Movement Technique and Standing Balance After Graded Exercise-Induced Dehydration

William M. Adams, PhD, ATC*; Samantha E. Scarneo-Miller, PhD, ATC†‡; Lesley W. Vandermark, PhD, ATC§; Luke N. Belval, PhD, ATC, CSCSII; Lindsay J. DiStefano, PhD, ATC‡; Elaine C. Lee, PhD‡; Lawrence E. Armstrong, PhD¶; Douglas J. Casa, PhD, ATC†‡

*Department of Kinesiology, University of North Carolina at Greensboro; †Korey Stringer Institute and ¶Department of Kinesiology, University of Connecticut, Storrs; §Department of Health, Human Performance, and Recreation, University of Arkansas, Fayetteville; ||Institute for Exercise and Environmental Medicine, Texas Health Presbyterian Hospital Dallas, University of Texas Southwestern Medical Center; ¶|Hydration & Nutrition, LLC, Newport News, VA

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 [VO₂max] = 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% VO₂max; 8 minutes, 60% VO₂max; 8 minutes, 40% VO₂max; 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 pre-exercise, postexercise and passive rest (POSTEX), and 24 hours postexercise (POST24). Differences were assessed using separate mixed-design (trial × time) repeated-measures analyses of variance.

Results: The magnitude of hypohydration at POSTEX 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 pre-exercise (2.9 ± 1.6, 3.0 ± 2.1, 3.0 ± 2.0), POSTEX (3.3 ± 1.5, 3.0 ± 2.0, 3.1 ± 1.9), or POST24 (3.3 ± 1.9, 3.2 ± 1.4, 3.3 ± 1.6) among the EUR, EUR, and HYD trials, respectively (P = .90). Hydration status did not affect BESS scores (P = .11), but BESS scores at POSTEX (10.4 ± 1.1) were greater than at POST24 (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 hyperthermia8 have been shown to alter either movement technique or balance and may consequently increase the risk of injury. Researchers7,9–11 have postulated that...
hydration-mediated (depletion in plasma volume or increase in plasma osmolality [POSM] 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 POSM returns to normal, 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 al16 and Derave et al19 found that balance was impaired when the level of hypohydration reached 2% to 3% body mass loss; yet Seay et al16 and Patel et al17 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 evidence18 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 hyperthermia16 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 euvhydrated and given water to minimize fluid losses during exercise and immediately postexercise recovery (EUR), (2) arrived euvhydrated 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 [VO2max] = 51.7 ± 5.5 mL·kg⁻¹·min⁻¹, body fat = 14.2% ± 4.6%) volunteered for this study. All participants reported exercising at least 4 days per week. Each participant 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 VO2max test on a motorized treadmill (NordicTrack; ICON Health & Fitness, Logan, UT) to ensure they met the eligibility criteria (VO2max >45 mL·kg⁻¹·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 VO2max were (1) respiratory gas exchange ratio of >1.10, (2) ± 10 beats·min⁻¹ of age-predicted maximal heart rate, (3) plateau of ≤150 mL·O2·min⁻¹, and (4) rating of perceived exertion of >17 (6–20 scale).

After the VO2max 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% VO2max; 8 minutes, 60% VO2max; 8 minutes, 40% VO2max; 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 (UVOL) 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 (UOSM) 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 (TREC), and donned a heart-rate monitor (Ironman; Timex USA, Middlebury, CT). We assessed TREC and heart rate every 10 minutes throughout the trial. Pre-exercise (PREEX) measures of NBM, UVOL, USG, and UOSM were obtained, and participants performed PREEX 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 POSM assessment. They then performed six 30-minute cycles of exercise on a motorized treadmill (8 minutes at 40% VO2max; 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 quarter of flexion or abduction during 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

Participants returned to the laboratory 24 to 30 hours after the exercise trial (POST24) 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, UVOL, USG, UOSM, and POSM; 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 we identical across all tested times (PREEX, POSTEX, and POST24). 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 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, 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.

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
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 (PREEX, POSTEX, and POST24), participants provided 10 mL of blood taken from an antecubital vein (Vacutainer Safety-Lok Blood Collection Set; Becton Dickinson), drawn into lithium-heparin pretreated tubes (Vacutainer; Becton Dickinson), and centrifuged for 15 minutes at 3000 revolutions per minute for assessment of $P_{\text{OSM}}$. We measured $P_{\text{OSM}}$ 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 $2 \times 2$ repeated-measures analyses of variance (ANOVAs); no order effect was present ($P$ values > .05). Trial × time repeated-measures ANOVAs with $T_{\text{REC}}$ 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 $\eta^2$, 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 ± 2.24a                   | 1.57 ± 1.65     |
|                                              | EUR   | 1.35 ± 1.75     | 1.17 ± 1.53a                   | 1.17 ± 1.23     |
|                                              | HYD   | 1.96 ± 1.92     | 3.22 ± 2.11a                   | 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 ± 2.55a                   | 3.39 ± 1.97     |
|                                              | EUR   | 3.26 ± 1.96     | 3.26 ± 1.96a                   | 3.26 ± 1.91     |
|                                              | HYD   | 4.13 ± 2.01     | 5.17 ± 1.99a                   | 3.65 ± 1.94     |
| Tandem                                       | EUD   | 2.30 ± 2.65     | 2.39 ± 1.85a                   | 1.65 ± 1.80     |
|                                              | EUR   | 1.39 ± 1.72     | 2.17 ± 1.92a                   | 2.17 ± 1.82     |
|                                              | HYD   | 1.91 ± 1.65     | 3.39 ± 2.38b                   | 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; $P < .05$).
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 ($F_{1.308,28.870} = 4.179, P = .04, \eta^2 = 0.160$), 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 POSTEX versus POST24 (total, SL Firm, and SL Foam) and PREEX (TD Foam) timepoints. We noted a main effect of trial in the total BESS score ($F_{3.23} = 7.737, P = .003, \eta^2 = 0.260$) 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 (PREEX, POSTEX, and POST24) 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 (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 PREEX (2.9 ± 1.6, 3.0 ± 2.1, 3.0 ± 2.0, 3.1 ± 1.9), POSTEX (3.3 ± 1.5, 3.0 ± 2.0, 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 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<sup>a</sup> | | | | |
| Single-legged stance | 0.160<sup>b</sup> | 0.164<sup>b</sup> | 0.133 | 0.033 | 0.014 | 0.049 |
| Tandem stance | −0.027 | −0.027 | −0.08 | −0.038 | 0.054 |
| Foam surface | | | | | |
| Double-legged stance | 0.194<sup>b</sup> | 0.054 | −0.121 | −0.069 | 0.132 |
| Single-legged stance | 0.186<sup>b</sup> | 0.045 | −0.039 | −0.064 | 0.183<sup>b</sup> |
| Tandem stance | 0.186<sup>b</sup> | 0.045 | −0.039 | −0.064 | 0.183<sup>b</sup> |
| Landing Error Scoring System | | | | | |
| | 0.054 | 0.035 | −0.114 | 0.114 | −0.089 |

<sup>a</sup> Correlation ($P < .05$).

<sup>b</sup> Correlation ($P < .01$).

Table 3. Physiological Measures of Hydration Status

| Variable | Pre-exercise | Postexercise and Passive Recovery | 24 h Postexercise |
|----------|--------------|----------------------------------|------------------|
| 24-h Urine volume, L | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD |
| 24-h Urine osmolality, mOsm/kg | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD |
| 24-h Urine specific gravity | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD |
| Plasma osmolality, mOsm/kg | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD | EUD | EUR | HYD |

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.

<sup>a</sup> Difference between the HYD and EUR trials ($P < .05$).

<sup>b</sup> Difference between the HYD and EUR trials ($P < .05$).

<sup>c</sup> Difference between the EUD and EUR trials ($P < .05$).

<sup>d</sup> Main effect of time between pre-exercise and 24 h postexercise ($P < .05$).
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 POST24, measures of U_{\text{VOL}} (F_{1,65} = 20.549, P < .001, \eta^2 = 0.237), USG (F_{1,65} = 18.665, P < .001, \eta^2 = 0.220), and U_{\text{OSM}} (F_{1,65} = 10.466, P = .002, \eta^2 = 0.139) were greater than those at PREEX. The P_{\text{OSM}} was greater in the HYD trial (F_{4,126} = 31.148, P < .001, \eta^2 = 0.497) at PREEX and POSTEX than in the EUD (PREEX: MD = 10 mOsm·kg^{-1} [95% CI = 3, 18 mOsm·kg^{-1}]; P = .002, \eta^2 = 0.98; POSTEX: MD = 9 mOsm·kg^{-1} [95% CI = 2, 16 mOsm·kg^{-1}]; P = .008, \eta^2 = 0.65) and EUR (PREEX: MD = 9 mOsm·kg^{-1} [95% CI = 2, 16 mOsm·kg^{-1}]; P = .01, \eta^2 = 0.75; POSTEX: MD = 16 mOsm·kg^{-1} [95% CI = 9, 23 mOsm·kg^{-1}]; P < .001, \eta^2 = 2.17) trials. The P_{\text{OSM}} was also greater in the EUD than in the EUR trial at POSTEX (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_{\text{REC}} was greater in the HYD and EUR 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 hyphydration on neuromuscular control after 24 hours of recovery. We are the first to examine movement technique and postural control 24 hours after exercise-induced hyphydration. After acute (1 hour) and prolonged (24 hours) recovery from bouts of exercise in the heat, neuromuscular control remained unaffected despite graded hyphydration 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 POST24, 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. were the first to investigate the individual and combined effects of hyphydration and hyperthermia on movement technique without the confounding variable of fatigue. They showed that a combination of hyperthermia and hyphydration induced by exercise impaired movement technique on the LESS both immediately postexercise and after a 60-minute recovery period. We noted that at 60 minutes after prolonged exercise in hot conditions, LESS scores were unaffected by hyphydration 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 hyphydration (range, −0.1% to 5.7%) in the earlier study 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\textsubscript{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\textsuperscript{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\textsuperscript{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\textsuperscript{16,17,19} 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\textsubscript{EX} than at POST\textsubscript{24} independent of hydration status, which contrasts with the findings of DiStefano et al.\textsuperscript{5} Patel et al.\textsuperscript{17} and Ely et al.\textsuperscript{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\textsubscript{EX} BESS score (10.4 ± 1.1) was higher than the average PRE\textsubscript{EX} BESS score (8.2 ± 0.9); however, this finding was not significantly different (P = .08, η\textsuperscript{2} = 2.19).

The differences in balance in our investigation versus the lack of differences in balance observed postexercise in other research\textsuperscript{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\textsuperscript{8} (90 minutes) and Patel et al\textsuperscript{17} (45 minutes). Our exercise intensity varied between 40% and 60% VO\textsubscript{2max}, whereas in the previous works\textsuperscript{8,16,17} remained fixed (range = 1.34–1.78 m.s\textsuperscript{-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\textsubscript{EX} BESS scores because the T\textsubscript{REC} values in the HYD and EUD trials at POST\textsubscript{EX} were higher than those at the start of these exercise trials. This aligns with the findings of DiStefano et al.,\textsuperscript{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\textsubscript{24}, measures of balance returned to baseline levels with no differences among trials. Our results coincide with those of Seay et al.,\textsuperscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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 personalized 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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Address correspondence to William M. Adams, PhD, ATC, Department of Kinesiology, University of North Carolina at Greensboro, 1408 Walker Avenue, Greensboro, NC 27412. Address email to wmadams@uncg.edu.