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Preprint
not peer reviewed

Rowing Performance After Dehydration: An Unexpected Effect of Method

Received: 3 June 2021
Supplementary materials: www.osf.io/xxx
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Please cite as: Kelly, D.J., Nepotiuk, A. & Brown, L. E. (2021, June 3). Rowing performance after dehydration: An unexpected effect of method. *SportRχiv*. https://doi.org/10.31236/osf.io/pv9dw

ABSTRACT

Purpose: To investigate whether mild dehydration, as a weight reduction strategy for lightweight rowers, compromises rowing performance despite a two-hour rehydration window. Both 2000m time trial and visuomotor performance were assessed for impairment. Methods: Experienced rowers (N=14) twice performed a 2000 m rowing ergometer time trial and visuomotor battery: once euhydrated and once after mild dehydration (-1.68 ± .23% body mass reduction). Weight loss was achieved through a combination of 12-hour (overnight) fluid restriction and sauna exposure. Results: Participants were significantly slower on the 2000 m rowing trial in the dehydration condition than in the euhydration condition (2.44 ± 4.5 s, $p<0.05$). Hierarchical linear regression analyses revealed that these rowing performance decrements were better accounted for by dehydration achieved overnight through fluid

All authors have read and approved this version of the manuscript. This article was last modified on June 4, 2021.

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restriction (r^2=.504, $p<0.01$) than by dehydration achieved in the sauna (r^2=.025, n.s.). Hierarchical regression also revealed a relationship between dehydration-related rowing performance decrements and dehydration-related changes in visuomotor function (r^2=.310, $p<0.01$). Conclusions: These findings suggest that rowing time-trial performance is negatively affected by relatively small changes in hydration status (<2% body-mass dehydration) and that the method by which dehydration is achieved is important. Performance losses were associated with prolonged fluid abstinence and not with short-term thermal exposure.

INTRODUCTION

Lightweight is a division of rowing in which all participants must weigh below a criterion to be eligible for competition, providing a level of competition for smaller athletes [1]. Height and weight are still strongly positively related to performance in this category, so lightweight rowers commonly weigh above the weight limit and use pre-race weight-loss techniques 24 hours before competition to make weight. Acute dehydration is a prevalent technique used as it allows for weight loss without diminishing muscle protein mass [2]. The degree to which acute mild dehydration negatively effects rowing performance is a subject of debate [1].

Lightweight rowers are required to weigh in two hours before international competition, providing a window of rehydration before competition. Within this area of research, the severity of dehydration is most-often measured as the percentage of weight lost as a function of the individual's euhydrated weight, termed percent body mass dehydration (%BMD) [3-6]. This measure of dehydration has been found to be more closely related to changes in performance than other measures such as urine or plasma volume [7].

The effect of dehydration on performance depends both on the extent of dehydration achieved and the nature of the performance task. Studies of cyclists and runners suggest that participants who perform aerobically-demanding tasks at approximately 2% or greater BMD experience performance impairments in comparison to their euhydrated performance [8-12]. By contrast, in studies focusing on sprinting or performing maximal voluntary contractions – tasks that rely more heavily on anaerobic energy systems – performance does not seem as vulnerable to 2% BMD [13-15]. Thus, performance that relies more heavily on anaerobic energy systems is not as vulnerable to dehydration as performance that relies on aerobic systems.

The vulnerability of the aerobic system to dehydration may be linked to the onset of exercised-induced hyperthermia [16]. Dehydration decreases blood volume resulting in reduced cutaneous blood flow and sweating rates, leading to increases in core temperature [17, 18]and promoting fatigue [19]. This lowered blood volume may also lead to increased cardiac strain. Reductions in blood volume induce compensatory increases in heart rate and peripheral vasoconstriction to maintain blood pressure and cardiac output [20]. As a result, the dehydrated performer will be subjected to increases in the peripheral resistance of the vasculature, reduction of muscle blood flow, and greater strain on the heart at lower levels of oxygen consumption. These dehydration-related conditions are thought to interfere with performance of tasks with high aerobic demands due to their reliance on the cardiovascular system and extensive heat production.

According to Shepherd [21], the 2000 m sprints that characterize rowing races are composed of 70% aerobic and 30% anaerobic activity. Although rowing contains a significant anaerobic component, studies testing rowers at 4-5.2% BMD have consistently found dehydration-related declines in rowing performance [3, 5, 6, 22, 23]. This decline occurs despite the two-hour rehydration window, suggesting athletes in these investigations may be more hydrated than stated due to the opportunity to rehydrate before exercise. This situation leaves open the question of whether rowers' performance is impaired at lower levels of %BMD.

Whereas the rowing ergometer task is a reliable measure of power and speed in a rower, another aspect of on-water racing is that performance depends critically on oar placement and control, a facet of the task that engages mechanisms of sensorimotor control in the brain. Brain function can be degraded by dehydration [24], leaving open another possible source of performance degradation in rowers.

The goal of the present study was to investigate whether 2000 m rowing performance is susceptible to mild BMD. A convenience sample of collegiate rowers performed two maximal-intensity 2000 m rowing ergometer time-trials, once euhydrated and once following a dehydration with rehydration protocol. This within-subjects design is the best way to detect effects of dehydration because it eliminates the potential effect of inter-individual variance on comparisons in the dehydration condition. The order in which participants experienced the euhydration and dehydration conditions was counterbalanced across participants to allow us to test for and eliminate order effects. Due to rowing's aerobic-system dependence and the clear susceptibility of aerobic performance to dehydration, we hypothesized that rowing

DOI: 10.31236/osf.io/pv9dw

performance will be susceptible to dehydration. We also sought to test the vulnerability of rowers' visuomotor skills to dehydration by asking them to perform three tasks that measure different aspects of visuomotor control: visual motion tracking, targeted reaching and visual updating, and response inhibition. We predicted that performance of these tasks would suffer with dehydration and that the changes in performance on the visuomotor tasks would be related to the changes experienced in the time trial.

METHOD

Participants

A sample of eleven male (mean weight = 82.3 ± 13.1 kg, mean age = 21.3 ± 2.0 years, Height = 184.7 ± 10.2 cm) and three female (Mean weight = 62.1 ± 5.9 kg, Mean age = 20.3 ± 2.1 years, Height = 166.4 ± 8.1 cm) competitive rowers participated in the study. We restricted participation to individuals ≥18 years of age who had experience rowing at the university or college level and were free from complicating medical conditions or disability status. All participants provided written informed consent and all methods were reviewed and approved by the Trent University Research Ethics Board.

Research Design

The study employed a 2-hydration (euhydrated, dehydrated) x 2-order (dehydrated on Day 1, dehydrated on Day 2) mixed design. Participants performed one time trial and three visuomotor tasks once while adequately hydrated and once following dehydration with rehydration on two separate testing days occurring seven days apart. Dehydration (goal of 2% BMD) was achieved both through 12 hours of fluid abstinence and time in the sauna before two hours of rest and rehydration. The order in which participants experienced the dehydration condition was counter-balanced such that half of the participants experienced dehydration on testing day 1 and the other half experienced dehydration on testing day 2. Counterbalancing controls for potential factors that can differ between test days (e.g., familiarity with test procedures).

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Instruments and Tasks

Dehydration was assessed using several instruments. Weight was tracked using a scale (Etekfit Scale Model No.:CF351, Etekcity Corp, Anaheim, CA, USA) precise to +/- 0.30 kg at 49.9 kg, +/- 0.40 at 99.8 kg, +/- 0.50 at 149.7 kg. As a safety precaution for sauna use, temperature was measured using an oral thermometer (BULK720, PharmaSystems Inc., Markham, ON, Canada). Thirst, a perceptual state closely associated with dehydration, was assessed using The Visual Analogue Scale of Thirst (VAST) [25], and other symptomatology associated with dehydration [which are known to overlap considerably with the symptomatology of concussion [26]] were assessed using the Symptom Evaluation subscale (SES) of the Sport Concussion Assessment Test 3 (SCAT3) [27]. Rowing performance was assessed using the Concept II Rowing Ergometer (Concept2, Morrisville, Vermont, US). The rowing ergometer is widely used as a marker of rowing performance and has been shown to be closely related to actual on-water rowing performance [28]. The participants' task was to row 2000 meters in as little time as possible. Rowing time (seconds), power (watts), and strokes taken per 100 meters were recorded.

Visuomotor skills were assessed on a tablet computer (iPad2, Apple Inc., Cupertino, CA) fitted with custom-developed applications (programmed in Xcode https://developer.apple.com/xcode/) that assess visuospatial updating (double-step task), target motion perception and interception (interception task), and response inhibition (stop-signal task). The tablet tasks were performed at a dimly-lit office desk with minimal distractions present.

Double-step task.

The participants' task was to move their index finger from the starting position, as quickly and accurately as possible, to one of three grey targets upon their appearance. On 75% of the trials, the target location initially shown did not change (no-jump trials). On the other 25% trials, the target location unexpectedly shifted either up or down (jump trials). The jump trials were randomly interspersed with the no-jump trials, and the participants were not informed that the experimental blocks would contain jump trials. Movement adjustment was gauged through movement time (in milliseconds; ms) and end-point accuracy (in mm).

Interception task.

Participants' task was to intercept a cartoon fish target, that moved left-to-right across the tablet screen, by making a quick reaching movement from a designated start position to touch the fish as it passed through a fixed interception zone. We used a 3 velocity (13.5 cm/s, 21.4 cm/s, and 26.5 cm/s) × 2 acceleration (present, absent) within-subjects design. Success rate (percentage of successful hits) and arrival time difference (the difference in time between when the target fish arrived at the interception zone and when the finger landed there, in ms) were measured.

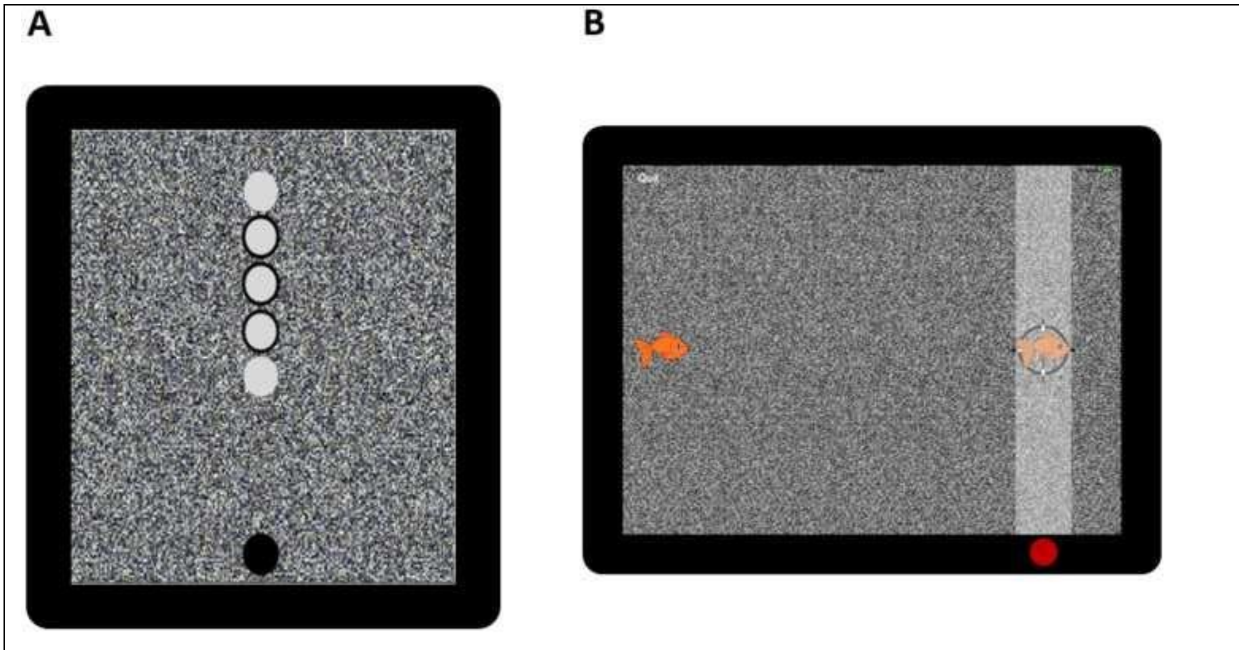

Figure 1: Panel A - A rendition of the displays used in the double-step task. The black dot represents the location of the start position. The grey circles outlined in black show the three initial target locations. The grey circles show the 5 potential final target locations used for jump trials. Panel B - Displays used for the interception task. The fish target appeared on the left of the screen and then moved rightward across the screen. Participants placed their dominant-hand index fingertip on the red dot and made a quick reaching movement to intercept the fish as it moved through the interception zone (the light-gray region where the muted fish is seen). The target could move with three different speeds and with or without acceleration.

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Stop-signal task.

Participants initiated each trial with their finger on a red start circle that appeared at the bottom of the screen. After a short, variable delay, a filled, coloured circle (blue or green) appeared in the centre of the screen. Blue instructed participants to rapidly touch the screen anywhere to the left of the start circle whereas green indicated a movement to the right. On 50% of trials ("go" trials), the trial ended when this movement was made. On the other 50% of trials ("stop" trials), a brief (50 ms) audible tone was presented at a particular time after target appearance. This tone indicated that no movement should be made, that is, that any movement planned in response to the target circle should be completely interrupted so that the finger remained in contact with the start circle. The relative timing of the target ("go") signal and the tone ("stop") signal could be one of four pseudorandomly-presented stimulus-onset asynchronies (SOA): 50, 100, 150, or 200 ms. The main dependent measure was error rate, the proportion of trials on which the finger failed to remain in continuous contact with the start circle in response to the tone.

Determination of baseline nude body mass.

Baseline nude body mass was computed from five pre-test weigh-in sessions in addition to weight on the euhydrated testing day. Participants were weighed in the morning prior to eating but after urinating and defecating. On the first weigh-in date, participants were weighed completely nude and their own designated weigh-in clothing was measured in grams on a gram lab scale. Participants wore this clothing on subsequent weigh-ins and nude body mass was determined from these measures by subtracting clothing weight. Participants' oral temperature and score on the VAST and SES questionnaires were also recorded at each session to develop a baseline score. Any single measure greater than three standard deviations from a participant's own mean -- as computed from the other four baseline-measurement days -- was excluded from the baseline calculations.

Procedure

Baseline weigh-ins and information sessions were conducted at the Peterborough Rowing Club. Testing was performed at the Trent University Athletic Center at a temperature of 20ºC on Day 1 and a temperature of 22ºC on Day 2. The facility's saunas (>40ºC) were used to elicit pre-weigh-in dehydration and remained at consistent temperature across testing days. Participants were provided with diet logs and identical training programs over the course of the study. Participants were asked to restrict their training the day prior to testing to either rest or light steady state exercise and to keep their training routine consistent across tests.

On the day of testing, participants arrived 2 hours of prior to their official weigh-in time, having already completed 12 hours of fluid restriction over the evening and night before. Participants were instructed to abstain from food consumption between 12 AM and their time of official weigh-in. Upon arrival, participants weighed in, and their oral temperature, VAST, and SES scores were recorded. Participants in the euhydrated condition proceeded to the waiting room and continued to hydrate at will. If a participant in the dehydrated condition was determined to have reached 2% BMD (98% of their mean nude body mass), they were instructed to sit in a waiting room maintaining dehydration until their official weigh-in time (preserving the time permitted for rehydration). Participants who had not reached 2% BMD experienced sauna exposure, in 15 minutes intervals, until 2% BMD was achieved for up to a total of 60 minutes maximum. Participants were then moved to the waiting room to maintain dehydration until their weigh-in time. In this manner, time between onset of fluid abstinence and time of official weigh-in was controlled across subjects. At the official weigh-in weight, temperature, VAST score, and SES scores were again recorded.

Our goal was to design a rehydration period that accurately reflected lightweight rowing competition in practice. In the two-hour time frame between official weigh-in and the 2000 m time trial, participants completed the tablet visuomotor tasks and rested and rehydrated. Water and sport electrolyte drink (Kirkland, CHO 58.33 mg/mL, Sodium 0.46 mg/mL) and breakfast foods (granola bars, bagels with jams, cream cheese, chocolate-hazelnut and peanut butter spreads) were provided for participants to drink and eat *ad libitum*. While participant rehydration and caloric intake was uncontrolled to better simulate competition, participants were instructed to, and verbally confirmed, drinking and eating to satiety. Participants were permitted to begin warming up within one hour of testing: any length or style of warm was allowed provided consistency was again maintained across test days.

Participants completed the 2000 m time trial in groups of two, on ergometers arranged so that participants were facing away from each other. Participants were asked to use a familiar ergometer damper setting and to maintain consistency across testing days. Before beginning the time trial, each participant was asked to predict whether their performance would be better, worse, or same as their personal best. The time trial started with a consistent 1 minute warning, followed by a ready-go procedure. Following the trial, participants were asked to rate their performance and complete the VAST and SES scales.

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Results

For measures of dehydration (weight, perception of thirst, and symptom reports), each participant's measure or report provided on test days was converted to values that reflected how the measure differed from pre-test measurements. Percent body mass dehydration (%BMD) was calculated as follows:

$$\%BMD = \frac{Test\ Day\ Weight\ (kg) - mean\ Pretest\ Weight\ (kg)}{mean\ Pretest\ Weight\ (kg)}\ x\ 100$$

Perception of thirst on test days was converted to a Z score as a function of each parti [1] s own mean and standard deviation based on values reported on the six baseline weigh-ins. The symptom questionnaire produced two measures, (1) the number of symptoms reported, and (2) the average rating of symptom intensity. Again, both of these values were converted to Z scores as a function of each participant's own mean and standard deviation from values reported on the five baseline weigh-ins (see Table 1).

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Table 1: Participants' weight and change in weight as a function of condition and method of weight loss

	Baseline	Euhydration Day		Dehydration Day			
P	Mean Weight (n=3; kg)	Final Weight (kg)	Total %BMD	Final Weight (kg)	Total %BMD	% BMD Achieved Overnight	% BMD Achieved in Sauna
1	69.3	69.03	-.40	67.93	-1.99	0.32	-2.31*
2	71.6	71.05	-.73	70.35	-1.70	-0.72	-0.98
3	89.5	90.36	.92	89.46	-.089	0.13	-0.22
4	73.1	73.44	.47	71.24	-2.54	-0.63	-1.91*
5	65.9	64.53	-2.03	64.03	-2.79	-2.64	-0.15ǂ
6	55.3	55.37	.14	54.27	-1.84	-1.12	-0.72
7	107.8	107.69	-.13	105.50	-2.17	-1.06	-1.11*
8	87.7	88.12	.52	87.02	-.73	1.89	-2.62*
9	96.8	97.61	.78	94.81	-2.11	-1.28	-0.83
10	88.2	87.03	-1.34	86.13	-2.36	-1.57	-0.79
11	72.1	71.70	-.61	70.80	-1.86	-0.06	-1.80*
12	65.7	64.85	-1.31	65.35	-.55	-0.24	-0.31
13	83.3	83.52	.22	81.52	-2.18	-1.58	-0.60
14	65.2	65.01	.34	64.81	-.644	0.74	-1.38*

* Ps who achieved the majority of dehydration in the sauna.

ǂ P5 did not enter sauna, but did lose weight during time allotted to sauna. This value was included in sauna regression.

Dehydration

To check our manipulation of hydration level, %BMD and z-scores for thirst, number of symptoms of dehydration reported, and mean symptom intensity were submitted to paired t-tests comparing dehydration and euhydration conditions (α = .05). Mean %BMD, mean ratings of thirst (Z), the mean number of dehydration-related symptoms reported (Z), and mean ratings of symptom intensity (Z) were all significantly greater on dehydration day than on euhydration day (see Table 2). These data consistently suggest that participant hydration levels were successfully manipulated.

Table 2: Measures designed to check the manipulation of hydration levels.

Measure	*Euhydration Day Mean (± S.E.M.)*	*Dehydration Day Mean (± S.E.M.)*	*Paired T (df = 13)*	*P (One-tailed)*
% Change Body Mass (%BMD)	.27 (.24) %	1.68 (.23) %	-5.19	< .001
Thirst Ratings (Z)	-1.36 (.56)	6.16 (1.65)	-4.19	.001
Symptom Intensity Ratings (Z)	0.25 (.62)	3.54 (1.30)	-2.47	.014
Number of Symptoms Reported (Z)	.26 (.50)	2.56 (.80)	-2.95	.005

Rowing Performance Depended on Hydration Condition

To begin our analysis, we ruled out effects of testing order by submitting our dependent measures of rowing performance [time (s) to completion, total power (Watts), and total number of strokes during a 2000 m time-trial] to a 2-hydration level (euhydration, dehydration) by 2-order (dehydration first, dehydration second) mixed analysis of variance (ANOVA). For all measures this analysis revealed no main effect of order (all ps > .11) and no interaction between hydration and order (all ps > .24). These analyses revealed that there was no effect of test-day order on hydration levels, and rule out the possibility that any differences between hydration conditions are due to familiarity with the test protocol or to learning.

Our measures of rowing performance were submitted to planned paired one-tailed t-tests (see Table 3). Both 2000 m time and power were significantly reduced in the dehydration condition over the euhydration condition, suggesting that dehydration did indeed impact 2000 m time-trial performance. This finding cannot be explained by an order effect or any significant interaction between testing order and hydration level.

Table 3: Planned comparisons of rowing performance measures as a function of hydration levels.

Measure	*Euhydration Day Mean (S.E.M.)*	*Dehydration Day Mean (S.E.M.)*	*Paired T (df = 13)*	*P (One-tailed)*
2-Km Time Trial (s)	418.2 (10.0)	420.6 (10.0)	-2.03	.032
Power (Watts)	664 (36)	642 (35)	-1.78	.049
Total Number of Strokes	209.6 (3.7)	206.3 (3.8)	-1.73	.054

We also collected data regarding pace (time/100-meters) achieved over each 100 m of the 2000 m time-trial. We normalized the time for each 100-m interval to each participant's own mean pace and submitted these proportions to a 2-hydration by 20-interval repeated measures ANOVA. There was a significant main effect of pace interval, $F(1, 13) = 14.67$, $p < .001$, such that pace was significantly faster than the average pace at every measure during the first 400 m, was significantly slower than average between 700 and 1500 m, and returned to be significantly faster than average during the last 100 m. This pattern was expected as the early and late portions of the race are commonly sprinted. There was no significant interaction with hydration level and pace interval, $p = .686$, indicating that dehydration appears to impair participants evenly over the course of their time trial.

Relationships between Dehydration and Performance

We conducted a series of post-hoc analyses to determine the degree to which dehydration explained the decline in rowing performance. We conducted hierarchical regression analyses to capitalize on the natural variation in dehydration levels in our sample. Our participants varied with regard to the method by which overall dehydration was achieved; some participants experienced more dehydration through fluid abstinence, whereas others experienced more dehydration in the sauna. We conducted regression analyses to determine whether these differences impacted performance. We calculated the change in 2000 m performance across hydration conditions for each participant (where a positive value indicates that the dehydrated 2000 m time was longer than the euhydrated time), and submitted these values to linear regression with %BMD on dehydration day as the only predictor variable. This regression revealed that overall dehydration accounted for a nonsignificant 16.5% of the variance in 2000m performance decline, $F(1, 12) = 2.36$, $p = .150$.

DOI: 10.31236/osf.io/pv9dw

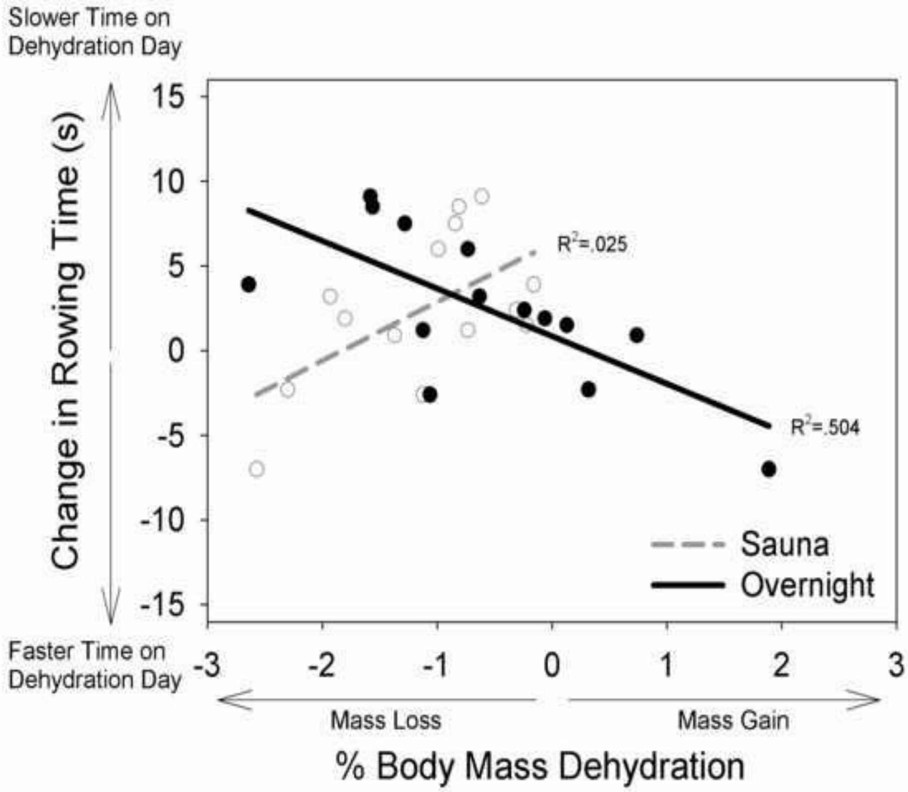

Figure 2: Change in 2000 m trial time as a function of % body mass dehydration achieved in the sauna or overnight.

Some participants achieved their peak level of dehydration by abstaining from liquids overnight ($\%BMD_{Overnight}$; see Table 3), whereas others lost a greater percentage of weight in the sauna ($\%BMD_{Sauna}$). In a next step, change in 2000m performance was submitted to a hierarchical regression with $\%BMD_{Overnight}$ on the first level and $\%BMD_{Sauna}$ on the second level. This model revealed that overnight dehydration uniquely accounted for 50.4% of the variance in the change in performance, $F(1, 12) = 12.18$, $p = .004$. Adding sauna dehydration to the model uniquely accounted for an additional nonsignificant 2.5% of the variance in change in performance, $F(1, 11) = .59$, $p = .459$. Partial correlations revealed that overnight dehydration was negatively correlated with change in 2000 m performance ($pr_{Overnight} = -.522$, $p = .061$), indicating that losses of body mass due to overnight dehydration were correlated with increases in 2000 m trial time, whereas sauna dehydration was not significantly correlated with change in 2000 m performance ($pr_{Sauna} = .225$, $p = .459$). These results indicate that declines in performance may be explained by overnight dehydration but cannot be easily attributed to dehydration achieved in the sauna (see Figure 2).

To further examine this unexpected result, we selected the subset of six participants who achieved the majority of their dehydration in the sauna (marked by an asterisk in Table 2) and used a paired, one-tailed t-test to compare their 2000 m time-trial performance as a function of hydration level. In this select group, mean trial time on dehydration day (415 ± 14 s) was not significantly different from euhydration day (415 ± 14 s), $t(5) = .195$, $p = .428$. By contrast, when we selected the subset of eight participants who achieved the majority of dehydration overnight, mean trial time on dehydration day (425 ± 15 s) was significantly longer than performance on euhydration day (420 ± 14 s), $t(7) = 4.45$, $p = .002$.

Role of Subject Factors

Subject variables such as sex (males vs females), $t(12) = .395$, $p = .700$, weight class (heavyweights vs. lightweights), $t(12) = -.87$, $p = .932$, or ability (measured by % gold-medal standard of their euhydrated 2000 m time), $t(12) = .375$, $p = .714$, did not have any effect on change in 2000 m time-trial performance. Participants were not blind to their dehydration condition, and so it remained a possibility that performance decrements in the dehydration condition were attributable to participants expectations about their own performance while dehydrated. To address this possibility, immediately before their dehydration 2000 m time trial, each participant predicted whether their performance would be better, the same, or worse than their personal best. A regression found the participants' prediction alone explained 35.2% of the variance in change in 2000 m performance with dehydration, $F(1, 12) = 6.52$, $p = .025$. Participants' prediction, however, was not significantly correlated with symptom ratings, thirst ratings, or dehydration levels (%BMD) in either the sauna or overnight (all *p*s > .195), and once overnight dehydration ($\%BMD_{Overnight}$) was factored into the regression, participants' predictions accounted for a non-significant 12.5% of the variance in change in 2000m trial time with dehydration, $F(1, 11) = 3.18$, $p = .077$. Finally, the relationship between change in 2000 m trial time and the change in measures of self-reported well-being (thirst, experience of symptoms, and %BMD) was determined and none of these relationships were significant (all *p*s > .294), indicating that change in performance was not a result of feeling unwell or thirsty.

Performance on Tests of Visuomotor Skill

As mentioned in the introduction, rowers' performance depends critically on oar placement and control, a facet of the task that engages mechanisms of upper-limb sensorimotor control. Brain function can be degraded by dehydration, leaving open another possible source of performance degradation in rowers. We sought to test the vulnerability of rowers' visuomotor skills to dehydration by asking them to perform three tasks measuring different aspects of visuomotor control. For each of the tests below, we ran initial analyses that included order (test conducted on day 1, test conducted on day 2) as a factor with the goal of determining whether differences between day 1 and day 2 could be attributed to factors like learning or increasing familiarity with the test. These analyses revealed no significant effects or interactions involving order.

Performance on our test of visual motion perception and interception (interception task) did not vary with dehydration. We measured success rate (percentage of successful interceptions or hits) and arrival time difference (the difference in time between when the target fish arrived at the interception zone and when the finger landed there, in ms). Success rate (%) was submitted to a 2-hydration (euhydrated, dehydrated) by 2-acceleration (present, absent) by velocity (slow, medium, fast) repeated-measured ANOVA, and it revealed no significant main effect of hydration levels, $F(1, 13) = .67$, $p = .429$, and no interaction involving hydration levels (all *p*s > .40). A similar analysis of arrival time difference revealed no significant effect of hydration, $F(1, 13) = .56$, $p = .468$, and no interaction involving hydration levels (all *p*s > .06). Likewise, there was no relationship between change in success rates and %BMD ($r = -.184$, $p = .273$), %BMD_{sauna} ($r = -.273$, $p = .184$), or %$BMD_{overnight}$ ($r = -.027$, $p = .465$) and there was no relationship between change in relative arrival time and %BMD ($r = .165$, $p = .295$), %BMD_{sauna} ($r = .397$, $p = .090$), or %$BMD_{overnight}$ ($r = .039$, $p = .382$). Interception performance was not affected by the manipulation of hydration levels, and it was not dependent on whether dehydration was achieved overnight or in the sauna.

Hydration levels did, however, influence participants' ability to perform speeded, targeted reaching movements and adjust to an unpredictable change in target position (measured by the double-step task) and their ability to interrupt a planned response (measured by the stop-signal task). The double-step task measured participants' ability to adjust a visually-guided reaching movement to an unpredictable perturbation in target location. Mean movement time (MT) and mean absolute end-point error along the direction of movement were submitted to separate 2-hydration (euhydrated, dehydrated) by 2-jump presence (present, absent) repeated-measured ANOVAs. Whereas the ANOVA showed that MT was not affected by hydration, jump presence or their interaction (all ps > .129), mean absolute error was greater for jump-present trials (28.5 ± 1.6 mm) than jump-absent trials (18.7 ± .6 mm), $F(1, 13) = 14.73$, $p = .002$.

In the next analysis, MT and mean absolute error from jump trials only were submitted to 2-hydration (euhydrated, dehydrated) by 2-jump direction (forward, backward) repeated-measured ANOVAs. Again, whereas MT was not affected by hydration levels, $F(1, 13) = 1.46$, $p = .249$, there was a significant main effect of jump direction indicating that participants needed more time to adjust their movements to target jumps requiring a reversal in direction (338 ± 9 ms) than to perturbations requiring a forward jump (259 ± 7 ms), $F(1, 13) = 43.22$, $p < .001$. There was no interaction of hydration and jump direction, $F(1, 12) = 3.37$, $p = .091$. When mean absolute error was submitted to this same ANOVA, a significant hydration-level by jump-direction interaction was revealed, $F(1, 12) = 4.37$, $p = .041$. When the target jump required the response to be extended along the same movement direction, hydration levels did not influence the response, $F(1, 13) = .049$, $p = .828$. When the target jump required a reversal in movement direction, however, hydration levels did influence the accuracy of the response, $F(1, 13) = 5.14$, $p = .042$. Participants errors were significantly smaller when they were euhydrated (4.4 ± .8 mm) than when they were dehydrated (6.7 ± .9 mm).

Although dehydration influenced performance on the double-step task in the group level analysis, after accounting for the natural inverse relationship existing between movement time and spatial error (lower movement times are associated with larger errors), hierarchical regressions revealed no significant relationships between the level of dehydration achieved (overall, in the sauna, or overnight) and change in performance errors or time between the euhydration and dehydration conditions (all ps > .252).

To assess how dehydration affected participants' ability to interrupt a planned response, we submitted the percentage of correct interruptions to a 2-hydration level (euhydrated, dehydrated) by 4 – stimulus-onset asynchrony (SOA; 50, 100, 150, 200 ms) repeated-measures ANOVA. This analysis revealed a significant main effect of SOA, $F(3,13) = 5.52$, $p =.003$, such that as the timing of the stop signal was increasingly delayed (as SOA increased), it became increasing more difficult to interrupt the planned response. Longer SOAs of 150 ms (71.6 ± 3.2%) or 200 ms (66.2 ± 3.2%) generated fewer correct interruptions than SOAs of either 50 ms (81.3 ± 3.2%) or 100 ms (83.9 ± 3.2%).

Although there was no significant main effect of hydration level, $F(1, 13) = .01$, $p = .912$, there was a significant interaction of delay and hydration level, $F(3, 13) = 3.68$, $p = .041$. Planned comparisons of hydration levels at each SOA level revealed that at the longest SOA (200 ms), participants interrupted their planned responses more successfully when euhydrated (74.5 ± 4.6%) than when dehydrated (57.9 ± 5.2%), $p = .019$. Finally, regression analyses focused on the 200 ms SOA revealed no significant relationships between the level of dehydration achieved (overall, in the sauna, or overnight) and change in ability to interrupt planned movements between the euhydration and dehydration conditions (all ps > .074).

Do Performance Changes on Visuomotor Tasks Explain Changes in Rowing Performance?

We were curious about whether declines in rowing performance could be in part explained by dehydration-related changes in performance on the visuomotor tasks, proxies of changes in neural-level functioning. To answer this question, we submitted change in 2000 m time to hierarchical regressions with $\%BMD_{overnight}$ on the first level and measures of visuomotor performance on the second (and third, if necessary) level. The results of these analyses are presented in Table 4. Analysis of change in movement time on double-step

DOI: 10.31236/osf.io/pv9dw

performance showed that there was a significant predictive relationship between the change in performance on double step after dehydration and the change in performance on the 2000 m time trial after dehydration. Increases in double-step task movement time accounted for an additional 31% of the dehydration-related increases in rowing time above and beyond the change in performance accounted for by $\%BMD_{overnight}$. Together with our group-level finding that accuracy on movement reversals is compromised in the dehydration condition, this result indicates that change in rowing performance with overnight dehydration can be partially accounted for by changes in time needed for the central nervous system to plan and execute speeded, targeted movements.

Table 4: Results of Hierarchical Regression Assessing If Change in 2000 m Time (s) is Explained by Change in Performance on Visuomotor Tasks Over and Above $\%BMD_{overnight}$

Predictor Variable	*R^2 change*	*pr*	*T (df)*	*P*
Interception				
$\%BMD_{overnight}$	.470	-.694	-2.89 (11)	.018
Change in Success Rates	.042	.162	.494 (10)	.633
Change in Arrival Time	.000	-.028	-.085 (9)	.934
Double-Step Task				
$\%BMD_{overnight}$	.472	-.883	-10.95 (11)	.001
Change in Movement Time	.310	.806	7.93 (10)	.001*
Change in Accuracy	.034	.392	2.49 (9)	.018*
Stop Signal Task				
$\%BMD_{overnight}$	.504	-.728	-3.48 (11)	.005
Change in Success Rates	.022	.208	.706 (10)	.495

Discussion

The goal of the present investigation was to determine the effect of mild BMD dehydration on rowing performance. The participants experienced significant performance declines in the dehydration condition on mean 2000 m trial time and power, on tests of their ability to adjust to a visual perturbation during reaching performance, and on their ability to interrupt a planned motor response, in comparison to their euhydrated performance. These declines occurred despite a two-hour rehydration window, implemented to simulate competition circumstances, between reaching peak dehydration and performing. While participants' overall level of dehydration did not predict their increase in rowing trial-time, increases in rowing trial-time were significantly accounted for by the proportion of dehydration participants achieved through fluid abstinence overnight. Increases in rowing trial-time were not significantly related to the proportion of dehydration participants achieved in the sauna. Finally, increases in rowing trial times were also explained by dehydration-related changes in movement time and accuracy on reaching trials demanding an adjustment to a visual perturbation, once the relationship between rowing trial time and overnight dehydration was accounted for. These findings indicate that the method by which dehydration is achieved is important: dehydration methods that involve abstaining from drinking fluids for an extended period of time predicted rowing performance declines, whereas achieving similar levels of dehydration over a relatively short duration (in the sauna) had no effect on rowing performance. The finding that performance impairment is associated more strongly with prolonged fluid abstinence than with a short-term method such as thermal dehydration is novel and may explain discrepancies between previously-reported studies.

Several other studies in which rowers performed time trials have reported significant declines in performance after prolonged fluid abstinence with rehydration. Performance impairments on the order of 1-4 seconds have been found consistently on 2000 m time trials (all with the same two-hour pre-race rehydration window) when participants achieve 4%BMD and no specific weight loss technique is mandated [5, 22, 23]. However, when dehydration is prolonged and maintained over longer time frames, its effects on performance are increased substantially. For example, rowers who achieved 5.6% BMD the night before weigh-in (using a combination of light exercise and fluid restriction) and were required to maintain that dehydration overnight experienced a 22-second performance decrement relative to euhydrated performance [3]. Although participants in the latter investigation faced greater levels of dehydration (~5.6 %BMD) than the aforementioned studies (~ 4% BMD), some degree of this weight change is likely attributable to the fact that food as well as fluid was restricted. By contrast, when dehydration is maintained over a shorter time, performance effects are reduced. Rowers who achieved 3.3% BMD by combining fluid abstinence with an exercise task immediately before the weigh-in found a negligible change in rowing performance [4]. In line with the findings of the present study, dehydration practices that increase the time over which individuals must be dehydrated seem to exacerbate performance impairments. Although it is possible that these inconsistent findings may be attributable to different rehydration protocols, the time frame and technique through which dehydration occurs may be equally as important to performance as the degree of dehydration achieved.

Differences in thermal dehydration and fluid abstinence may be explained by their duration

Blood parameters were not monitored in the present investigation, so we offer the following as a possible explanation for differences between fluid abstinence and thermal dehydration. Further research will be required to test the details of this explanation. We propose that the observed difference in performance associated with these two dehydration techniques may be related to the difference in time implicit in each. This difference in duration may have distinct effects on the plasma osmolality increase expected as blood water content declines with dehydration [29]. While both fluid abstinence and thermal dehydration stimulated an equivalent decline in the mass of total body water lost, fluid abstinence achieved this over a much longer time frame than sauna exposure (thermal dehydration). We suggest that this longer time frame allowed a greater involvement of the renal system in regulating plasma osmolality [29], limiting increases in blood osmolality in rowers who relied primarily on fluid abstinence as compared to those who relied on thermal dehydration at a given BMD [30, 31]. This hypothesis is supported by research showing that a long-duration, 12-hour fluid restriction protocol produced 1.5% BMD and blood osmolality levels that were not different from no-dehydration controls in cyclists [32]. A short-duration, 2-hour exercise-based dehydration protocol, by contrast, resulted in significant increases in plasma osmolality across 4 different levels of %BMD ranging from 1.1 %BMD to 4.2 %BMD dehydration [16].

If this hypothesis is correct, and blood osmolality changes do depend on the method by which dehydration is induced, this difference may have important implications for competition because it may change the rate of rehydration during the rehydration period. Elevated blood osmolarity drives water from the gut into the vasculature restoring blood volume more rapidly [29], and greater blood volume at time of competition is associated with improved performance by maintaining cardiac efficiency and heat dissipation during maximal exertion [33]. Indeed, research shows that treatments designed to elevate blood osmolality – the administration of sodium pills to dehydrated participants – speed rehydration [29]: Participants receiving doses of sodium while rehydrating displayed a 60% plasma volume recovery in the first hour of rehydration compared to 13% plasma volume restoration in participants rehydrating with water alone [29]. Thus, individuals experiencing short-term dehydration in the sauna may be protected from dehydration-related performance declines by faster restoration of lost plasma volume when rehydrating before competition.

Reductions in visuomotor performance partially explain reductions in rowing performance

We found that dehydration-related changes in the time needed to plan and execute speeded, targeted movements partially accounted for dehydration-related changes in rowing performance. Measures of visuomotor ability were initially included to probe the central nervous system functions on which the execution of proper rowing technique (control of blade timing and placement) relies. Although rowing technique plays a greater role in performance on open-water races than on the rowing ergometer, visuomotor control is involved in judging reach distance, stroke length, and maintaining balance on the ergometer, all factors that affect stroke efficiency. Recent reports indicate that golfing performance [i.e., the speeded use of a tool to hit a visual target precisely [15]] and changes in balance control [34] are directly related to levels of mild dehydration. Even small changes in the neural control of targeted reaching movements may have significant accumulating effects on overall trial time.

Our participants included both male and female heavyweights and lightweights, and no effect of sex or weight class was detected, suggesting no differences across these demographics. The age range and level of experience of the sample is reflective of university rowers. While Olympic rowers tend to be slightly older and more experienced, we have no reason to believe a physiological mechanism of dehydration would affect this population any differently. Though the mindset of such athletes may be different – elite athletes may better ignore the knowledge of being dehydrated – multiple regression found no statistically significant effect of predicted performance after either magnitude of dehydration or time of dehydration was factored in. To better model competition, the amount of fluid or food ingested during the two-hour recovery phase was not controlled. Participants were instructed to, and verbally confirmed, having eaten and drank to satiety. Any measure of hydration by weight following the recovery phase would have been artificially elevated by the concurrent

DOI: 10.31236/osf.io/pv9dw

consumption of food. Future studies including measures of blood plasma levels will address these issues.

Conclusion

We found that even mild levels of dehydration had significant effects on rowing performance and measures of visuomotor control. In addition, we found that that prolonged fluid restriction is more detrimental to rowing performance than short-term thermal dehydration. Such an effect of dehydration method may explain the wide range in performance impairment (from 0 to 22 seconds) found, despite similar magnitudes of water loss (3.3-5.6 %BMD), in previous investigations of rowing performance and dehydration [3-5 22, 23]. Future research should test the effect of dehydration method on performance and plausibility of our proposed mechanism. Should it be found with reliability that utilizing short-term thermal dehydration tactics proximate to weigh-ins is superior to prolonged fluid restriction, the global lightweight community in rowing and perhaps in other sporting events that have weight criteria could use this information to modify their practices.

Contributions

Contributed to conception and design: DJK, LEB

Contributed to acquisition of data: DJK, AN

Contributed to analysis and interpretation of data: DJK, LEB, AN

Drafted and/or revised the article: DJK, LEB, AN

Approved the submitted version for publication: DJK, AN, LEB,

Acknowledgements

The authors would like to acknowledge the advice of Ingrid Brenner and Sarah West. Evan Brault assisted with data collection. This study benefited from the cooperation of the Trent University Athletics Centre and Peterborough Rowing Club, who provided space for data collection. The authors declare that they have no conflicts of interest. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

Funding information

This study was funded by a NSERC Undergraduate Student Research Award to DJK and an NSERC Discovery Grant to LEB.

Data and Supplementary Material Accessibility

Please contact the authors for access to data.

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DOI: 10.31236/osf.io/pv9dw