion based on the 6–20 Borg scale greater than 17 (18).

### Experimental Protocol

All subjects completed the experimental protocol on three separate visits, first for familiarization followed by two experimental trials in a counterbalanced manner. The protocol consisted of 2-h steady-state exercise (55% $\dot{V}O_{2peak}$) followed by a 5-km time trial at 4% grade (19). The protocol was designed so that the 2 h of steady-state exercise would lead to the desired hydration status (dehydration or euhydration). The subjects performed the two experimental trials without being thirsty and maintaining euhydration (euhydrated not thirsty, or EUH-NT) or while becoming progressively dehydrated (dehydrated not thirsty, or DEH-NT). To clamp thirst at low levels in both trials, subjects were drinking 25 mL of water every 5 min during the 2-h steady-state phase of the protocol and every 1 km during the 5-km time trial. During the EUH-NT trial, water was infused to the stomach via the nasogastric tube attached to an intravenous infusion pump to ensure steady flow. The infusion rate was designed to match fluid losses based on the subject's familiarization trial. The amount of water infused was corrected for water ingested to clamp thirst (25 mL every 5 min). The water for ingestion and gastric infusion was warmed to body temperature (37°C) to prevent the subject from sensing the cooler water entering the stomach during infusion, as well as to avoid any cooling effect. To ensure blinding, the nasogastric tube was inserted in both trials. Lastly, the experimental trials were performed in the morning, at the same time of day, to avoid diurnal variations (20).

*Familiarization session*. One week before the two experimental trials, subjects completed the cycling session to get familiarized with the experimental protocol (21). During this familiarization, subjects were instructed to bring their own water bottles and drink as much as they wanted from the water provided. Sweat rate was estimated based on changes in body weight corrected for water intake and urine output. The protocol of this session was identical to the two experimental trials, apart from blood draws and nasogastric tube placement. After the familiarization session, subjects were provided standardized, frozen meals (560 kcal, 10 g fat, 76 g carbohydrates, 30 g protein) to consume the night before each of their experimental visits and were instructed to fill out a 24-h food diary which was replicated before their second experimental trial. Subject were also instructed to consume plenty of fluid the day before their trial to ensure proper hydration.

**Experimental trials.** Upon arrival to the laboratory, a urine sample was collected to assess pretrial hydration state and proceeded to testing only when urine specific gravity (USG) was less than 1.020 (3). Subjects then self-inserted a rectal thermistor and a nasogastric tube (10-F, Corflo; Corpak Medsystems. Buffalo Grove, IL) was then inserted at a depth equal to the distance between the tip of the nose, to behind one ear, then down to the xiphoid process of sternum. Placement was confirmed by analyzing gastric fluid for pH testing (pH <5). After securing the nasogastric tube on the nose with tape, the external portion of the nasogastric tube was connected to an extension tube running over the ear and toward the shoulder.

The subject then entered the environmental chamber (35°C ± 0.3°C, 30% ± 0.2% relative humidity) and sat on the ergometer for 20 min before a baseline blood sample was taken from an antecubital vein without stasis. After baseline measurements, the subjects cycled for 2 h at 55% $\dot{V}O_{2peak}$. Subjects performed both trials in a randomized, counterbalanced fashion separated by at least 1 wk. A fan producing an air speed of 4.5 $m \cdot s^{-1}$ was directed at the subjects throughout exercise, and subjects wore the same clothing for each trial.

**Physiological and perceptual measurements.** Wireless skin temperature sensors (Maxim Integrated Products, Sunnyvale, CA) were attached on the arm, chest, thigh, and leg. Mean weighted skin temperature ($T_{sk}$) was calculated using the Ramanathan equation (22). To record rectal temperature ($T_{re}$), as an index of core temperature, a rectal thermistor (Physiotemp Instruments Inc., Clifton, NJ) was inserted 10 cm past the

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TABLE 1. Preexercise fluid balance results for both DEH-NT and EUH-NT.

| | Body Mass, kg | UOsm, mmol·kg$^{-1}$ | USG | POsm, mmol·kg$^{-1}$ |
|---|---|---|---|---|
| DEH-NT | 72.4 ± 7.7 | 497 ± 184 | 1.012 ± 0.005 | 292 ± 3 |
| EUH-NT | 72.2 ± 8.0 | 382 ± 131 | 1.010 ± 0.004 | 291 ± 2 |

POsm, Plasma osmolality; UOsm, urine osmolality.

anal sphincter. HR was recorded via wireless HR monitor (Polar Electro T31, Kempele, Finland). During the time trial, all thermoregulatory and cardiovascular measurements were recorded every 1 km. Whole-body sweating rate was estimated based on changes in body weight corrected for water intake and urine output. Cycling power output (W) and finishing time (s) of the 5-km time trial were recorded in real time by the cycling computrainer software (RacerMate Inc., Seattle, WA). Subjects could view the screen profile of the course, but could not see their time, cadence, power output, or HR. During the steady state, subjects provided their rate of thirst ("how thirsty are you now") and stomach fullness ("how full is your stomach now") every 10 min using visual analog scales (23). The visual analog scales used consisted of a 180-mm line with an anchor on the left side (0 mm, "not at all") and a second anchor on the 125-mm mark with the label "extremely." Because 25 mL of water was provided every 5 min, the assessment of thirst was done before drinking water to provide fair and objective indication. Lastly, after the conclusion of the entire experiment, all subjects were asked if they could perceive which trial they were in and if they "felt like they performed better" in one trial compared with the other.

**Blood and urine analyses.** Blood samples were obtained via venipuncture without stasis at baseline, following steady state, and immediately after the time trial. Urine was obtained at baseline as well as after trial. USG and total plasma proteins were measured using a hand-held refractometer (Atago SUR-NE, Tokyo, Japan). Hematocrit was determined in triplicate from whole blood using the microcapillary technique, after centrifugation for 5 min at 10,000 rpm. Hemoglobin was also measured in triplicate from whole blood via the cyanmethemoglobin technique, using a commercially available kit (Drabkin's reagent; Sigma, St. Louis, MO). Percent change in plasma volume was calculated using the Dill and Costill equation (24). Plasma and urine osmolalities were measured in duplicate via freezing-point depression from fresh samples (3250 Osmometer; Advanced Instruments Inc., Norwood, MA).

### Statistical Analysis

All variables are presented as mean ± SD because they were normally distributed. Differences in the mean values or the distributions of parameters between EUH-NT and DEH-NT were assessed using Student's paired $t$-tests. Two-way (treatment–time) repeated measures of ANOVA were used to analyze differences in variables across time points between treatments. *Post hoc* analysis for comparing mean values between trials across time points, as well as different time points, was applied by using the sequential Bonferroni correction rule. Using the data of Kenefick et al. (25), an alpha level of 0.05, and a statistical power of 0.8, it was estimated that six subjects would be required to reject the null hypothesis for the primary outcome (i.e., time-trial performance). All statistical analyses were performed using JMP Pro (version 12.1.0; SAS Inc., Gary, NC). A value of $P < 0.05$ was regarded as statistically significant.

## RESULTS

**Familiarization visit.** During the 2-h steady state of the familiarization visit, subject sweat loss was 2.3 ± 0.1 L with average sweating rates of 1.2 ± 0.1 L·h$^{-1}$. Despite subjects drinking *ad libitum* during the 2-h steady state, body weight declined by −1.2% ± 0.7%. During the 5-km time trial, subject sweat loss was −0.4 ± 0.2 L with average sweating rates of 1.7 ± 0.8 L·h$^{-1}$. Final percent dehydration for the whole familiarization visit was −1.8% ± 1.1% body weight. Power output and cycling speed during the familiarization visit were 281 ± 39 W and 22.4 ± 1.7 km·h$^{-1}$, respectively.

**Fluid balance.** Preexercise body mass, USG, urine osmolality, and plasma osmolality did not differ between EUH-NT and DEH-NT (Table 1, $P > 0.05$). Fluid balance measurements during and after the 2-h steady state and 5-km time trial are presented in Table 2. After 2 h of steady-state exercise, body mass losses for the EUH-NT and DEH-NT trials were −0.2 ± 0.5 kg (−0.2% ± 0.6% of body weight) and −1.6 ± 0.3 kg (−2.2% ± 0.4% of body weight), respectively ($P < 0.05$). No significant differences in percent change in plasma volume (EUH-NT, −4.9% ± 1.9%; DEH-NT, −4.9% ± 3.4%), sweat losses (EUH-NT, 2021 ± 707 mL; DEH-NT, 2037 ± 223 mL; $P > 0.05$), or sweating rate (EUH-NT, 0.2 ± 0.1 mg·m$^{-2}$·s$^{-1}$; DEH-NT, 0.2 ± 0.0 mg·m$^{-2}$·s$^{-1}$; $P > 0.05$). During the 5-km time trial, sweat losses seemed to be 84 mL greater in the EUH-NT than in the DEH-NT trial, but did not reach statistical significance (EUH-NT, 670 ± 222 mL; DEH-NT, 586 ± 164 mL; $P > 0.05$).

**Physiological, perceptual, and performance.** During 2 h of steady-state cycling, there were no differences between EUH-NT and DEH-NT in $T_{\mathrm{re}}$ ($P > 0.05$; Fig. 1). During the 5-km time trial, $T_{\mathrm{re}}$ was higher in the DEH-NT trial (39.2°C ± 0.7°C) compared with the EUH-NT trial (38.8°C ± 0.2°C; $P > 0.05$). The $T_{\mathrm{re}}$ data during the 5-km time trial are presented in Figure 1. DEH-NT resulted in significantly higher core temperatures compared with the EUH-NT ($P < 0.05$; Fig. 1).

TABLE 2. Fluid balance measurements during 2-h steady state and 5-km time trial.

| | 2-h Steady State | | 5-km Time Trial | |
|---|---|---|---|---|
| | EUH-NT | DEH-NT | EUH-NT | DEH-NT |
| Drinking, L | 0.6 | 0.6 | 0.1 | 0.1 |
| Gastric infusion, L | 1.7 ± 0.3 | 0 | 0.3 ± 0.1 | 0 |
| Total fluid intake, L | 2.3 ± 0.3 | 0.6 ± 0.0 | 0.4 ± 0.1 | 0.1 ± 0.0 |
| Body mass change, kg | −0.2 ± 0.5 | −1.6 ± 0.3* | −0.5 ± 0.4 | −2.1 ± 0.3* |
| Body mass change, % | −0.2 ± 0.6 | −2.2 ± 0.4* | −0.7 ± 0.5 | −2.9 ± 0.4* |
| Sweat rate, mg·m$^{-2}$·s$^{-1}$ | 0.2 ± 0.1 | 0.2 ± 0.0 | 0.5 ± 0.2 | 0.4 ± 0.1 |
| Sweat losses, mL | 2021 ± 707 | 2037 ± 223 | 670 ± 222 | 586 ± 164 |
| Plasma volume change, % | −4.9 ± 1.9 | −4.9 ± 3.4 | −4.3 ± 3.7 | −7.6 ± 5.4 |

*Statistically significantly different from EUH-NT at the same time point of the protocol ($P < 0.05$).

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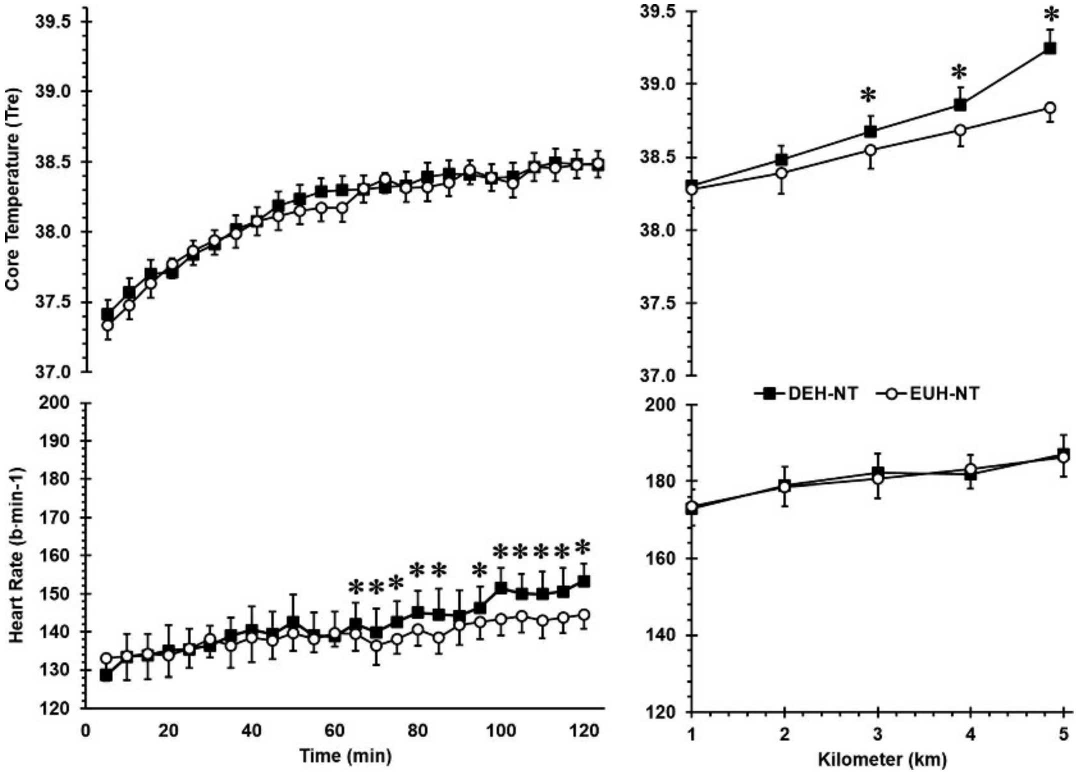

**FIGURE 1—Core temperature and HR during 5-km cycling time trial between DEH-NT and EUH-NT. *Statistically significant differences, $P < 0.05$ between trials at same time point.**

Final $T_{sk}$ recordings were 35.4°C ± 0.3°C vs 35.3°C ± 0.5°C for EUH-NT and DEH-NT, respectively. Furthermore, HR was lower during the EUH-NT when compared with DEH-NT ($P < 0.05$) from 55 min until the end of the 2-h steady state. Final HR recording from 2 h of steady state was 144 ± 10 for EUH-NT and 153 ± 13 for DEH-NT ($P < 0.05$). HR during both EUH-NT and DEH-NT time trials reached 85% ± 14% of age-predicted maximal HR, but did not differ between the two trials ($P > 0.05$; Fig. 1). Thirst perception and stomach fullness did not change during the 2 h of steady-state cycling and no differences were observed between trials (Fig. 2). Cycling power output was significantly greater during the performance test in the EUH-NT (295 ± 29 W; $P < 0.05$; Fig. 3) compared with DEH-NT (276 ± 29 W). Similarly, cycling speed was significantly higher in the EUH-NT (23.2 ± 1.5 $\text{km·h}^{-1}$; Fig. 3) compared with the DEH-NT (22.3 ± 1.8 $\text{km·h}^{-1}$; $P < 0.05$). Thus, cyclists on the EUH-NT (12.9 ± 0.8 min) completed their 5-km time trial 32.9 ± 14.3 s faster than the DEH-NT (13.5 ± 1.0 min; $P < 0.05$). Six of the seven subjects performed better in the 5-km time trial during the EUH-NT than during the DEH-NT trial (Fig. 4). Lastly, four of seven subjects said they "felt better" in the DEH-NT trial, whereas all seven of the subjects could not differentiate between the two trials in terms of treatment. Although the study was designed to be a performed in a counterbalanced crossover fashion, with an odd number of subjects ($n = 7$), it was not totally possible. Thus, four and three subjects performed the DEH-NT and EUH-NT trials first, respectively. Order-effect analysis indicated that there was no significant effect neither on power output ($P = 0.38$) nor on time to completion ($P = 0.33$).

## DISCUSSION

The aim of the present study was to investigate the effect of dehydration on cycling time-trial performance independently of thirst with subjects blinded to their hydration status. The main finding of this study was that euhydration (EUH-NT) led to better exercise performance in the 5-km time trial compared with the dehydration (DEH-NT). Furthermore, these performance results occurred with similar, albeit low, thirst perceptual responses.

These data agree with previous literature concluding that hypohydration impairs endurance exercise performance. Logan-Sprenger et al. (26,27) found that progressive dehydration significantly increased core temperature, HR, whole-body carbohydrate oxidation, and muscle glycogenolysis, whereas these changes were apparent when body mass loss was <1%. Furthermore, Bardis et al. (28) found that hypohydration of −1.8% body mass as a response to *ad libitum* drinking resulted in increased core temperature, lower cycling power output, and slower cycling speed during time trial.

In the present study, although no differences in core temperature were observed during the steady-state cycling, the DEH-NT trial induced higher core temperature in the time trial. This core temperature difference between the two trials

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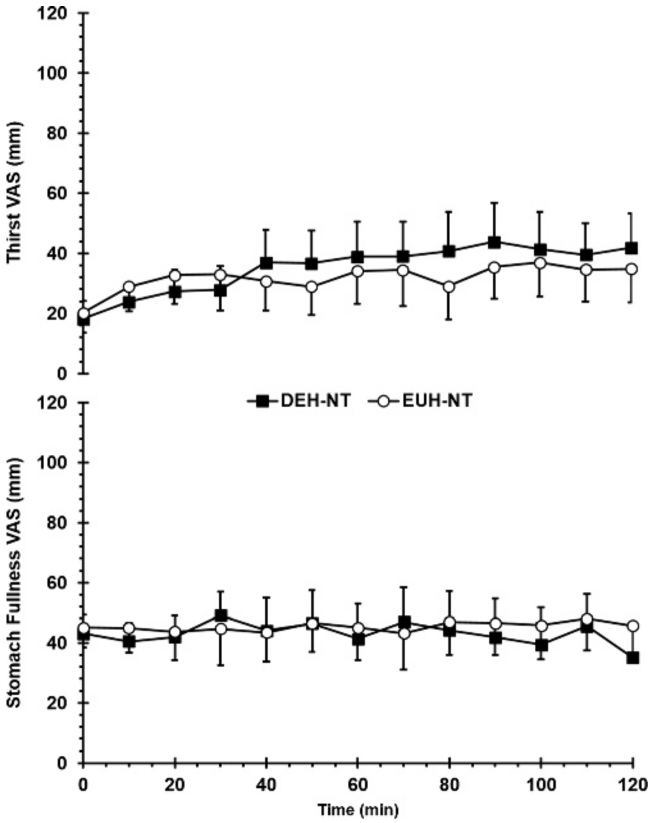

FIGURE 2—Thirst and stomach fullness visual analog scale responses during 2-h steady state between DEH-NT and EUH-NT.

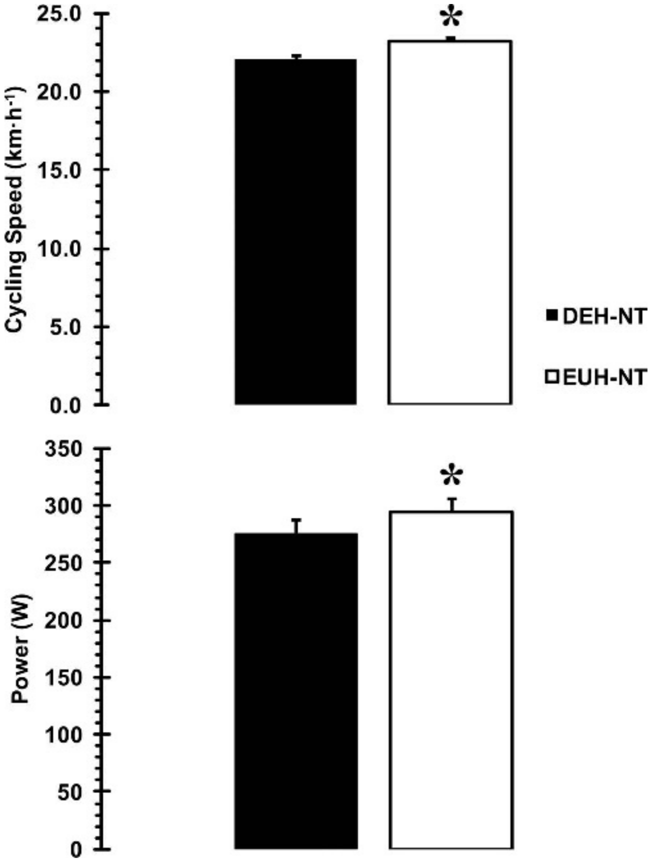

FIGURE 3—Mean cycling speed and mean power output during the 5-km cycling time trial between DEH-NT and EUH-NT. Percentage values signify the percent difference between the two trials. *Statistically significant differences, $P < 0.05$ between trials.

was almost 0.5°C when the subjects finished the 5 km. It should also be noted that subjects in the DEH-NT trial had higher core temperature despite cycling at a slower speed and lower power output. As a result, during the DEH-NT, the higher core temperature was a result of lower metabolic heat, indicating impaired sweat sensitivity and thermoregulatory capacity. Interestingly, the sweating in the EUH-NT trial seemed to be 84 mL greater than in the DEH-NT, although this difference did not reach statistical significance. The magnitude of this small and not statistically significant difference in sweating could explain the differences in core temperature. The difference in cyclists' core temperature between trials could be also explained by two other potential mechanisms: (a) lower skin blood flow during the DEH-NT and (b) poorer heat distribution within the body, secondary to reduced tissue blood flow.

Kenefick et al. (25) found that increasing skin temperature proportionally accentuated hypovolemia and any additional plasma volume loss likely results from increased net filtration rate at the capillaries. Despite several other studies concluding that skin temperature modifies the effect of hydration state on endurance performance (29,30), no differences in skin temperature were found in the present study after 2 h of steady-state exercise.

Numerous studies have shown that dehydration impairs cardiovascular function during exercise (25,31,32) via elevated HR to compensate for decreased stroke volume (30). In the present study, HR was higher during the 2-h steady-state cycling in the DEH-NT trial from 55 to 120 min of the steady-state exercise component. These differences in HR could affect overall cardiac function, thermoregulation (i.e., skin blood flow), and exercise performance due to possibly lower stroke volume. However, despite the gastric infusion

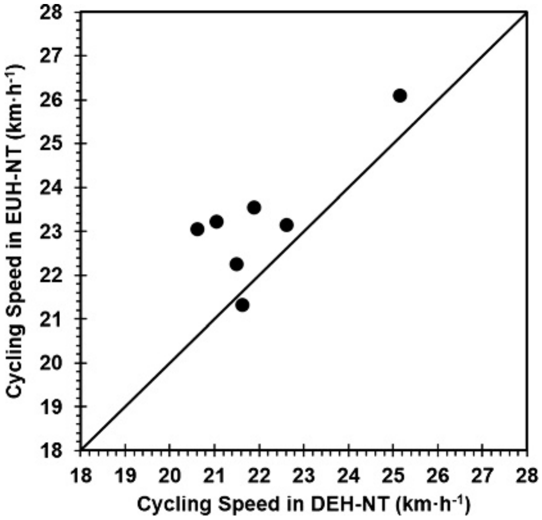

FIGURE 4—Individual performance data during the 5-km time trial in DEH-NT and EUH-NT trials plotted with a line of identity. Each point represents a different individual participant.

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of water, no differences were found in plasma volume between trials. Lastly, no differences were observed in HR during the time trial. Kenefick et al. (25) also found no differences in HR at the end of 15-min time trial independently of ambient temperature (10°C, 20°C, 30°C, 40°C) or hydration state.

Despite the large body of literature consistently showing the detrimental effect of hypohydration on exercise performance (1,4,23,25,33,34), the vast majority of these studies are confounded by the lack of experimental blinding on hydration state. In previous studies, hydration has been manipulated via a number of methods such as exercise-induced hypohydration (35,36), overnight fluid restriction (37), diuretics (38), and intravenous fluid administration (9,10). With few exceptions (13,28,37), the previous methods have been conducted in a nonblind manner; thus, the subjects were aware of whether they were in the hypohydrated or euhydrated trial. Despite the majority of data showing that fluid restriction impairs exercise performance (39), there is a possibility that knowing you are hypohydrated and expecting a decline in performance could work as nocebo. However, in the present study, hydration status was manipulated during exercise in a blinded manner by infusing water to the stomach, via a nasogastric tube. Therefore, the impairment in performance seen in the present study is not the result of subjects' expectation.

In 2015, two studies attempted to eliminate the bias of thirst on exercise performance and blind subjects to their fluid balance. Wall et al. (10) found that when cyclists were dehydrated by −3% of body mass, they exhibited higher core temperatures during their 25-km time trial, despite having similar ratings for thirst perception. In this study, after exercise-induced dehydration, euhydration was induced by intravenous infusion of 3% of body weight, −2% dehydration by infusion only 1% of body weight, and −3% by sham infusion. What is interesting is that after rehydration, during the −2% dehydration, plasma volume expanded significantly, although subjects were still −2% hypohydrated. This plasma volume expansion was no different between the −2% body mass loss trial and the euhydrated trial (i.e., full fluid replacement), thus justifying the fact that dehydration of −2% showed no performance impairment compared with the euhydrated trial. The mechanism behind this lack of difference could therefore be plasma volume expansion, rather than the dehydration, based on the body water deficit.

Similarly, Cheung et al. (9) found that when cyclists were hypohydrated by 3% body mass, they experienced higher core temperatures and HR during the last half of their 20-km time trial. Furthermore, the cyclists were also provided mouth rinse to control for thirst, as both previous studies did not allow drinking. The process of drinking water has been shown to reduce thirst, increase performance, and inhibit vasopressin release, via oropharyngeal stimulation (7,11). In the present study, the nasogastric tube bypassed the oropharyngeal receptors; however, subjects were provided a small amount of drinking throughout the protocol, to keep thirst low. This technique did not prevent dehydration, but could keep thirst perception low and similar between the two conditions (Fig. 2).

Recently, James et al. (13) used a similar blinding protocol to examine the effect of hypohydration on exercise performance via gastric infusion and drinking in recreation cyclists. Despite having no differences in bloating and stomach fullness throughout the protocol, the subjects showed differences in thirst perception after 155 min of steady-state exercise. This difference in thirst could have been due to the small amount of water ingestion, 16 mL/10 min, which is a lesser volume than in the present study (25 mL/5 min) which showed no differences thirst between trials. However, when subjects were hypohydrated to −2.5% body mass, they exhibited higher HR during the steady state, as well as lower performance in the performance test, similar to the present study.

In conclusion, dehydration impaired cycling performance during a 5-km time trial in the heat, independently of thirst, when subjects were unaware of their hydration state. This impairment was likely the result of cardiovascular strain, which could then affect thermoregulation. Further research is needed to evaluate the effect of blinded rehydration in different sports of varying intensities while also examining the mechanistic causes of the impairment caused by dehydration (i.e., skin blood flow, cardiac output, etc.).

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J. D. A. participated in protocol planning, data collection, sample analysis, and data analysis, and was the primary author of the article. S. A. K. initiated the research question, and participated in protocol planning, data collection, sample analysis, data analysis, and manuscript revision and approval. Y. S., H. G. S., A. D. S., and C. A. S. participated in protocol planning, data collection, and manuscript revisions and approval.

APPLIED SCIENCES

## REFERENCES

1. Sawka MN, Cheuvront SN, Kenefick RW. Hypohydration and human performance: impact of environment and physiological mechanisms. *Sports Med*. 2015;45(1 Suppl):S51–60.
2. Cheuvront SN, Carter R, Sawka MN. Fluid balance and endurance exercise performance. *Curr Sports Med Rep*. 2003;2(4):202–8.
3. American College of Sports Medicine, Sawka MN, Burke LM, et al. American College of Sports Medicine Position Stand. Exercise and fluid replacement. *Med Sci Sports Exerc*. 2007;39(2):377–90.
4. Gamage JP, De Silva AP, Nalliah AK, Galloway SD. Effects of dehydration on cricket specific skill performance in hot and humid conditions. *Int J Sport Nutr Exerc Metab*. 2016;26(6):531–41.
5. González-Alonso J, Mora-Rodríguez R, Below PR, Coyle EF. Dehydration reduces cardiac output and increases systemic and

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cutaneous vascular resistance during exercise. *J Appl Physiol (1985)*. 1995;79(5):1487–96.

6. McKinley MJ, Johnson AK. The physiological regulation of thirst and fluid intake. *News Physiol Sci*. 2004;19:1–6.
7. Figaro MK, Mack GW. Regulation of fluid intake in dehydrated humans: role of oropharyngeal stimulation. *Am J Physiol*. 1997; 272(6 Pt 2):R1740–6.
8. Sawka MN, Noakes TD. Does dehydration impair exercise performance? *Med Sci Sports Exerc*. 2007;39(8):1209–17.
9. Cheung SS, McGarr GW, Mallette MM, et al. Separate and combined effects of dehydration and thirst sensation on exercise performance in the heat. *Scand J Med Sci Sports*. 2015;25(1985):104–11.
10. Wall BA, Watson G, Peiffer JJ, Abbiss CR, Siegel R, Laursen PB. Current hydration guidelines are erroneous: dehydration does not impair exercise performance in the heat. *Br J Sports Med*. 2015; 49(16):1077–83.
11. Arnaoutis G, Kavouras SA, Christaki I, Sidossis LS. Water ingestion improves performance compared with mouth rinse in dehydrated subjects. *Med Sci Sports Exerc*. 2012;44(1):175–9.
12. Takamata A, Mack GW, Gillen CM, Jozsi AC, Nadel ER. Osmoregulatory modulation of thermal sweating in humans: reflex effects of drinking. *Am J Physiol*. 1995;268(2):R414–22.
13. James LJ, Moss J, Henry J, Papadopoulou C, Mears SA. Hypohydration impairs endurance performance: a blinded study. *Physiol Rep*. 2017;5(12).
14. Guest S, Essick G, Young M, Lee A, Phillips N, McGlone F. Oral hydration, parotid salivation and the perceived pleasantness of small water volumes. *Physiol Behav*. 2006;89(5):724–34.
15. Armstrong LE, Johnson EC, Kunces LJ, et al. Drinking to thirst versus drinking ad libitum during road cycling. *J Athl Train*. 2014; 49(5):624–31.
16. Armstrong LE, Johnson EC, Bergeron MF. COUNTERVIEW: Is drinking to thirst adequate to appropriately maintain hydration status during prolonged endurance exercise? No. *Wilderness Environ Med*. 2016;27(2):195–8.
17. Greenleaf JE. Problem: thirst, drinking behavior, and involuntary dehydration. *Med Sci Sports Exerc*. 1992;24(6):645–56.
18. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–81.
19. Dantas JL, Pereira G, Nakamura FY. Five-kilometers time trial: preliminary validation of a short test for cycling performance evaluation. *Asian J Sports Med*. 2015;6(3):e23802.
20. Atkinson G, Todd C, Reilly T, Waterhouse J. Diurnal variation in cycling performance: influence of warm-up. *J Sports Sci*. 2005;23(3): 321–9.
21. Maughan RJ. Investigating the associations between hydration and exercise performance: methodology and limitations. *Nutr Rev*. 2012;70(2 Suppl):S128–31.
22. Ramanathan NL. A new weighting system for mean surface temperature of the human body. *J Appl Physiol*. 1964;19:531–3.
23. Bardis CN, Kavouras SA, Kosti L, Markousi M, Sidossis LS. Mild hypohydration decreases cycling performance in the heat. *Med Sci Sports Exerc*. 2013;45(9):1782–9.
24. Dill DB, Costill DL. Calculation of percentage changes in volumes of blood, plasma, and red cells in dehydration. *J Appl Physiol*. 1974;37(2):247–8.
25. Kenefick RW, Cheuvront SN, Palombo LJ, Ely BR, Sawka MN. Skin temperature modifies the impact of hypohydration on aerobic performance. *J Appl Physiol (1985)*. 2010;109(1):79–86.
26. Logan-Sprenger HM, Heigenhauser GJ, Killian KJ, Spriet LL. Effects of dehydration during cycling on skeletal muscle metabolism in females. *Med Sci Sports Exerc*. 2012;44(10): 1949–57.
27. Logan-Sprenger HM, Heigenhauser GJ, Jones GL, Spriet LL. Increase in skeletal-muscle glycogenolysis and perceived exertion with progressive dehydration during cycling in hydrated men. *Int J Sport Nutr Exerc Metab*. 2013;23(3):220–9.
28. Bardis CN, Kavouras SA, Adams JD, Geladas ND, Panagiotakos DB, Sidossis LS. Prescribed drinking leads to better cycling performance than ad libitum drinking. *Med Sci Sports Exerc*. 2017; 49(6):1244–51.
29. Kenefick RW, Sollanek KJ, Charkoudian N, Sawka MN. Impact of skin temperature and hydration on plasma volume responses during exercise. *J Appl Physiol (1985)*. 2014;117(4):413–20.
30. González-Alonso J, Teller C, Andersen SL, Jensen FB, Hyldig T, Nielsen B. Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol (1985)*. 1999;86(3):1032–9.
31. González-Alonso J, Mora-Rodríguez R, Below PR, Coyle EF. Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. *J Appl Physiol (1985)*. 1997;82(4):1229–36.
32. Montain SJ, Coyle EF. Influence of graded dehydration on hyperthermia and cardiovascular drift during exercise. *J Appl Physiol (1985)*. 1992;73(4):1340–50.
33. Cheuvront SN, Kenefick RW. Dehydration: physiology, assessment, and performance effects. *Compr Physiol*. 2014;4(1): 257–85.
34. Bardis CN, Kavouras SA, Arnaoutis G, Panagiotakos DB, Sidossis LS. Mild dehydration and cycling performance during 5-kilometer hill climbing. *J Athl Train*. 2013;48(6):741–7.
35. Armstrong LE, Maresh CM, Gabaree CV, et al. Thermal and circulatory responses during exercise: effects of hypohydration, dehydration, and water intake. *J Appl Physiol (1985)*. 1997;82(6): 2028–35.
36. Barr SI. Effects of dehydration on exercise performance. *Can J Appl Physiol*. 1999;24(2):164–72.
37. Arnaoutis G, Kavouras SA, Stratakis N, et al. The effect of hypohydration on endothelial function in young healthy adults. *Eur J Nutr*. 2017;56(3):1211–7.
38. Gebruers EM, Hall WJ, O'Brien MH, O'Leary D, Plant WD. Signals from the oropharynx may contribute to the diuresis which occurs in man to drinking isotonic fluids. *J Physiol*. 1985;363:21–33.
39. Cotter JD, Thornton SN, Lee JK, Laursen PB. Are we being drowned in hydration advice? Thirsty for more? *Extrem Physiol Med*. 2014;3:18.

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