Effect of Hydration State on Strength, Power, and Resistance Exercise Performance

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ABSTRACT

JUDELSON, D. A., C. M. MARESH, M. J. FARRELL, L. M. YAMAMOTO, L. E. ARMSTRONG, W. J. KRAEMER, J. S. VOLEK, B. A. SPIERING, D. J. CASA, and J. M. ANDERSON. Effect of Hydration State on Strength, Power, and Resistance Exercise Performance. *Med. Sci. Sports Exerc.*, Vol. 39, No. 10, pp. 1817–1824, 2007. **Purpose:** Although many studies have attempted to examine the effect of hypohydration on strength, power, and high-intensity endurance, few have successfully isolated changes in total body water from other variables that alter performance (e.g., increased core temperature), and none have documented the influence of hypohydration on an isotonic, multiset, multirepetition exercise bout typical of resistance exercise training. Further, no investigations document the effect of hypohydration on the ability of the central nervous system to stimulate the musculature, despite numerous scientists suggesting this possibility. The purposes of this study were to examine the isolated effect of hydration state on 1) strength, power, and the performance of acute resistance exercise, and 2) central activation ratio (CAR). **Methods:** Seven healthy resistance-trained males (age = 23 ± 4 yr, body mass = 87.8 ± 6.8 kg, body fat = 11.5 ± 5.2%) completed three resistance exercise bouts in different hydration states: euhydrated (EU), hypohydrated by approximately 2.5% body mass (HY25), and hypohydrated by approximately 5.0% body mass (HY50). Investigators manipulated hydration status via exercise-heat stress and controlled fluid intake 1 d preceding testing. **Results:** Body mass decreased 2.4 ± 0.4 and 4.8 ± 0.4% during HY25 and HY50, respectively. No significant differences existed among trials in vertical jump height, peak lower-body power (assessed via jump squat), or peak lower-body force (assessed via isometric back squat). CAR tended to decrease as hypohydration increased (EU = 95.6 ± 4.9%, HY25 = 94.0 ± 3.1%, HY50 = 92.5 ± 5.1%; $P = 0.075$, $\eta_p^2 = 0.41$). When evaluated as a function of the percentage of total work completed during a six-set back squat protocol, hypohydration significantly decreased resistance exercise performance during sets 2–3 and 2–5 for HY25 and HY50, respectively. **Conclusion:** These data indicate that hypohydration attenuates resistance exercise performance; the role of central drive as the causative mechanism driving these responses merits further research. **Key Words:** DEHYDRATION, NEUROMUSCULAR, WATER, WEIGHTLIFTING

Abundant research documents the detrimental effects of hypohydration (i.e., reduced total body water) on endurance exercise performance (9). Several studies have also attempted to determine whether these unfavorable effects extend to exercises requiring strength, power, or high-intensity endurance; unfortunately, the results of many of these investigations cannot be examined solely in the context of hydration because their research design 1) did not control mass-reduction procedures and/or 2) included factors (e.g., increased core temperature, caloric restriction, previous endurance training, uncontrolled menstrual status, and/or learning effect) that influence hydration or exercise performance (7,13,16,20). A small body of literature has successfully evaluated the effect of isolated hypohydration on high-intensity muscle function, demonstrating that hypohydration decreases (4–6,28,30,32,36) or fails to affect (2,4,5,7,16,30,34) muscular performance. Given this small pool of conflicting results (sometimes within the same study (4,5,30)), it is currently unclear whether and how hydration status affects strength, power, and high-intensity endurance (i.e., maximal effort activities lasting between 30 and 120 s).

Of this relatively small, inconsistent body of literature, most investigations have used outcome variables requiring single maximal efforts (normally isometric) or sustained contractions to fatigue (normally isometric or isokinetic). Although these performance measures exhibit high internal validity, they lack the external validity of isotonic, multiple-repetition, multiple-set, intermittent resistance exercise tasks characteristic of those completed by thousands of athletes, soldiers, and laborers each day. Because conventional resistance exercise taxes all aspects of muscle function (strength, power, and endurance), this type of exercise

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might experience greater susceptibility to the effects of hypohydration; the only study to examine repeated isotonic efforts (32) supports this hypothesis.

Although several physiological mechanisms explain hypohydration-induced performance decrements during endurance exercise (9), fewer physiological possibilities explain potential hypohydration-mediated changes in strength, power, and high-intensity endurance. Of these, alterations in the ability of the central nervous system to stimulate the musculature seem most likely. Despite limited, inconclusive evidence documenting the effects of hypohydration on electromyography (EMG) (2,13,14,33) and muscle membrane excitability (10,11), many reports hypothesize that the loss of total body water detrimentally affects some component of the neuromuscular system (4,14,19,32,34). Unfortunately, no scientific evidence evaluates the effect of hypohydration on a direct measure of central drive (e.g., twitch interpolation or central activation ratio). Therefore, the purpose of this study was to examine the effect of hydration state on 1) maximal strength, peak power, and performance of acute resistance exercise, and 2) a direct measure of central drive (i.e., central activation ratio).

METHODS

Subjects. Seven, healthy, nonsmoking, resistance-trained males volunteered to complete this study (age = 23 ± 4 yr, height = 1.79 ± 0.58 m, body mass = 87.8 ± 6.8 kg, body fat = 11.5 ± 5.2%, back squat one-repetition maximum (1RM) = 152 ± 20 kg). Inclusion criteria consisted of a minimum 6 months experience in the parallel back squat exercise and a medical history free of musculoskeletal, cardiac, endocrine, and heat-related illnesses. Before commencing participation, our medical monitor reviewed all medical histories and subjects signed an informed consent statement approved by the institutional review board of the University of Connecticut.

Experimental design. To assess the effects of hydration state on performance and physiological responses to resistance exercise, subjects completed three identical resistance exercise bouts in different hydration states: euhydrated (EU), hypohydrated by approximately 2.5% body mass (HY25), and hypohydrated by approximately 5.0% body mass (HY50). Subjects completed each resistance exercise bout in a randomized order, at the same time of day (in the morning, ± 1 h), and in temperate environmental conditions (~21°C). Investigators manipulated hydration status 1 d preceding each trial via exercise-heat stress and controlled fluid intake.

Study controls. Approximately 1 wk separated the experimental trials, during which time subjects completed self-directed workouts. To maintain similar training status throughout the study, subjects were asked to record and replicate individual exercise sessions between experimental testing sessions. Similar controls existed for dietary intake during the 2 d preceding experimental sessions. To minimize the potential effect of reduced caloric intake on exercise performance (24), investigators encouraged subjects to consume their typical diet throughout the study. To limit physiological fluctuations, subjects did not exercise, consume alcohol, or ingest stimulants for 36 h before each testing session. Finally, subjects began the three baseline testing sessions and the three 28-h experimental trials in a euhydrated condition (urine specific gravity ≤ 1.020 (1)) after a 12-h overnight fast. To promote euhydration on these specific days, subjects drank approximately 1 L of water the night before and 1 L of water the morning of these testing sessions.

Baseline testing and familiarization. During three preliminary visits, investigators obtained baseline subject characteristics (all three visits) and familiarized subjects to testing procedures (two visits only). On arrival to the laboratory for each preliminary testing session, subjects immediately emptied their bladder; urinary measures of specific gravity (U_{sg}) and osmolality (U_{osm}) quantitatively documented hydration state (1). Body mass was then measured via a platform scale (DS44L, Ohaus, Florham Park, NJ). Body masses measured on the three preliminary visits were used to calculate average euhydrated body mass (8).

Additional measures collected during the first preliminary visit included subjects' height, body composition (via skinfold analysis), and back squat 1RM. Briefly, subjects cycled for 5–10 min at a modest intensity, then completed several submaximal sets of back squat. After warming up, subjects attempted to lift a mass representing approximately 90% of their estimated 1RM. If successful, trials continued with gradually increasing resistance until the subject failed to lift a mass with correct form. Subjects performed all resistance exercise on a modified Smith Machine (LifeFitness, Rosemont, IL) (limiting movement to one plane of motion) and rested a minimum of 3 min between attempts. 1RM was defined as the greatest mass a subject lifted with correct form through a full range of motion—that is, top of the thigh parallel to the floor (23).

During the second visit, subjects completed a high-intensity resistance exercise challenge (REC) after measures of body mass. The REC consisted of six sets of the parallel back squat at 80% of subjects' predetermined 1RM; subjects attempted to complete 10 repetitions per set. If unable to complete 10 repetitions, subjects stopped at exhaustion, but they still attempted to complete all remaining sets using the initial load (i.e., 80% 1RM). Intraclass correlations for a similar exercise bout in our laboratory equaled 0.98. At the conclusion of each set, subjects provided a rating of perceived exertion (RPE) (3) and rested for 2 min before beginning the next set. The total number of repetitions completed during the six sets served as the standard for subsequent experimental REC testing.

Experimental trials. Each subject completed three experimental trials differing only in subjects' hydration status during exercise testing. Each trial lasted approximately 28 h and began when euhydrated subjects reported to the laboratory in the morning, approximately 24 h before exercise (see Study Controls). Subjects emptied their bladders; investigators then determined U_{sg}, U_{osm}, and subject body mass. After measurement of body mass, subjects abstained from the intake of fluids or fluid-rich foods for the remainder of the day. Subjects left the laboratory, returning later that afternoon to enhance water loss by walking on a motor-driven treadmill (initial speed = 1.5 $m \cdot s^{-1}$, initial incline = 3% grade) in a heated environmental chamber (36–37°C, 40–50% relative humidity) (Model 200, Minus Eleven Inc., Malden, MA). Every 20 min, subjects stopped exercising, dried all sweat off their bodies, and were weighed. Investigators measured rectal temperature (Model 401, Yellow Springs Instruments, Yellow Springs, OH), heart rate (Vantage XL, Polar Electro, Woodbury, NY), and RPE immediately before body mass measurements. A subject repeated this cycle (exercise, physiological measures, and body mass determination) until 1) he lost 5% of his baseline (prewater deprivation) body mass, 2) his heart rate exceeded 180 bpm for five consecutive minutes, 3) his rectal temperature exceeded 39.5°C, 4) he displayed signs or symptoms of an exercise-induced heat illness, or 5) he requested to stop exercising. Investigators gradually decreased exercise intensity on an individual basis to prolong the dehydration stress and maximize the opportunity for subjects to lose body mass without exceeding safety criteria. During the initial trial, two subjects requested to stop exercising, and the remaining five lost the entire 5% of body mass. To minimize the influence of the dehydration protocol on subsequent performance, subjects completed identical walking bouts during all three trials (i.e., characteristics of the first exercise-heat stress, regardless of the hydration state achieved, were repeated during trials 2 and 3). Manipulations of subsequent fluid intake (see below) accommodated minor fluctuations in body mass loss among trials of identical duration and intensity.

After dehydration, subjects exited the environmental chamber and sat in temperate conditions while investigators rehydrated them such that the following morning, subjects were approximately 0, 2.5, or 5% hypohydrated. To account for urination and overnight fluid losses, subjects rehydrated with a fluid volume slightly greater than that required to achieve the desired hydration state (29). Rehydration consisted of intravenous infusion of normal saline (rate = 1 $L \cdot h^{-1}$) and oral ingestion of an electrolyte-fortified, noncaloric, flavored solution (rate = 1 $L \cdot h^{-1}$ in 15-min increments). After rehydration, subjects consumed a high-calorie (13 $kcal \cdot kg^{-1}$ body mass), carbohydrate-rich (2.25 g of carbohydrate per kilogram of body mass) meal (Classic Hand-Tossed Cheese Pizza, Domino's Pizza, Ann Arbor, MI). Finally, subjects left the laboratory with instructions not to exercise or ingest anything (including water).

The following morning (10–12 h after rehydration), subjects returned to the laboratory and emptied their bladders; investigators documented hydration status and subject body mass. Subjects then sat and completed a computerized Profile of Mood States (POMS) questionnaire (25). After completion of the POMS, subjects inserted a rectal thermistor (Model 401, Yellow Springs Instruments, Yellow Springs, OH) 10 cm beyond the anal sphincter to determine core temperature. After removing the thermistor, subjects cycled for 5–10 min at a modest intensity and completed 5–10 min of self-directed stretching.

Subjects then completed performance tests to quantify vertical jump (VJ) height, peak lower-body power, peak lower-body force, and central drive. Subjects completed each test three times, resting 1 min (VJ) or 3 min (other tests) between attempts. For all performance tests, only the best result was subsequently analyzed. VJ was measured using a standard countermovement jump (Vertec, Sports Imports, Columbus, OH). Peak lower-body power was assessed via measures of ground reaction force (JUMP force platform, Advanced Mechanical Technology, Watertown, MA and AccuPower 1.0 software, Frappier Acceleration Sports Training, Fargo, ND) during a set of three consecutive squat jumps (30% 1RM). Peak lower-body force was obtained by measuring ground reaction forces during an isometric back squat. Subjects completed the isometric back squat test by assuming a standardized squat position (approximately one third of maximum depth, mean knee angle = 121°, mean hip angle = 124°) and maximally pressing upward against a stationary bar. Pilot work in our laboratory indicated that this depth resulted in the greatest force output. Intraclass correlations for the vertical jump, squat jump, and isometric back squat in our laboratory exceed 0.93.

Subjects then completed tests of central drive (the ability of the central nervous system to stimulate the musculature). Subjects sat on a modified leg-extension machine (NT-1260, Nautilus Fitness Products, Louisville, CO) with a knee angle of approximately 70° (full extension = 180°); velcro straps locked the dominant ankle to the extension bar, a seatbelt secured the subject's lower body, and adjustable straps placed over each shoulder fixed the location of the subject's upper body. Surface electrodes (5 cm × 5 cm, Dura-Stick II, Chattanooga Group, Hixson, TN) were placed on the superior–lateral aspect of the rectus femoris and the head of the vastus medialis. Before attachment, investigators shaved the electrode sites and lightly abraded the skin with an alcohol swab to maximize conductance. On command, each subject maximally extended his dominant knee for 4 s against a stationary padded bar located immediately superior to the ankle joint. Approximately 2 s into the contraction, investigators manually applied a single train of electrical stimuli (stimulation intensity = 150 V, train duration = 100 ms, stimulus rate = 100 Hz, pulse duration = 0.1 ms) to the quadriceps (S48 Square Pulse Stimulator and SIU8T Transformer Stimulus Isolation Unit, Grass Instrument Division, Astro-Med, West Warwick, RI). Testing during preliminary familiarization ensured this stimulus maximized force production. Intraclass correlations previously reported for this procedure equal 0.98 (31). Torque output was sampled at 5 kHz with a force transducer (SBO-300-T, Transducer Techniques, Temecula, CA), amplified (TMO-1, Transducer Techniques, Temecula, CA), low-pass filtered at 100 Hz (LPF30, World Precision Instruments, Sarasota, FL), converted to a digital signal (DAS1802AO, Keithley Instruments, Cleveland, OH), and displayed on a computer using customized Labview software (National Instruments, Austin, TX). Central activation ratio (CAR) was calculated (21) as

$$\text{CAR} = 100(\text{maximal voluntary torque})/(\text{maximal voluntary torque} + \text{electrically evoked torque})$$

After the four performance tests described above, subjects repeated the REC (six sets of the squat exercise at 80% 1RM; see above). If a subject failed to complete the same total number of repetitions during the six sets as during baseline testing, he completed additional make-up sets until total repetitions during the experimental REC equaled total repetitions during the baseline REC. Mandating equal repetitions between trials was necessary for aspects of the research reported elsewhere.

Biochemical analysis. At each of the urine collections (baseline, pretrial, and preexercise), urine was collected in a clean plastic container and immediately analyzed. U_{sg} was assessed via refractometry (A300CL, Atago Co., Tokyo, Japan). U_{osm} was assessed in duplicate via freezing-point depression (3DII, Advanced Digimatic, Needham Heights, MA).

Data analysis. To normalize the individual total work completed by each subject during the REC, the raw number of repetitions completed during each set was converted to a cumulative percentage of total work. This score was calculated by dividing the total number of repetitions the subject completed after a given number of sets by the total repetitions he completed during the entire REC. For example, if a subject completed 40 total repetitions during the REC and completed 10 repetitions during the first set, the total cumulative percentage for set 1 equaled 25% (10/40). If the same subject completed eight repetitions during the second set, the total cumulative percentage for set 2 equaled 45% ((10 + 8)/40).

Statistical analysis. We calculated sample size using the data of Caterisano et al. (6), because the research design in that investigation most closely resembled the current study in terms of exercise protocol, hydration states achieved, and subject population. Using those data and examining a two-tailed hypothesis at a power of 0.80, the number of subjects required to demonstrate a significant difference at $P = 0.05$ was calculated to be about four. Descriptive data (means, standard deviations, and standard errors of the mean) were calculated for all test variables. Differences between trials were analyzed with a three (hydration state) by X (time) two-way repeated-measures ANOVA, where X represents the number of times the variable was assessed during one trial (e.g., for CAR, $X = 1$, for REC performance, $X = 6$). In the event of a significant F ratio, specific pairwise differences were examined with Fisher's LSD *post hoc*. Effect sizes ($\eta_p{}^2$) were calculated for specific variables that approached statistical significance, using the formula

$$\eta_p{}^2 = (\text{SS}_{\text{effect}})/(\text{SS}_{\text{effect}} + \text{SS}_{\text{error}})$$

where SS = sum of squares. Significance was set at $P < 0.05$. Data are presented as means ± SD, unless otherwise noted.

RESULTS

Dehydration procedures. No significant differences existed among trials for room temperature, relative humidity, or duration of the exercise-heat stress (all trial averages = 36 ± 1°C, 44 ± 6%, and 184 ± 14 min, respectively). Heart rates, rectal temperatures, and RPE data measured at the conclusion of the exercise-heat stress were also similar among trials (all trial averages = 150 ± 14 bpm, 38.53 ± 0.28°C, and 14 ± 2, respectively). After the exercise-heat stress, subjects replaced significantly different volumes of fluid (EU = 4.669 ± 0.308 L, HY25 = 2.531 ± 0.336 L, HY50 = 0.594 ± 0.328 L), but they consumed similar energy (EU = 1122 ± 92 kcal, HY25 = 1076 ± 113 kcal, HY50 = 1098 ± 128 kcal). Core temperature decreased to normal resting values by the next morning, but hypohydration significantly increased preexercise core temperature (HY25 = 36.84 ± 0.32°C, HY50 = 36.98 ± 0.42°C) compared with EU (36.56 ± 0.37°C).

Hydration measures. No significant differences existed in body mass between the euhydrated baseline determined during familiarization trials and the baseline experimental measures preceding each trial (familiarization average = 87.78 ± 6.82 kg, EU BASE = 87.81 ± 7.48 kg, HY25 BASE = 87.71 ± 6.96 kg, HY50 BASE = 87.99 ± 7.38). Figure 1 presents the percent changes in body mass experienced during each of the experimental trials. Immediately before resistance exercise, all points significantly differed; mean percent changes in body mass were −0.2 ± 0.4, −2.4 ± 0.4, and −4.8 ± 0.4% for EU, HY25, and HY50, respectively.

Baseline U_{sg} was less than 1.020 for all trials. Dehydration, rehydration, and the overnight fast caused significantly greater U_{sg} in HY trials (HY25 = 1.026 ± 0.004, HY50 = 1.027 ± 0.004) than EU (1.020 ± 0.003), but no differences existed between HY25 and HY50. Baseline U_{osm} was less than 800 $\text{mOsm}\cdot\text{kg}^{-1}$ for all trials. Similar to U_{sg}, hypohydration and rehydration caused significantly greater U_{osm} during HY trials (HY25 = 1031 ± 88 $\text{mOsm}\cdot\text{kg}^{-1}$, HY50 = 1067 ± 100 $\text{mOsm}\cdot\text{kg}^{-1}$) than EU (887 ± 102 $\text{mOsm}\cdot\text{kg}^{-1}$), but no differences occurred between HY25 and HY50.

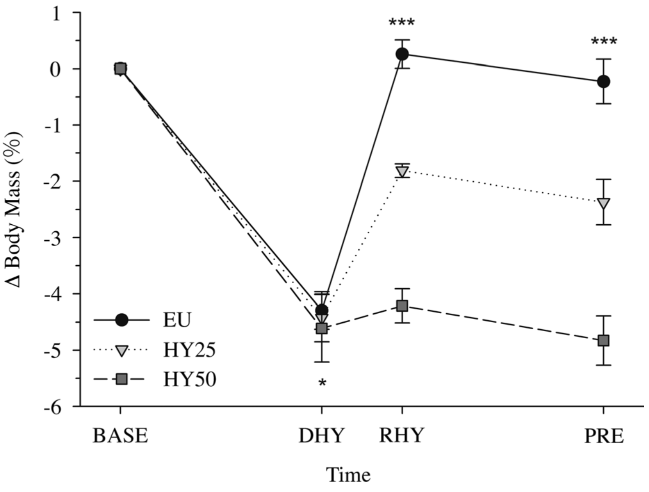

FIGURE 1—Percent changes in body mass (mean ± SD) experienced during the three experimental trails. EU, euhydrated; HY25, hypohydrated by approximately 2.5%; HY50, hypohydrated by approximately 5.0%; BASE, euhydrated baseline measure; DHY, immediately after dehydration via exercise-heat stress; RHY, immediately after rehydration; PRE, immediately preexercise. * Significant difference between EU and HY50; *** all points significantly differ at a given time.

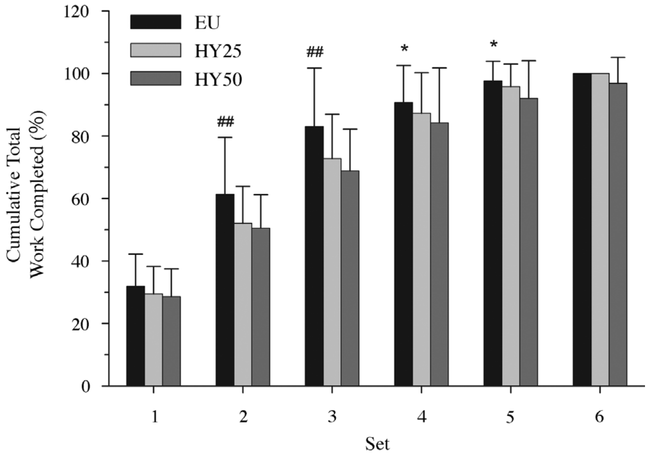

FIGURE 2—Cumulative total work completed (mean ± SD) after each set during the REC (for description of this calculation, please see Methods). EU, euhydrated; HY25, hypohydrated by approximately 2.5%; HY50, hypohydrated by approximately 5.0%. ## Significant difference between EU and both hypohydrated trials; * significant difference between EU and HY50.

Exercise performance. Table 1 displays results from the performance tests. Technical difficulties eliminated data from one subject for the jump squat, isometric press, and CAR test, resulting in an $N = 6$. No significant differences existed among trials for VJ height, peak concentric power during jump squats, or maximum force produced during the isometric squat. CAR decreased incrementally (~1.5%) at each hydration state, but these results failed to reach statistical significance ($P = 0.075$, $\eta_p^2 = 0.41$). Figure 2 presents results from the REC. Using preliminary testing as the performance standard (see above), subjects completed 34 ± 14 repetitions during the six-set workouts. Subjects completed significantly more work during the initial two and three sets of exercise when euhydrated than hypohydrated and significantly more work through the initial four and five sets of exercise during EU than HY50. Total cumulative percent of work completed was identical between hypohydrated trials after all sets.

Psychological/perceptual measures. Table 2 shows results from the POMS questionnaire. Hypohydration failed to affect tension–anxiety, depression–dejection, anger–hostility, vigor–activity, fatigue–inertia, and confusion–bewilderment. Total mood disturbance increased incrementally (about six points) at each hydration state, but these results failed to reach statistical significance ($P = 0.077$, $\eta_p^2 = 0.35$). No significant differences occurred among trials in RPE.

TABLE 1. Performance measures.

Trial	VJ Height (cm)	Jump Squat Power (W)	Isometric Squat Force (N)	CAR (%)
EU	61.1 ± 9.4	5908 ± 660	2829 ± 622	95.6 ± 4.9
HY25	62.6 ± 8.5	5942 ± 552	2723 ± 370	94.0 ± 3.1
HY50	62.8 ± 9.2	5959 ± 702	2898 ± 644	92.5 ± 5.1

Data are means ± SD. VJ, vertical jump height; CAR, central activation ratio; EU, euhydrated; HY25, hypohydrated by about 2.5% body mass; HY50, hypohydrated by about 5.0% body mass. No significant differences existed among trials. $N = 6$ for jump squat, isometric squat, and CAR.

DISCUSSION

The primary findings of this study were that hypohydration 1) has little demonstrable effect on single, maximal-effort strength and power, but it 2) limited the ability of healthy, resistance-trained males to perform a six-set back squat protocol. These results suggest that hypohydrated individuals who complete isotonic, multiple-repetition, multiple-set, intermittent resistance exercise tasks will likely experience impaired performance.

The experimental challenges associated with isolating the effect of hydration state on exercise performance and physiological changes are significant because the dehydrating stimulus (as opposed to the actual hypohydration) frequently affects study outcomes. If the dehydration procedures used to reduce total body water are not adequately controlled, incorrectly performed, or immediately precede performance testing, confounding variables such as muscle fatigue, caloric deficit, and elevated temperature can strongly influence exercise outcome variables (27). We believe the current research design effectively responded to the majority of these challenges. The hydration data, principally percent change in body mass (Fig. 1), indicate that subjects achieved three distinctly different hydration states before performing exercise despite completing identical dehydration bouts the night before. The overnight rest separating the exercise-heat stress from the resistance exercise helped to further minimize the effect of the dehydration process on experimental testing. Subjects also replicated dietary intake for 48 h preceding each trial and

TABLE 2. Profile of Mood States Questionnaire responses to hypohydration.

Trial	Tension–Anxiety	Depression–Dejection	Anger–Hostility	Vigor–Activity	Fatigue–Inertia	Confusion–Bewilderment	Total Mood Disturbance
	(0 to 32)	(0 to 60)	(0 to 48)	(0 to 32)	(0 to 28)	(0 to 24)	(−32 to 192)
EU	5 ± 3	1 ± 1	1 ± 2	10 ± 5	6 ± 2	3 ± 2	7 ± 11
HY25	6 ± 4	3 ± 5	3 ± 4	11 ± 4	8 ± 3	4 ± 1	14 ± 16
HY50	7 ± 3	3 ± 4	4 ± 6	10 ± 6	10 ± 5	5 ± 4	19 ± 17

Data are means ± SD. EU, euhydrated; HY25, hypohydrated by about 2.5% body mass; HY50, hypohydrated by about 5.0% body mass. Values in parentheses represent the possible range of scores for a given construct. No significant differences existed between trials.

ingested a standardized high-calorie, high-carbohydrate meal approximately 12 h before resistance exercise to limit differences in energy stores. Admittedly, resting core temperatures differed between hypohydrated trials and the euhydrated trial, but 1) the temperate environmental conditions (~21°C) and 2) the minor thermal load provided by the resistance exercise (estimated to increase core temperature by approximately 0.2°C (12)) suggest the REC would only modestly increase core temperature. As isometric force production is normally maintained at core temperatures below 38°C (26), we believe relative differences in resting core temperature among trials would not significantly affect the results, because absolute temperatures likely never achieved a performance-altering magnitude.

Exercise performance. Although one study has documented a hypohydration-induced improvement in jumping performance (34), the present investigation supports most previous research (19,35) and suggests that hypohydration fails to influence vertical jump height (Table 1). These results describing exercise performance do not necessarily reflect the physiological capacity of muscle, however, because the decreased body mass characteristic of hypohydration might offset reduced muscular strength and/or power (7,17). Specifically, if hypohydration fails to reduce muscle force or power, vertical jump height should increase as total body water decreases, because the jumper must move less mass. To accurately measure the effects of hydration state on muscle power, we calculated power output during jump squats through direct measures of force and time, independent of body mass. The lack of change among trials in peak concentric power during jump squats (Table 1) suggests that hypohydration truly does not influence muscular power. Four other investigations (7,30,34,36) describe the isolated effect of hypohydration on power measures independent of confounding factors (e.g., body mass, endurance training, caloric restriction, increased core temperature, and/or fatigue); typical of this body of literature, two demonstrate a hypohydration-induced decrement in performance (30,36), and two show that hypohydration failed to influence power output (7,34). Combined with the current results, these conflicting findings (possibly attributable to exercise mode and amount of body water lost) clearly warrant further investigation into the effects of hypohydration on muscle power.

Hypohydration also failed to influence peak lower-body force (Table 1), supporting some (2,16,34), but not all (4,5,28), previous investigations into the effect of hydration on single, maximal-effort force production. No obvious disparities in research design (muscle group, muscle action, velocity of contraction, subject population, etc.) explain these differences. Interestingly, peak force was unchanged despite possible differences in nervous stimulation of the musculature. Although the data failed to achieve statistical significance, central activation seemed to decrease as hypohydration increased, implying that alterations in the central nervous system, the peripheral nervous system, and/or excitation–contraction coupling might be related to hydration-induced decrements in endurance or resistance exercise performance. The notable effect size ($\eta_p^2 = 0.41$) in a small sample ($N = 6$) further strengthens the chances that this relationship exists. Understanding the limits to these data, we take these inconclusive findings as a possibility that hypohydration might affect central drive, and we recommend that these results serve as a basis for future investigations examining larger subject pools. If hypohydration truly limits central drive, different patterns of muscle fiber recruitment potentially explain the equivalent peak forces produced during HY25 and HY50 isometric tests, as previous research demonstrates hypohydration potentially alters EMG output (2,14,33).

Despite similar muscle force and power production, hypohydration significantly decreased performance of the REC. These findings support most other studies examining the effect of hydration state on high-intensity muscular endurance (2,4,6,32). Unlike those previous investigations, the current results indicate that hypohydration significantly attenuates performance of an isotonic, multirepetition, multiset exercise bout typical of conventional resistance exercise. The magnitude of this effect seemed dose dependent: HY25 reduced performance through sets 2 and 3 but HY50 decreased performance through sets 2–5. These results demonstrate high external validity, as moderate hypohydration (as low as 2.4% body mass loss) decreased performance during three sets of resistance exercise (a very common exercise volume).

Although this reduction in muscular performance has implications for acute exercise, these findings also relate to training adaptations of those individuals who routinely complete resistance exercises in a hypohydrated condition (e.g., astronauts, the elderly, and some athletes). Because hypohydration seems to limit individual workout volume (in this case, by three to five repetitions within the first three sets of exercise), overall training volume might suffer. Quantifying the importance of three to five repetitions per exercise across an entire training program is challenging, but research suggests that small increases in daily training volume significantly benefit strength development as long as exercisers avoid overtraining (15). Theoretically, increasing the rest interval between sets might maintain training volume despite hypohydration through enhanced recovery. Even if increased rest restored training volume, however, overall adaptations might still suffer because of the indirect relationship between rest interval and the anabolic hormonal response that crucially modulates training adaptations to resistance exercise (18,22). Thus, although estimating the exact effects of hypohydration on long-term adaptations to resistance training is difficult, evidence reasonably suggests that hypohydration will attenuate some benefits of a resistance exercise program.

CONCLUSIONS

In conclusion, hypohydration up to 4.8% body mass loss 1) failed to affect vertical jump height, peak lower-body power, and peak lower-body force, but it 2) significantly compromised the ability to perform a resistance exercise bout. Preliminary results evaluating the effect of hypohydration on the ability of the central nervous system to maximally stimulate the musculature suggest further work should continue to investigate this plausible mechanism.

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