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Movement Technique and Standing Balance After Graded Exercise-Induced Dehydration

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Context: Hypohydration has been shown to alter neuromuscular function. However, the longevity of these impairments remains unclear.

Objective: To examine the effects of graded exercise-induced dehydration on neuromuscular control 24 hours after exercise-induced hypohydration.

Design: Crossover study.

Setting: Laboratory.

Patients or Other Participants: A total of 23 men (age = 21 ± 2 years, height = 179.8 ± 6.4 cm, mass = 75.24 ± 7.93 kg, maximal oxygen uptake [VO_2max] = 51.7 ± 5.5 mL·kg^{-1}·min^{-1}, body fat = 14.2% ± 4.6%).

Intervention(s): Participants completed 3 randomized exercise trials: euhydrated arrival plus fluid replacement (EUR), euhydrated arrival plus no fluid (EUD), and hypohydrated arrival plus no fluid (HYD) in hot conditions (ambient temperature = 35.2°C ± 0.6°C, relative humidity = 31.3% ± 2.5%). Each trial consisted of 180 minutes of exercise (six 30-minute cycles: 8 minutes at 40% VO_2max; 8 minutes, 60% VO_2max; 8 minutes, 40% VO_2max; 6 minutes, passive rest) followed by 60 minutes of passive recovery.

Main Outcome Measure(s): We used the Landing Error Scoring System and Balance Error Scoring System (BESS) to measure movement technique and postural control at preexercise, postexercise and passive rest ($POST_{EX}$), and 24 hours postexercise ($POST_{24}$). Differences were assessed using separate mixed-design (trial × time) repeated-measures analyses of variance.

Results: The magnitude of hypohydration at $POST_{EX}$ was different among EUR, EUD, and HYD trials (0.2% ± 1%, 3.5% ± 1%, and 5% ± 0.9%, respectively; $P < .05$). We observed no differences in Landing Error Scoring System scores at preexercise (2.9 ± 1.6, 3.0 ± 2.1, 3.0 ± 2.0), $POST_{EX}$ (3.3 ± 1.5, 3.0 ± 2.0, 3.1 ± 1.9), or $POST_{24}$ (3.3 ± 1.9, 3.2 ± 1.4, 3.3 ± 1.6) among the EUD, EUR, and HYD trials, respectively ($P = .90$). Hydration status did not affect BESS scores ($P = .11$), but BESS scores at $POST_{EX}$ (10.4 ± 1.1) were greater than at $POST_{24}$ (7.7 ± 0.9; $P = .03$).

Conclusions: Whereas exercise-induced dehydration up to 5% body mass did not impair movement technique or postural control 24 hours after a prolonged bout of exercise in a hot environment, postural control was impaired at 60 minutes after prolonged exercise in the heat. Consideration of the length of recovery time between bouts of exercise in hot environments is warranted.

Key Words: fluid replacement, recovery, balance, jump-landing task

Key Points

- Prolonged, moderate-intensity exercise followed by 1 hour of passive rest in a hot environment impaired static balance, regardless of hydration status.
- These impairments were negated at 24 hours postexercise, suggesting that they were acute.
- The disruption in balance may increase the risk of lower extremity injuries when individuals are required to perform prolonged bouts of physical activity with minimal break time.
- Clinicians should incorporate adequate work-to-rest ratios with individualized hydration plans to optimize human health and performance when individuals perform prolonged exercise or physical activity in hot environmental conditions.

Musculoskeletal injury has been associated with deficits in neuromuscular control, with alterations in balance or movement technique being the primary risk factors for lower extremity injuries.[1–3] Identifying the physiological mechanisms that contribute to impairment of neuromuscular control may assist in reducing the risk of lower extremity injury. Factors including exercise-induced fatigue,[4,5] hypohydration,[6,7] and a combination of hypohydration and exercise-induced hyperthermia[8] have been shown to alter either movement technique or balance and may consequently increase the risk of injury. Researchers[7,9–11] have postulated that

hydration-mediated (depletion in plasma volume or increase in plasma osmolality [P_{OSM}] or both) alterations in neuromuscular control are derived from changes in vestibular function and vestibular afferent sensitivity; however, these mechanisms may not explain any changes in neuromuscular control after P_{OSM} returns to normal limits, albeit the individual remains underhydrated as evidenced by increased vasopressin and cortisol secretion. With evidence indicating that hypohydration impairs balance and neuromuscular function, mitigating this risk by modifying behaviors, such as improving hydration strategies during exercise in the heat, may optimize safety and performance during physical activity.

Whereas hypohydration has been noted to adversely affect physiological function,[12] exercise performance,[13,14] and cognitive function,[15] its effects on neuromuscular control remain unclear.[6–8,16,17] Gauchard et al[7] and Derave et al[6] found that balance was impaired when the level of hypohydration reached 2% to 3% body mass loss; yet Seay et al[16] and Patel et al[17] observed no differences despite hypohydration of the same magnitude. These results may be inconclusive due to the confounding effects of hyperthermia and fatigue, given other evidence[18] that exercise-induced fatigue impaired standing balance up to 15 minutes postexercise. In attempts to control for hyperthermia and exercise-induced fatigue,[8,16,19] investigators demonstrated that impairments in neuromuscular control were present only when hypohydration was coupled with hyperthermia[8] or exposure to a cold environment.[19]

Researchers have examined the effects of hypohydration, hyperthermia, and fatigue on neuromuscular control immediately postexercise and after an acute recovery period (60–90 minutes). However, little is known about how exercise-induced hypohydration affects neuromuscular control after a longer bout of recovery, which is important in the context of sport, where consecutive days of training or training plus competition or both are not uncommon. Therefore, the purpose of our study was to examine how neuromuscular control, as measured by a movement-technique task and standing-balance task, was affected at 24 hours after exercise-induced dehydration in a hot environment. We hypothesized that greater levels of hypohydration during a prolonged bout of exercise in a hot environment would impair neuromuscular control at 24 hours postexercise.

METHODS

Design

We used a counterbalanced, crossover design in which participants were randomly assigned to each exercise session. The exercise sessions varied with respect to the participant's hydration status on arrival and during exercise: (1) arrived euhydrated and given water to minimize fluid losses during exercise and immediately postexercise recovery (EUR), (2) arrived euhydrated and given no access to water during exercise and immediately postexercise recovery (EUD), and (3) arrived hypohydrated and given no access to water during exercise and immediately postexercise recovery (HYD). Sessions were separated by at least 5 days to allow participants to fully recover before the next testing session. All exercise sessions took place in a climate-controlled chamber (model 2000; Minus-Eleven Inc, Malden, MA) with conditions set at an ambient temperature of 35.2°C ± 0.6°C and a relative humidity of 31.3% ± 2.5%.

Participants

A total of 23 recreationally active men (age = 21 ± 2 years, height = 179.8 ± 6.4 cm, mass = 75.24 ± 7.93 kg, maximal oxygen uptake [VO_2max] = 51.7 ± 5.5 $mL \cdot kg^{-1} \cdot min^{-1}$, body fat = 14.2% ± 4.6%) volunteered for this study. All participants reported exercising at least 4 to 5 days per week for a minimum of 30 minutes each day. Volunteers were excluded if they were observed to have 1 of the following: (1) fever or illness at the time of testing; (2) a history of cardiovascular, metabolic, or respiratory disease; (3) current musculoskeletal injury that limited their level of physical activity; (4) consumption of >3 alcoholic beverages per day (>21 alcoholic beverages per week); or (5) VO_2max <45 $mL \cdot kg^{-1} \cdot min^{-1}$. Participants provided written informed consent, and the study was approved by the University of Connecticut's institutional review board.

Procedures

Familiarization Sessions. Before the 3 exercise trials, participants reported to the laboratory for familiarization sessions that consisted of 2 stages. For the first stage, participants arrived at the laboratory and we obtained their height using a standard stadiometer and body fat percentage using skinfold (Lange skinfold caliper; Beta Technologies Inc, Ann Arbor, MI) measurements at the chest, abdomen, and thigh.[20] Next, participants performed a VO_2max test on a motorized treadmill (NordicTrack; ICON Health & Fitness, Logan, UT) to ensure they met the eligibility criteria (VO_2max >45 $mL \cdot kg^{-1} \cdot min^{-1}$) for inclusion in the study. Oxygen uptake and related gas exchange were measured using open-circuit spirometry (TrueOne 2400 metabolic measurement system; Parvo Medics Inc, Salt Lake City, UT). The criteria used to determine VO_2max were (1) respiratory gas exchange ratio of >1.10, (2) ± 10 $beats \cdot min^{-1}$ of age-predicted maximal heart rate, (3) plateau of ≤150 mL $O_2 \cdot min^{-1}$, and (4) rating of perceived exertion of >17 (6–20 scale).

After the VO_2max test, participants provided a nude body mass (NBM) to the nearest 0.01 kg using a calibrated scale (Defender 5000; OHAUS Corp, Parsippany, NY), performed the movement-technique and standing-balance tasks to familiarize themselves with these tasks to reduce the likelihood of a learning effect occurring during the exercise trials, and completed 30 minutes of exercise on the motorized treadmill (8 minutes at 40% VO_2max; 8 minutes, 60% VO_2max; 8 minutes, 40% VO_2max; 6 minutes, passive rest) in the climate-controlled chamber that mimicked the exercise intensity of the testing sessions. A final NBM was measured after the 30-minute exercise bout to enable calculation of total sweat loss, which was used to establish individualized fluid needs during exercise in the EUR exercise trial.

For the second stage of familiarization, participants arrived at the laboratory on 3 consecutive mornings in a fasting state to provide an accurate baseline hydration assessment. For 24 hours before each familiarization day, they collected their urine and recorded food and fluid intake. On each of the 3 familiarization days, participants

arrived at the laboratory between 6:00 AM and 9:00 AM (24 hours after the start of the collection period), provided their 24-hour urine sample and diet record, and obtained NBM to the nearest 0.01 kg. The 24-hour urine sample was assessed for total volume (U_{VOL}) to the nearest 0.0001 kg (Ranger 3000; OHAUS, Parsippany, NJ), urine specific gravity (USG; Reichert TS 400; Reichert Inc, Depew, NY), and urine osmolality (U_{OSM}) using freezing-point depression (model 3320; Advanced Instruments, Norwood, MA).

Exercise Trials. For the EUR and EUD exercise trials, participants were instructed to consume an additional 500 mL of water before going to sleep and upon waking the next morning to ensure euhydration. For the HYD trial, they were restricted from consuming fluids or water-heavy foods for 22 hours before the start of the trial to approximate a hypohydration level of approximately 1% to 2% of baseline body mass. To account for any potential confounding effects of time, participants were tested at the same time of day ± 1 hour.

At 24 hours before each testing session, participants arrived at the laboratory, provided NBM, and were given a clean container in which to collect all urine for the 24 hours leading up to the testing session. Upon arrival at the laboratory for the testing session, they provided their 24-hour urine void, inserted a rectal thermistor (model 401AC; Measurement Specialties, Hampton, VA) 10 cm past the anal sphincter to assess rectal temperature (T_{REC}), and donned a heart-rate monitor (Ironman; Timex USA, Middlebury, CT). We assessed T_{REC} and heart rate every 10 minutes throughout the trial. Pre-exercise (PRE_{EX}) measures of NBM, U_{VOL}, USG, and U_{OSM} were obtained, and participants performed PRE_{EX} postural- and movement-control assessment tests and entered the climate-controlled chamber for the exercise portion of the testing session.

They sat inside the climate-controlled chamber for 15 minutes to equilibrate to the environmental conditions. Before the start of exercise and while remaining seated, each participant provided a blood sample for P_{OSM} assessment. They then performed six 30-minute cycles of exercise on a motorized treadmill (8 minutes at 40% VO_2max; 8 minutes, 60% VO_2max; 8 minutes, 40% VO_2max; 6 minutes, rest while seated), followed by a 60-minute period of passive rest while seated. Our intent for this exercise protocol was to determine an exercise length that resulted in progressive dehydration during testing sessions in which no fluid was consumed. For the session in which fluid losses were minimized (EUR trial), participants consumed a fluid volume that matched their calculated sweat rate, rationed in equal boluses during each exercise cycle. After exercise and passive rest ($POST_{EX}$), each person provided a blood sample while seated and then exited the climatic chamber to perform the postural- and movement-control protocols.

Before leaving the laboratory, participants were instructed to collect all urine and record all foods and fluids consumed for 24 hours after the exercise trial. This study was part of a larger study examining the effects of prescribed and ad libitum rehydration protocols on urinary and hematologic hydration markers at 24 hours postexercise. Participants were randomly allocated to either the prescribed or ad libitum rehydration group for all 3 exercise trials. Those in the prescribed rehydration group were instructed to consume 150% of their fluid losses to ensure adequate rehydration and account for associated urinary losses. The ad libitum group was not given any instruction regarding rehydration to allow for free-living fluid consumption. Statistical analyses revealed no differences in any neuromuscular measures between the prescribed and ad libitum groups ($P > .05$); thus, their results were combined to compare only the effects of the exercise trials.

Participants returned to the laboratory 24 to 30 hours after the exercise trial ($POST_{24}$) to return their 24-hour urine sample and 24-hour diet record, provide a blood sample while in a seated position, and perform the postural- and movement-control protocols. We measured NBM, U_{VOL}, USG, U_{OSM}, and P_{OSM}; participants then completed the movement-technique and standing-balance tasks in a thermoneutral environment.

Movement and Postural-Control Assessments. The movement-technique and standing-balance tasks were identical across all tested times (PRE_{EX}, $POST_{EX}$, and $POST_{24}$). The assessments consisted of the Balance Error Scoring System (BESS) and a jump-landing test that was graded using the Landing Error Scoring System (LESS). The BESS is a validated test[21] used to assess postural control and consists of 3 stances on 2 surfaces: double-legged stance (DL) on a firm surface (Firm), DL on a foam surface (Foam), single-legged stance (SL) Firm, SL Foam, tandem stance (TD) Firm, and TD Foam. Each position was performed for 20 seconds, and participants were instructed to keep their hands on their hips and their eyes closed for the duration of each stance. For the SL Firm and Foam positions, they were instructed to stand on the dominant foot with the contralateral limb flexed at the hip and knee. The *dominant foot* was self-selected by the participant as the foot used to kick a ball for maximal distance. The TD Firm and Foam positions required participants to stand with the nondominant foot in front of and in line with the dominant foot.

Given the high interrater (intraclass correlation coefficient = 0.93) and intrarater (intraclass correlation coefficient = 0.96) reliability of the BESS,[22] 2 experienced authors (W.M.A. and L.W.V.) graded the test in real time. The examiners were not blinded to the condition or trial. the errors during each stance were totaled, and the values for the 6 positions were then summed for the overall score. The following movements constituted errors: hands lifting off of the iliac crest, opening the eyes, stepping down, stumbling, moving the hip in >30° of flexion or abduction during the SL, lifting the forefoot or heel, or remaining out of the position for >5 seconds.[21]

During the jump-landing task, participants were instructed to jump down from a 30-cm–high box with both limbs to a distance equaling 50% of their standing height. Immediately upon landing, they were to jump straight up in the air for maximal vertical height. Participants performed 3 jump landings; if 1 of the 3 jumps was performed incorrectly, an additional jump was performed. The jump-landing task was videotaped using cameras (model FS400; Canon USA Inc, Lake Success, NY) placed in front and to the side of the participant to capture movement in both the frontal and sagittal planes. The videos were graded at a later time by a single rater (S.E.S.M.) who had experience grading the LESS-4 (intraclass correlation coefficient = 0.89) and was blinded to all

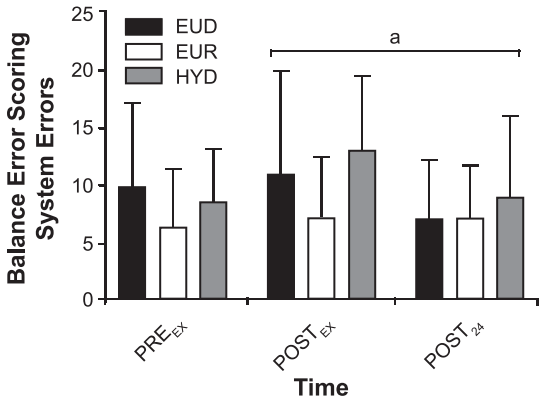

Figure 1. Total Balance Error Scoring System scores during the EUD, EUR, and HYD trials at pre-exercise (PRE_{EX}), postexercise and passive recovery ($POST_{EX}$), and 24 hours postexercise ($POST_{24}$). Error bars depict 95% confidence intervals. Abbreviations: EUD, euhydrated arrival and progressive dehydration during exercise and recovery; EUR, euhydrated arrival, fluid intake to match sweat losses during exercise, and fluid replacement during recovery; HYD, hypohydrated arrival and progressive dehydration during exercise and recovery. [a] Main effect for time between postexercise and passive recovery and 24 hours postexercise ($P < .05$).

test sessions involving the LESS. Higher scores on the LESS are associated with higher-risk lower extremity movement patterns, which have been correlated with an increased incidence of lower extremity injuries.[3]

Blood-Collection Measures. For each blood-sampling timepoint (PRE_{EX}, $POST_{EX}$, and $POST_{24}$), participants provided 10 mL of blood taken from an antecubital vein (Vacutainer Safety-Lok Blood Collection Set; Becton Dickinson, Franklin Lakes, NJ), drawn into lithium-heparin pretreated tubes (Vacutainer; Becton Dickinson), and centrifuged for 15 minutes at 3000 revolutions per minute for assessment of P_{OSM}. We measured P_{OSM} in duplicate using freezing-point depression (model 3320; Advanced Instruments).

Statistical Analyses

All values are presented as mean ± standard deviation. In addition, differences between variables are depicted as mean differences (MDs) and 95% CIs. Normality was assessed using Q-Q normal plots and the Shapiro-Wilk test. If sphericity was violated (Mauchly sphericity test value $<$ 0.05), we applied the Greenhouse-Geisser correction. To confirm the lack of an order effect on the outcomes of the BESS and LESS across the randomized and counterbalanced trials, we conducted 2 × 2 repeated-measures analyses of variance (ANOVAs); no order effect was present (P values $>$ .05). Trial × time repeated-measures ANOVAs with T_{REC} as a covariate were used to evaluate differences between hydration measures and movement- and balance-task measures independent of the mode of rehydration. To assess the differences in physiological variables (ie, hematologic, urinary, and changes in body mass), separate trial × time repeated-measures ANOVAs were computed. For findings that were different, we performed Tukey post hoc analysis to determine where the differences lay between factors. The magnitude of differences was measured using η^2, with the effect sizes interpreted as *small* ($\eta^2 < 0.01$), *medium* ($0.01 < \eta^2 > 0.06$), or *large* ($\eta^2 > 0.14$). Pearson product moment correlations were determined to assess the relationships between hydration variables and BESS and LESS scores. All statistical analyses were calculated using SPSS (version

Table 1. Balance Error Scoring System Individual Component Scores

Balance Error Scoring System Component Stance	Trial	Time, Mean ± SD		
		Pre-exercise	Postexercise and Passive Recovery	24 h Postexercise
Firm surface				
Double legged	EUD	0 ± 0	0 ± 0	0 ± 0
	EUR	0 ± 0	0 ± 0	0 ± 0
	HYD	0 ± 0	0.04 ± 0.21	0 ± 0
Single legged	EUD	1.91 ± 1.95	2.65 ± 2.24[a]	1.57 ± 1.65
	EUR	1.35 ± 1.75	1.17 ± 1.53[a]	1.17 ± 1.23
	HYD	1.96 ± 1.92	3.22 ± 2.11[a]	1.87 ± 2.12
Tandem	EUD	0.57 ± 1.20	1.00 ± 1.88	0.48 ± 0.90
	EUR	0.26 ± 0.54	0.52 ± 1.04	0.48 ± 0.95
	HYD	0.52 ± 0.95	1.17 ± 1.30	0.83 ± 1.47
Foam surface				
Double legged	EUD	0.35 ± 1.67	0.48 ± 2.09	0 ± 0
	EUR	0.13 ± 0.46	0.13 ± 0.63	0 ± 0
	HYD	0.09 ± 0.29	0.13 ± 0.46	0.22 ± 0.74
Single legged	EUD	4.78 ± 2.49	4.43 ± 2.55[a]	3.39 ± 1.97
	EUR	3.26 ± 1.96	3.26 ± 1.96[a]	3.26 ± 1.91
	HYD	4.13 ± 2.01	5.17 ± 1.99[a]	3.65 ± 1.94
Tandem	EUD	2.30 ± 2.65	2.39 ± 1.85[b]	1.65 ± 1.80
	EUR	1.39 ± 1.72	2.17 ± 1.92[b]	2.17 ± 1.82
	HYD	1.91 ± 1.65	3.39 ± 2.38[b]	2.39 ± 2.10

Abbreviations: EUD, euhydrated arrival and progressive dehydration during exercise and recovery; EUR, euhydrated arrival, fluid intake to match sweat losses during exercise, and fluid replacement during recovery; HYD, hypohydrated arrival and progressive dehydration during exercise and recovery.

[a] Main effect of time (postexercise and passive recovery >24-h postexercise; $P < .05$).

[b] Main effect of time (postexercise and passive recovery >pre-exercise; $P < .05$).

Table 2. Associations Between Hydration Variables and Movement-Technique and Postural-Control Variables

Variable	Percentage of Body Mass Loss	Urine Volume	Urine Specific Gravity	Urine Osmolality	Plasma Osmolality
Balance Error Scoring System score					
Total	0.098	0.06	−0.002	−0.06	0.086
Firm surface					
Double-legged stance	0.139[a]				−0.035
Single-legged stance	0.180[b]	−0.026	0.06	−0.065	0.227[b]
Tandem stance	0.133	0.164[a]	0.033	0.014	−0.049
Foam surface					
Double-legged stance	−0.027	−0.027	−0.08	−0.038	0.054
Single-legged stance	0.194[b]	0.054	−0.121	−0.069	0.132
Tandem stance	0.186[b]	0.045	−0.039	−0.064	0.183[b]
Landing Error Scoring System	0.054	0.035	−0.114	0.114	−0.089

[a] Correlation ($P < .05$).
[b] Correlation ($P < .01$).

21.0; IBM Corp, Armonk, NY). The α level was set a priori at .05.

RESULTS

Balance Error Scoring System

We observed no trial × time interactions for total BESS score ($F_{4,88} = 1.937$, $P = .11$, $\eta^2 = 0.081$) or any individual components of the BESS (P values $> .05$). However, a main effect of time was present for total BESS score ($F_{1.569,34.520} = 5.963$, $P = .01$, $\eta^2 = 0.213$; Figure 1) and several of the individual components: SL Firm ($F_{1.308,28.780} = 4.179$, $P = .04$, $\eta^2 = 0.160$), SL Foam ($F_{2,44} = 3.781$, $P = .03$, $\eta^2 = 0.147$), and TD Foam ($F_{2,44} = 3.985$, $P = .03$, $\eta^2 = 0.153$; Table 1). The analyses depicted an increase in BESS score at $POST_{EX}$ versus $POST_{24}$ (total, SL Firm, and SL Foam) and PRE_{EX} (TD Foam) timepoints. We noted a main effect of trial in the total BESS score ($F_{1.636,35.994} = 7.737$, $P = .003$, $\eta^2 = 0.260$) and SL Firm ($F_{2,44} = 11.272$, $P < .001$, $\eta^2 = 0.339$) and SL Foam ($F_{2,44} = 7.556$, $P = .002$, $\eta^2 = 0.256$) conditions; these main effects indicated that the mean BESS scores for the HYD trial across all 3 times (PRE_{EX}, $POST_{EX}$, and $POST_{24}$) were greater than the mean BESS scores for the EUR trial.

Pearson product moment correlation analyses revealed that an increase in the percentage of body mass loss (%BML) was associated with increased scores (ie, impairments) in the DL Firm ($r = .139$, $P = .045$), SL Firm ($r = .180$, $P = .01$), SL Foam ($r = .194$, $P = .005$), and TD Foam ($r = .186$, $P = .007$) components of the BESS (Table 2). Similarly, an increase in P_{OSM} was associated with increased scores (impairments) in the SL Firm ($r = .227$, $P = .001$), TD Firm ($r = .164$, $P = .02$), and TD Foam ($r = .183$, $P = .009$) components of the BESS.

Landing Error Scoring System

We observed no differences in LESS scores at PRE_{EX} (2.9 ± 1.6, 3.0 ± 2.1, 3.0 ± 2.0), $POST_{EX}$ (3.3 ± 1.5, 3.0 ± 2.0, 3.1 ± 1.9), or $POST_{24}$ (3.3 ± 1.9, 3.2 ± 1.4, 3.3 ± 1.6) among the EUD, EUR, and HYD trials, respectively ($F_{4,80} = 0.259$, $P = .90$, $\eta^2 = 0.013$). Scores on the LESS were not associated with any of the hydration variables assessed (P values $> .05$; Table 2).

Table 3. Physiological Measures of Hydration Status

Variable	Trial	Time, Mean ± SD		
		Pre-exercise	Postexercise and Passive Recovery	24 h Postexercise
24-h Urine volume, L	EUD	2.62 ± 1.40		1.74 ± 1.26[d]
	EUR	2.58 ± 1.23		2.11 ± 1.40[d]
	HYD	1.72 ± 1.03		1.36 ± 1.22[d]
24-h Urine osmolality, mOsm/kg	EUD	441 ± 177		583 ± 262[d]
	EUR	411 ± 207		443 ± 158[d]
	HYD	605 ± 212		705 ± 295[d]
24-h Urine specific gravity	EUD	1.013 ± 0.005		1.017 ± 0.007[d]
	EUR	1.012 ± 0.006		1.013 ± 0.004[d]
	HYD	1.016 ± 0.006		1.020 ± 0.008[d]
Plasma osmolality, mOsm/kg	EUD	289 ± 8	301 ± 10[c]	294 ± 7
	EUR	290 ± 9	285 ± 7	291 ± 7
	HYD	298 ± 11[a,b]	309 ± 14[a,b]	292 ± 9

Abbreviations: EUD, euhydrated arrival and progressive dehydration during exercise and recovery; EUR, euhydrated arrival, fluid intake to match sweat losses during exercise, and fluid replacement during recovery; HYD, hypohydrated arrival and progressive dehydration during exercise and recovery.

[a] Difference between the HYD and EUR trials ($P < .05$).
[b] Difference between the HYD and EUD trials ($P < .05$).
[c] Difference between the EUD and EUR trials ($P < .05$).
[d] Main effect of time between pre-exercise and 24 h postexercise ($P < .05$).

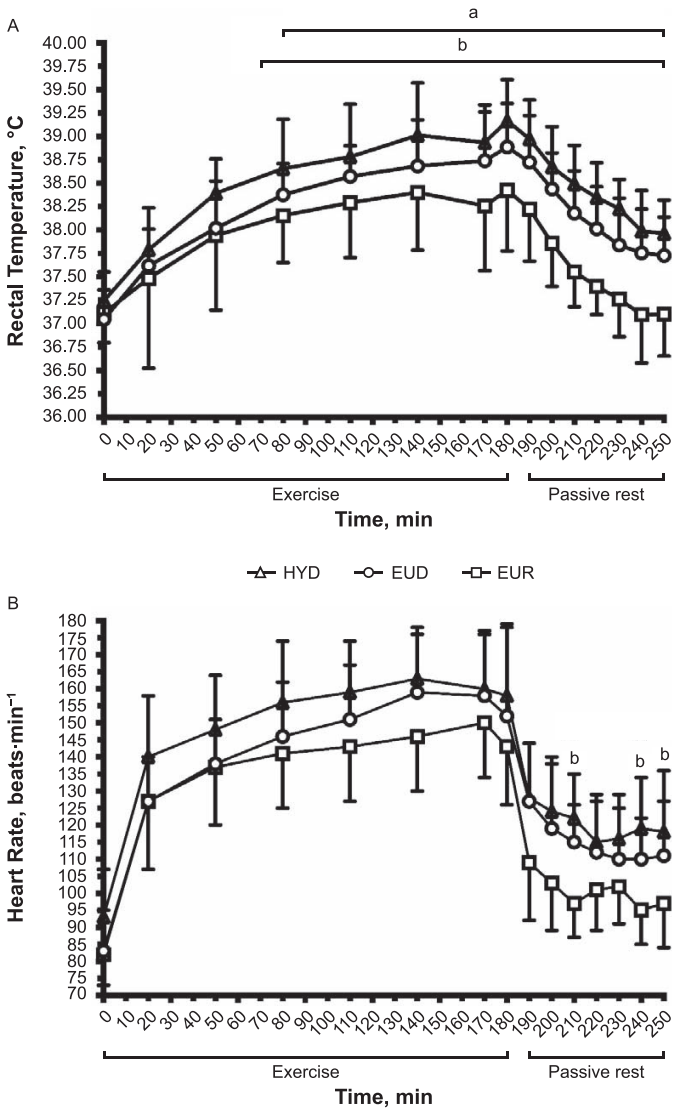

Figure 2. A, Rectal temperature and, B, heart rate during the 3-hour exercise and 1-hour passive rest protocol. Error bars depict 95% confidence intervals. Abbreviations: EUD, euhydrated arrival and progressive dehydration during exercise and recovery; EUR, euhydrated arrival, fluid intake to match sweat losses during exercise, and fluid replacement during recovery; HYD, hypohydrated arrival and progressive dehydration during exercise and recovery. [a] Difference between the EUD and EUR trials ($P < .05$). [b] Difference between the HYD and EUR trials ($P < .05$).

Physiological Variables

Hydration Variables. We found no differences in NBM at 24 hours before each testing session for the EUD, EUR, and HYD trials versus the baseline measures ($F_{2,66} = 0.607$, $\eta^2 = 0.018$, $P = .55$), which suggested that participants' day-to-day hydration status remained consistent throughout the study. At PRE_{EX}, the %BML was greater ($F_{2,66} = 30.149$, $\eta^2 = 0.477$) in the HYD (1.26% ± 1.45%) than in the EUD (MD = 2.15% [95% CI = 1.40%, 2.90%]; $P < .001$) and EUR (MD = 2.06% [95% CI = 1.31%, 2.81%]; $P < .001$) trials. At $POST_{EX}$, the %BML was greater ($F_{2,66} = 138.390$, $\eta^2 = 0.807$) in the HYD (5.00% ± 2.23%) than in the EUD (MD = 1.55% [95% CI = 0.85%, 2.26%]; $P < .001$, $\eta^2 = 1.58$) and EUR (MD = 4.79% [95% CI = 4.08%, 5.49%]; $P < .001$, $\eta^2 = 4.93$) trials. The %BML was greater in the EUD (3.45% ± 1.04%) than in the EUR (MD = 3.23% [95% CI = 2.53%, 3.94%]; $P < .001$, $\eta^2 = 1.34$) trial at $POST_{EX}$ ($F_{2,66} = 138.390$, $P < .05$, $\eta^2 = 0.807$).

The urinary and hematologic measures are shown in Table 3. We observed no differences among trials for any of the urinary and hematologic measures (P values $> .05$); however, at $POST_{24}$, measures of U_{VOL} ($F_{1,65} = 20.549$, $P < .001$, $\eta^2 = 0.237$), USG ($F_{1,66} = 18.665$, $P < .001$, $\eta^2 = 0.220$), and U_{OSM} ($F_{1,65} = 10.466$, $P = .002$, $\eta^2 = 0.139$) were greater than those at PRE_{EX}. The P_{OSM} was greater in the HYD trial ($F_{4,126} = 31.148$, $P < .001$, $\eta^2 = 0.497$) at PRE_{EX} and $POST_{EX}$ than in the EUD (PRE_{EX}: MD = 10 mOsm·kg^{-1} [95% CI = 3, 18 mOsm·kg^{-1}]; $P = .002$, $\eta^2 = 0.98$; $POST_{EX}$: MD = 9 mOsm·kg^{-1} [95% CI = 2, 16 mOsm·kg^{-1}]; $P = .008$, $\eta^2 = 0.65$) and EUR (PRE_{EX}: MD = 9 mOsm·kg^{-1} [95% CI = 2, 16 mOsm·kg^{-1}]; $P = .01$, $\eta^2 = 0.75$; $POST_{EX}$: MD = 16 mOsm·kg^{-1} [95% CI = 9, 23 mOsm·kg^{-1}]; $P < .001$, $\eta^2 = 2.17$) trials. The P_{OSM} was also greater in the EUD than in the EUR trial at $POST_{EX}$ (MD = 7 mOsm·kg^{-1} [95% CI = 0, 14 mOsm·kg^{-1}]; $P = .03$, $\eta^2 = 1.85$).

Body Temperature and Heart Rate. The T_{REC} was greater in the HYD and EUD trials than in the EUR trial beginning at minutes 70 and 80 of exercise, respectively ($F_{50,250} = 2.709$, $P < .001$, $\eta^2 = 0.351$; Figure 2A). We detected no differences in heart rate among trials during exercise (Figure 2B), but heart rate in the HYD trial was higher than in the EUR trial ($F_{7.366,73.659} = 2.123$, $P = .049$, $\eta^2 = 0.175$) during recovery at minutes 20, 50, and 60.

DISCUSSION

The purpose of our study was to examine the effects of exercise-induced hypohydration on neuromuscular control after 24 hours of recovery. We are the first to examine movement technique and postural control 24 hours after exercise-induced hypohydration. After acute (1 hour) and prolonged (24 hours) recovery from bouts of exercise in the heat, neuromuscular control remained unaffected despite graded hypohydration of up to 5% body mass. We did find, however, that balance was altered more with prolonged moderate-intensity exercise (3 hours) and 1 hour of passive rest in a hot environment than at $POST_{24}$, independent of hydration status. Our results suggest that any disturbances in balance after prolonged exercise in a hot environment were likely due to the duration and volume of exercise and values returned to baseline by the next day.

DiStefano et al[8] were the first to investigate the individual and combined effects of hypohydration and hyperthermia on movement technique without the confounding variable of fatigue. They showed that a combination of hyperthermia and hypohydration induced by exercise impaired movement technique on the LESS both immediately postexercise and after a 60-minute recovery period.[8] We noted that at 60 minutes after prolonged exercise in hot conditions, LESS scores were unaffected by hypohydration and hyperthermia, which conflicts with the aforementioned findings. The extent of hyperthermia immediately postexercise (range = 38.35°C–39.33°C) and at 60 minutes postexercise (range = 37.52°C–38.48°C) in a hot environment and the magnitude of hypohydration (range, –0.1% to 5.7%) in the earlier study[8] were similar to what we demonstrated (ranges = 38.42°C–39.16°C, 37.09°C–

37.96°C, and 0.2%–5%, respectively). Whether a difference between body temperature at $POST_{EX}$ (37.96°C) and that reported in the previous study (38.48°C) resulted in the different LESS scores is unclear, though other factors may have contributed. The methodologic designs differed in that DiStefano et al[8] required participants to wear a 20.45-kg rucksack on their backs during the exercise bout and while completing the balance and jump-landing tasks, which may have exacerbated the actual and perceived stresses placed on the body.

Researchers[8,18,23–26] who addressed the effects of hypohydration on balance suggested that fatigue was a contributing factor in the increased injury risk postexercise. However, other authors[16,17,19,27] showed that the fatigue-related impairments of postural control are short-lived and can return to baseline soon after exercise ends. Our results revealed that balance errors, measured using the BESS, were higher at $POST_{EX}$ than at $POST_{24}$ independent of hydration status, which contrasts with the findings of DiStefano et al,[8] Patel et al,[17] and Ely et al,[19] who reported that balance scores returned to baseline levels after 25 to 90 minutes of passive rest postexercise. We also determined that the average $POST_{EX}$ BESS score (10.4 ± 1.1) was higher than the average PRE_{EX} BESS score (8.2 ± 0.9); however, this finding was not significantly different ($P = .08$, $\eta^2 = 2.19$).

The differences in balance in our investigation versus the lack of differences in balance observed postexercise in other research[8,17,19] could be attributed to variations in exercise duration and intensity. Specifically, our exercise duration (180 minutes) was longer than that of DiStefano et al[8] (90 minutes) and Patel et al[17] (45 minutes). Our exercise intensity varied between 40% and 60% $V_{O_2}max$, whereas that in the previous works[8,16,17] remained fixed (range = 1.34–1.78 $m \cdot s^{-1}$ and 65%–70% of Karvonen maximal heart rate) and may have been less demanding than ours. It is unclear which exercise-related factor contributed more to this observed difference in balance. In addition, the interaction between the aforementioned factors and the extent of hyperthermia, while not controlled, must not be discounted. The extent of hyperthermia may have contributed to the differences we saw in $POST_{EX}$ BESS scores because the T_{REC} values in the HYD and EUD trials at $POST_{EX}$ were higher than those at the start of these exercise trials. This aligns with the findings of DiStefano et al,[8] who reported that the interaction between hypohydration and hyperthermia resulted in alterations in neuromuscular control. We stress, however, that this is only speculation, because we did not control for the extent of hyperthermia.

At $POST_{24}$, measures of balance returned to baseline levels with no differences among trials. Our results coincide with those of Seay et al,[16] who found no effect of hypohydration on balance after a prolonged recovery despite differences in the magnitude and mechanism of dehydration. The ability to return to baseline measures of balance at $POST_{24}$ may be attributed to the ability of our participants to fully recover to baseline levels of euhydration. Future researchers may wish to examine the effect of prolonged hypohydration after exercise on balance to explain any possible relationship between hypohydration and balance while controlling for fatigue.

It is interesting that the only hydration-related variables associated with BESS scores were changes in body mass and P_{OSM}. The urinary hydration variables were not associated with either BESS or LESS scores in our study, which may be due to the insensitivity of the 24-hour urinary hydration variables to explain alterations in neuromuscular control. This insensitivity is most likely guided by the hormone-regulated (ie, vasopressin and aldosterone) processes that act to conserve body water by increasing urine concentration. Given the role of vasopressin as an upstream regulator of cortisol secretion, we suggest that future authors examine how changes in hydration-related hormonal profiles affect central and peripheral mechanisms of neuromuscular control.

This study had limitations. Our participants returned at $POST_{24}$ in a hydration state similar to baseline and, therefore, it is unclear how individuals who remained in a state of hypohydration (>2% from baseline) would respond to measures of neuromuscular control. Also, generalizability may be limited because we tested only college-aged, recreationally active men. Investigating women and girls, adolescent athletes, and older physically active populations may enable us to better understand the effects of hypohydration and exercise in the heat on neuromuscular control. More work is needed to further elucidate the factors responsible for impaired balance after prolonged exercise in hot environments, identify the physiological mechanisms responsible for these impairments, and characterize the risk of injury from exercise-associated balance impairments in order to develop evidence-based strategies to mitigate this risk.

CONCLUSIONS

Using the present experimental protocol, we observed that prolonged, moderate-intensity exercise followed by 1 hour of passive rest in a hot environment impaired static balance regardless of hydration status (range, approximately 0%BML–5%BML). However, when assessed at $POST_{24}$, these impairments were negated, which suggests that they were acute. In an athletic, military, or occupational setting where individuals are required to perform prolonged bouts of physical activity with minimal break time, balance disruption may increase the risk of lower extremity injuries. We recommend that clinicians incorporate adequate work-to-rest ratios, including individualized hydration plans, when individuals are pursuing prolonged exercise or physical activity in hot environmental conditions to optimize human health and performance.

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