Effects of dehydration and rehydration on EMG changes during fatiguing contractions

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ABSTRACT

BIGARD, A-X., H. SANCHEZ, G. CLAVEYROLAS, S. MARTIN, B. THIMONIER, and M. J. ARNAUD. Effects of dehydration and rehydration on EMG changes during fatiguing contractions. *Med. Sci. Sports Exerc.*, Vol. 33, No. 10, 2001, pp. 1694–1700. **Purpose:** This study measured the effects of sauna-induced dehydration (Dhy) and the effectiveness of rapid rehydration on muscle performance and EMG frequency spectrum changes associated with fatigue during isometric contractions. **Methods:** Knee extensor muscle strength during isometric maximal voluntary contraction (MVC) and endurance time at 25% and 70% of MVC (ET25 and ET70, respectively) were measured three times in 11 healthy male subjects, under euhydration conditions (Eu), after Dhy, and after rehydration following Dhy (Rhy). **Results:** Dhy led to a decrease in body weight by 2.95 ± 0.05%. No significant effect of the hydration status was shown on MVC values. A 23% decrease in ET25 was recorded during Dhy ($P < 0.01$), whereas ET70 only tended to decrease (−13%, $P = 0.06$). ET25 was higher during Rhy than Dhy (8%, $P < 0.05$) but remained lower than during Eu (−17%, $P < 0.05$). The EMG root mean square (RMS) increased earlier during Dhy than Eu. Opposite changes were shown for the mean power frequency (MPF) of EMG, and Dhy resulted in an accelerated fall in MPF. However, because ET25 decreased with dehydration, RMS and MPF changes were similar during Eu and Dhy when reported to normalized contraction time, exhaustion was thus associated with similar values of RMS and MPF for all conditions. RMS and MPF changes during Rhy showed an intermediate pattern between Eu and Dhy. **Conclusions:** Dhy induced an increase in muscle fatigue, associated with early changes in EMG spectral parameters. It is not clear whether these alterations could be attributed to biochemical modifications, and the role of increased perception of effort when subjects were dehydrated should be clarified. **Key Words:** FATIGUE, EMG, KNEE EXTENSION, MPF, ROOT MEAN SQUARE, RAPID WEIGHT LOSS, HEAT STRESS

A number of previous studies have shown that dehydration results in impaired performance during both prolonged low- and high-intensity dynamic exercises (3,6,22,30). Less known are the effects of dehydration on skeletal muscle performance during small muscle exercise. Dehydration mainly results from imbalance between the volume of fluid ingested and sweat loss during exercise, or is designed to achieve rapid and voluntary weight loss before weight-class sporting events (27,29).

Rapid weight loss is a common practice in weight-class sporting events in order to permit the competitors to be certified for a weight class lower than their normal body weights. The maintenance of skeletal muscle performance is determinant in such sports. Whether rapid weight reduction affects muscular performance is thus a critical point when this practice is applied in weight-class sporting events. Most published studies have reported no change in muscular strength after dehydration (13,14,25,27). More equivocal are the effects of hypohydration on muscular endurance. Earlier studies indicated either an impairment (29) or no change in muscle endurance (27). Two recently published papers gave contradictory results regarding the effects of hypohydration on muscle resistance to fatigue. One reported a 15% decrease in the endurance time of knee-extensor muscles after a 4% body weight loss (25), whereas the other study showed that muscular endurance was unaffected by a similar level of dehydration (14). However, the methods used to achieve dehydration (exercise plus fluid restriction and passive heat exposure, respectively) and those to determine muscle performance (dynamic leg knee-extension and sustained isometric contraction, respectively) were different. Whether or not the potential effects of hydration status on muscle endurance are influenced by the duration of contraction remains to be determined.

Decline in muscle performance during sustained contraction has been correlated with cellular mechanisms, such as alterations in excitation-contraction coupling or cell metabolism. A recent study showed that hypohydration reduces muscle endurance without any change in H^+ and inorganic phosphate (Pi) concentrations and is probably without direct effect on muscle metabolism (25). However, in addition to intramuscular factors, muscle fatigue at low force involves alterations in central motor drive (19). The analysis of the surface electromyographic activity (EMG) is increasingly used to study muscle fatigue (9). During a sustained submaximal contraction, the power spectrum of the surface EMG shows a shift to lower frequencies and an increase in the signal power over time (1,31). Although the exact

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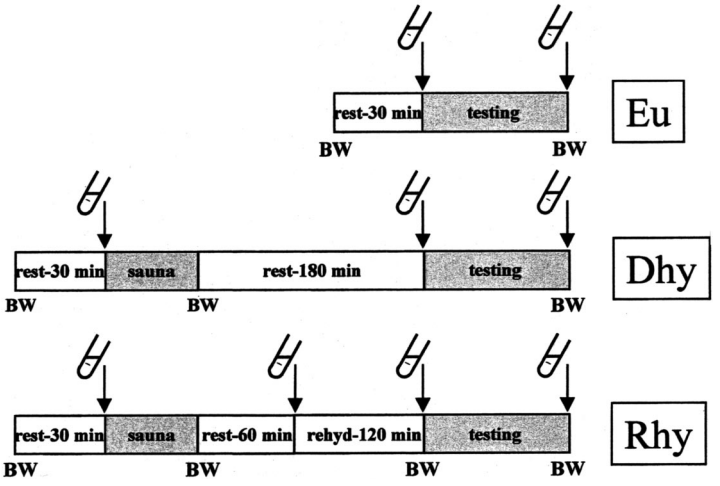

FIGURE 1—Experimental design of the study. Eu, euhydration condition; Dhy, sauna-induced dehydration; Rhy, passive dehydration followed by rehydration. *Test tube symbol* denotes blood samples; BW, body weight measurement; testing, testing of knee extensor muscles.

mechanisms of these alterations remain to date a matter of debate, changes in the myoelectric signals provide information relating to events that reflect neurogenic changes or that occur within the muscle (9). Whether alteration in muscle endurance expected during sustained contraction at low force when subjects were hypohydrated is associated with EMG changes characteristics of fatigue remains to be determined.

Acute thermal dehydration is a technique frequently used by athletes who are competing within weight classification to induce rapid weight loss. Replacement of water and electrolyte losses is of crucial importance for recovery, and only few data exist regarding the effectiveness of rapid rehydration on muscle performance. Torranin et al. (29) showed that rapid rehydration with a commercial glucose-electrolyte solution was ineffective in restoring muscle performance. However, in this study, it is not known to what extent measurements of muscle performance were altered, due to the repetition of isometric contractions at exhaustion after dehydration and after rehydration. There is thus a need to evaluate the effectiveness of rapid fluid replacement on skeletal muscle performance.

It was the main purpose of this study to investigate the changes in hydration status on skeletal muscle performance during small muscle exercise. This investigation was designed to 1) investigate the effects of sauna-induced dehydration on muscular strength and endurance at two submaximal force levels, 2) examine the relationship between the changes in muscular endurance and EMG frequency spectrum after voluntary dehydration, and 3) examine the effectiveness of rapid rehydration with mineral water on the restoration of strength and muscular endurance.

MATERIALS AND METHODS

Subjects. Eleven healthy male college students volunteered to participate in the study (mean ± SEM: age, 22 ± 1 yr; stature, 173 ± 2 cm; body weight, 78.9 ± 2.3 kg). The experimental procedures were approved by the Ethics Committee of the Grenoble Hospital. The protocol was explained, and subjects gave their written informed consent to participate in this study. All subjects were physically active, but none was involved in a training program. Subjects did not use a sauna or any other methods that could have caused acclimatization before this investigation.

Experimental procedures. After several initial familiarization trials, subjects took part in three different experimental trials at weekly intervals. Each subject was tested three times, under euhydration conditions (Eu), after sauna-induced dehydration (Dhy), and after rehydration following passive heat dehydration (Rhy). The day before each trial, subjects were required to abstain from strenuous exercise.

At their arrival at the laboratory at least 3 h after a standard breakfast, the subjects relaxed in a sitting position for 30 min in a room maintained at a temperature of approximately 20°C. A 10-mL blood sample was obtained from a superficial forearm vein. The subjects emptied their bladders and were weighed nude. Dehydration was induced by exposing subjects to electric sauna heat (80–85°C dry bulb, with a mean relative humidity of 20%). The subjects were submitted to successive sessions of 15 min, with 5-min recovery periods until a 3% weight reduction was reached. The duration of the sweating session varied slightly between subjects but did not exceed 90 min. After dehydration, each subject showered and relaxed in prone position for 120 min to allow cooling. An indwelling needle was then inserted in an antecubital vein, and blood samples were obtained after subjects had remained in a sitting position for at least 15 min.

Measurements for Eu trials were performed 30 min after subjects came to the laboratory, whereas for Dhy trials, muscular performance was measured 180 min after the last sauna period. For the Rhy trial, dehydration was followed by a 60-min rest period and thereafter a rehydration program with mineralized water (Na, 3.8 $mg \cdot L^{-1}$; Ca, 202 $mg \cdot L^{-1}$, Mg, 36 $mg \cdot L^{-1}$; K, 2 $mg \cdot L^{-1}$, HCO_3^-, 402 $mg \cdot L^{-1}$, SO_4^-, 306 $mg \cdot L^{-1}$). At each 30-min interval, subjects ingested a volume of fluid equal to 25% of the weight loss achieved during the dehydration period, so that after 120 min, the subjects had consumed a volume of fluid equal to their weight loss. After fluid ingestion, subjects emptied their bladders and were weighed. Urine volume was recorded and

the time elapsed between the end of sauna exposure, and the muscular test was approximately 180 min. Muscular strength and endurance testing were conducted at same time of day, approximately 5 h after the last meal. The order of trials was randomized (Fig. 1).

Muscle testing. Both left and right isometric knee extension forces were measured with the subjects in a sitting position and securely strapped in a muscle testing chair. The seated posture met the following specifications: hip angle 100° and knee angle 80°. An inelastic strap was placed around the ankle and connected to a strain gauge (AG-30, Scaime, Annemasse, France) calibrated against known weights. The signal from the strain gauge was amplified with low-pass filter at 10 Hz, digitized in real time at a rate of 1000 samples per second by a 12-bit analog-to-digital converter, and stored on the hard disk of a personal computer. The isometric strength of knee extensor muscles was displayed on a monitor screen visible for both the subject and the experimenter. The apparatus was calibrated with known weights three times during the experiment. During muscle tests, subjects were given verbal support by the experimenter.

As specified above, subjects were familiarized with the experimental dynamometer and strength testing procedures before testing. The experimental procedure included the following steps: i) subjects were asked to perform maximal isometric contractions of short duration (2–3 s) with the right knee extensor muscles. The maximal force was measured, and the best performance after 4 trials was selected as maximal voluntary contraction (MVC). Approximately 2–3 min elapsed between each of the four trials. ii) After a 10-min rest, subjects were asked to perform maximal isometric voluntary contractions of the left knee extensor muscles according to the same procedures. iii) After a 15-min recovery period, subjects maintained a prolonged isometric contraction of the right knee extensor muscles at 70% MVC for as long as possible. iv) After a 20-min rest, subjects were asked to sustain isometric contraction of the left knee extensor muscles at 25% MVC as long as possible under similar conditions. The required tension levels were displayed on the monitor screen providing a visual feedback of the force output during the contractions. Subjects were instructed to match the measured strength as closely as possible with the required target level. They were frequently encouraged to maintain the desired tension levels. Exhaustion was determined at the point when the subject could not sustain the contraction required to maintain the target level of force. The total times spent by each subject performing submaximal isometric contractions were recorded as the subject's endurance time at 70% MVC (ET70) and 25% MVC (ET25).

EMG analysis. The EMG activity of both left and right vastus lateralis muscle was recorded using one box electrode with a built-in preamplifier (Mazet Electronique, Le Mazet, France). This electrode had a bandwidth of 5 Hz–8 kHz, quiescent current <2 nA, and a direct current input impedance of 10 GΩ. Just before muscle testing, the skin was prepared by surface abrasion using a sand paste, cleaned with a mixture of ether, acetone, and ethyl alcohol in equal parts. The impedance was checked, and only values below 5 kΩ were accepted. The two electrodes were coated with electrode gel and fixed lengthwise over the motor point (~20 cm above the knee) with an interelectrode distance of 20 mm. The common reference ground of the vastus lateralis muscle was placed over the patella. The electrodes were also securely affixed to the skin by adhesive tape. A multichannel EMG amplifier equipped with adjustable gain and high-pass filters was used to register EMG activity. Both EMG and strain gauge signals were continuously monitored on the screen of a personal computer. After amplification, the signal was digitized at the sampling rate of 1.25 kHz by an on-line computer system.

TABLE 1. Changes in knee extensor muscle (KEM) performances.

	MVC (N.m)			
	Right KEM	Left KEM	ET70 (s)	ET25 (s)[a]
Eu	416 ± 26	420 ± 20	46 ± 3	195 ± 19
Dhy	422 ± 20	404 ± 20	40 ± 4	150 ± 18‡
Rhy	428 ± 22	418 ± 16	47 ± 4	163 ± 17†,*

Values are means ± SEM. MVC, maximal voluntary contraction; ET70, endurance time to exhaustion at 70% MVC; ET25, endurance time to exhaustion at 25% MVC.
Significant global effect of treatment, [a] $P < 0.01$. Significance difference with Eu, †, $P < 0.05$, ‡, $P < 0.01$; * difference from Dhy, $P < 0.05$.

The power spectral density function of each EMG signal recorded during ET70 and ET25 trials was calculated through fast Fourier transformation (FFT). The EMG signals were then analyzed by components of FFT. The root mean square (RMS) and the mean power frequency (MPF) of the power spectral density were computed (9).

Blood analyses. Venous blood samples were collected into tubes containing lithium heparin from subjects in a sitting position respectively before dehydration and rehydration as well as before and 3 min after muscular testing (Fig. 1). Triplicate measurements of hematocrit and hemoglobin were made and changes in plasma volumes (PV) relative to control values measured before dehydration or muscular testing were calculated according to Dill and Costill (8). Hemoglobin concentrations were determined in duplicate by reflectance photometry (Boehringer Mannheim Diagnostic, Indianapolis, IN). Plasma was separated by centrifugation and stored at −20°C for further analyses. Plasma Na^+ and K^+ concentrations were measured by flame photometry. Blood lactate concentration was measured using an automated analyzer and blood bicarbonate concentrations by using a commercially available kit (Boehringer Mannheim Diagnostic). Lactate and bicarbonate concentrations have been normalized for changes in plasma volumes.

Statistical analysis. Data are presented as means ± SEM. Data from measurements made only once during each trial (muscle strength and endurance) were analyzed with a one-way analysis of variance (ANOVA). Data collected repeatedly over time (blood analyses) were analyzed with a two-way ANOVA (treatment × time) with repeated measures. When a critical *F*-value was obtained for all analyses, a Newman-Keuls *post hoc* analysis was used to identify the significance of the differences. The null hypothesis was rejected when $P < 0.05$.

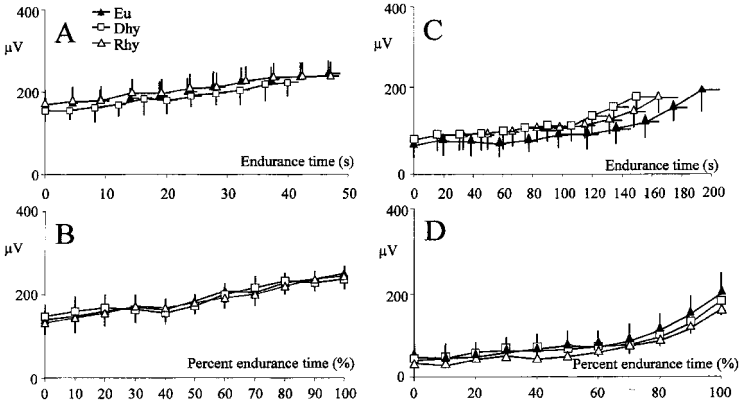

FIGURE 2—Changes in the root mean square (RMS) of EMG during prolonged isometric contraction at 70% (A and B) and 25% maximal voluntary contraction of knee extensor muscles (C and D) at euhydration (Eu), after dehydration (Dhy), and dehydration followed by rehydration (Rhy). A, C, mean values of RMS expressed as absolute values of endurance time; B, D, mean values of RMS expressed as percent of endurance time. Values are means ± SEM.

RESULTS

Body weight. The body weight was 79.3 ± 1.2 kg at rest and 76.9 ± 1.2 kg after dehydration. This represented a mean of 2.95 ± 0.05% reduction in body weight. Water replacement during Rhy was only partly effective, and body weight measured before muscle testing remained lower than before dehydration (−0.5%, $P < 0.005$). Total urine output 1 h after the end of the rehydration period contributed to explaining the lack of complete recovery of body weight (285 ± 54 mL).

Muscle performance. There was no significant effect of the hydration status on knee extensor muscle strength (Table 1). A 23% decrease in ET25 was shown during Dhy ($P < 0.01$), whereas the 13% decrease recorded in ET70 after passive dehydration was not statistically significant ($P = 0.06$). During Rhy, ET70 was similar to that measured during Eu, and ET25 was higher than during Dhy (8%, $P < 0.05$) but remained lower than during Eu (−17%, $P < 0.05$).

Changes in EMG spectral parameters. Under control conditions (Eu), RMS increased during the period of maintenance of the force level in the vastus lateralis muscle during prolonged contractions at 70% MVC and at 25% MVC (Fig. 2). This increasing myoelectrical activity was observed more frequently during the second half of the sustained contraction at 25% MVC (Fig. 2C). When normalized to endurance time, changes in mean RMS values were curvilinear over time (Fig. 2D). During the Dhy, RMS increased earlier than during Eu ($P < 0.01$), but because a significant decrease in ET25 occurred when the subjects were dehydrated, RMS changes showed similar patterns when expressed relative to contraction time (Fig. 2D). During 70% MVC contractions, the rate of increase of RMS was almost linear. Rapid rehydration (Rhy) induced intermediate patterns of changes in RMS values for both 70% and 25% MVC contractions (Fig. 2, A and C).

As previously reported, a significant decrease in the MPF of the EMG power spectral density function occurred during sustained contractions, leading to exhaustion when subjects were euhydrated. No significant changes in the decrease in MPF were observed during 70% MVC contractions between trials (Fig. 3A). As previously described, the decrease in MPF recorded during sustained contractions at 25% MVC was less than during sustained contractions at 70% MVC (12). When expressed as absolute ET25 values, sauna-induced hypohydration resulted in a earlier decrease in MPF during the second part of the sustained contraction ($P < 0.05$) (Fig. 3C). At exhaustion from the 25% MVC contractions, MPF calculated during Eu did not significantly differ from that calculated during Dhy. MPF changes during Rhy showed an intermediate pattern and exhaustion was also associated with similar MPF values (Fig. 3).

Blood analyses. Sauna-induced dehydration led to a significant decrease in PV ($P < 0.05$ to $P < 0.01$) (Table 2), associated with a significant increase in plasma Na^+ concentration (1.8–2.2 $mEq \cdot L^{-1}$, $P < 0.01$) (Table 3). After rapid rehydration, PV increased but remained below control

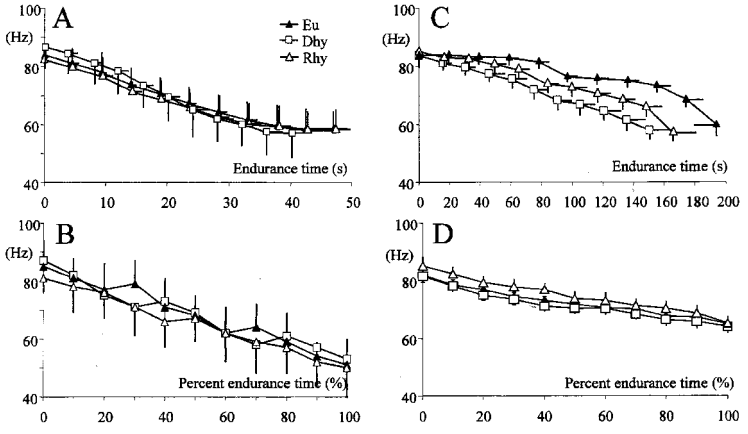

FIGURE 3—Changes in the mean power frequency (MPF) of EMG during prolonged isometric contraction at 70% (A and B) and 25% maximal voluntary contraction of knee extensor muscles (C and D) at euhydration (Eu), after dehydration (Dhy), and dehydration followed by rehydration (Rhy). A, C, mean values of MPF expressed as absolute values of endurance time; B, D, mean values of MPF expressed as percent of endurance time. Values are means ± SEM.

TABLE 2. Changes in plasma volume over time.

	Eu	Dhy	Rhy
After passive dehydration		−3.8 ± 1.1*	−4.2 ± 0.9**
After rapid rehydration			−2.6 ± 0.9*
After muscular testing	−3.7 ± 0.8*	−9.1 ± 0.9**	−9.1 ± 1.2**

Values are means ± SEM. Plasma volume changes are calculated relative to samples obtained at the beginning of each trial.
Significantly different from control value, * $P < 0.05$, ** $P < 0.01$.

values ($P < 0.05$). Plasma Na^+ concentration was lower after rehydration than before the trial ($P < 0.01$) and remained low after muscular testing ($P < 0.05$). Muscular exercise alone resulted in a significant decrease in PV ($P < 0.05$, Table 2), without significant changes in plasma Na^+ and K^+ concentrations (Table 3). During both Dhy and Rhy, exercise-induced changes in PV were higher than during EU. After rapid dehydration, muscle testing led to a slight increase in plasma Na^+ concentration ($P < 0.05$) without change in K^+ concentration while muscle exercise did not significantly change Na^+ or K^+ concentrations in dehydrated subjects.

As expected, muscular testing alone induced an increase in blood lactate concentration and a decrease in blood bicarbonate level ($P < 0.01$, Table 4). No significant differences in mean blood lactate accumulation and blood bicarbonate decrease resulting from muscular testing alone were shown between trials. Sauna exposure did not affect mean blood lactate but was associated with a significant decrease in blood bicarbonate concentrations ($P < 0.05$ to $P < 0.01$). The decrease in blood bicarbonate concentration related to muscular testing was observed both in Eu and Dhy ($P < 0.01$) and in Rhy ($P < 0.05$).

DISCUSSION

The purposes of this study were first to evaluate the effects of dehydration on skeletal muscle performance and to examine the changes of the surface EMG power spectrum during sustained isometric contractions; second to determine the effectiveness of rapid rehydration on the restoration of muscle performance. The results demonstrate that 1) hypohydration affects the skeletal muscle endurance at low force level, without significantly affecting muscle strength; 2) the EMG changes associated with muscular fatigue occurred earlier during Dhy; and 3) after rapid rehydration, muscle endurance remained affected in comparison with the control values.

TABLE 3. Changes in plasma sodium and potassium concentrations during passive dehydration, rapid rehydration, and muscular testing.

	Eu	Dhy	Rhy
Na^+ (mEq·L^{-1})			
Control value	140.1 ± 0.4	140.3 ± 0.4	139.6 ± 0.6
After passive dehydration		142.5 ± 0.7**	141.4 ± 0.9**
After rapid rehydration			137.4 ± 0.6**
After muscular testing	141.8 ± 0.4	142.9 ± 0.7**	138.2 ± 0.5*,†
K^+ (mEq·L^{-1})			
Control value	3.98 ± 0.10	3.88 ± 0.11	3.96 ± 0.06
After passive dehydration		3.95 ± 0.11	4.10 ± 0.11
After rapid rehydration			3.99 ± 0.06
After muscular testing	3.95 ± 0.09	4.01 ± 0.08*	3.83 ± 0.04

Values are means ± SEM.
Significantly different from control value, * $P < 0.05$, ** $P < 0.01$; significantly different from values measured after passive rehydration, † $P < 0.05$.

TABLE 4. Changes in blood lactate and bicarbonate concentrations during passive dehydration, rapid rehydration, and muscular testing.

	Eu	Dhy	Rhy
Lactate (mmol·L^{-1})			
Control value	1.62 ± 0.15	1.37 ± 0.07	1.24 ± 0.13
After passive dehydration		1.23 ± 0.07	1.04 ± 0.09
After rapid rehydration			1.38 ± 0.24
After muscular testing	4.74 ± 0.41**	4.01 ± 0.39**,‡	3.85 ± 0.49**,‡
Bicarbonate (mmol·L^{-1})			
Control value	23.12 ± 0.51	24.83 ± 0.55	23.34 ± 0.31
After passive dehydration		22.47 ± 0.41**	22.30 ± 0.47*
After rapid rehydration			21.92 ± 0.61*
After muscular testing	19.02 ± 0.53**	18.58 ± 0.82**,‡	19.59 ± 1.08**,†

Values are means ± SEM.
Significantly different from control value, * $P < 0.05$, ** $P < 0.01$. Significantly different from concentrations measured before muscular exercise, † $P < 0.05$, ‡ $P < 0.01$.

As shown in many previous studies, hypohydration does not affect muscle strength (14,25,27). Whether dehydration alters muscle endurance during small muscle exercise remains unclear to date. The lack of consensus regarding the effects of dehydration on resistance to fatigue can be explained, at least partly, by the diversity of methods used to determine muscular endurance. In addition to water loss from extra- and intra-cellular compartments, PV decreased by 8% after 4% body weight loss after exercise heat exposure (7). One of our hypotheses was that the effects of dehydration would be more obvious on muscle contractions at a low level of force, with a relative maintenance of blood flow (28). Although the decrease in PV observed in the present study did not exceed 4%, impaired muscle endurance is consistent with this hypothesis. Changes in spectral parameters of the EMG have often been used as indicators of muscle fatigue (9). One of the main results of the present study demonstrates that myoelectrical changes were closely correlated with endurance time and occurred sooner in dehydrated subjects than under control conditions.

Several biochemical factors have been suggested as responsible for the decrease in MPF during sustained contractions. It has been suggested that changes in the conduction velocity (CV) of action potentials, and a decrease in pH can play a significant role to explain the shift in MPF toward lower frequencies (21,26). The accelerated shift in MPF observed in the present study with dehydration could reflect a greater rate of H^+ accumulation. This hypothesis is not supported by previous results showing similar pH declines during exhaustive muscular exercise when subjects were either normo- or hypo-hydrated (25). An increase in intracellular lactate and in extracellular K^+ accumulation known to result in a decrease in membrane excitability and to a reduction in CV has been discussed as factor responsible for the shift in MPF (5,16,17). Previous studies showed that dehydration increased the intracellular and extracellular concentrations of K^+ proportionately and thus did not alter the excitability of the cell membrane (7). Because a significant relationship was found between EMG spectrum changes and diprotonated forms of inorganic phosphate ($H_2PO_4^-$) (20), the effects of the hydration status on the rate

of intramuscular $H_2PO_4^-$ accumulation during sustained contraction should be examined. There is thus no clear evidence that modifications of muscle metabolism could explain the accelerated rate of decline in MPF during dehydration.

A part of the decrease in MPF may also be attributed to a centrally mediated regulation of the motor unit activity, especially at low force level (19). In the present study, the task involved prolonged submaximal contractions at high and low force levels. Subjects were able to increase the motor command to counteract the fatigue-induced reduction in force, resulting in an increase in RMS (4). As expected, the fatigue-induced rise in RMS was less marked for contractions at 70% MVC, because the possibility for recruitment of additional motor units was smaller than for contractions at low force level (12). One interesting result is that the endurance point of isometric contractions was observed at the same RMS levels, whatever the hydration status (Fig. 2C). The similar levels of blood lactate accumulation and blood bicarbonate decrease over trials comply with this finding, and taken together, these results suggest that at exhaustion, the pool of activated motor units was similar at all trials.

A greater rate of RMS increase was observed during contractions at low force level when subjects were dehydrated. This finding suggests an accelerated central activation resulting from an increase in firing rates of motor units and/or an increase in the motor unit recruitment. A feedback loop between intramuscular metabolism and central motor drive has been suggested to account for muscle fatigue (18), but whether the increased rate of central activation results from peripheral or central factors cannot be ascertained in the present study. Moreover, the perception of effort is known to increase during hypohydration (2,24), and the role of increased sense of effort on the impairment of muscle endurance should be clarified.

Body and muscle temperature are known to influence the development of muscle fatigue (11). In the present study, a minimum of 180 min elapsed between the end of sauna exposure and muscle testing, and subjects were maintained at rest in a thermoneutral environment. In this context, we can expect similar values of muscle temperature at the initiation of testing under all trial conditions. A slight increase in muscle temperature is expected during isometric contraction (approximately $0.3°C \cdot min^{-1}$ for contraction of 30% MVC; 10). If changes in intracellular water volumes are associated with changes in PV, heat storage capacity of muscle tissue would be reduced during Dhy trials. However, because ET25 values during Dhy were lower than during Eu and Rhy trials, the rate of increase in muscle temperature during muscle testing may be questioned. A smaller increase in RMS is expected during sustained isometric contractions at high muscle temperatures (15). Because in the present study similar values of RMS and MPF were measured at the end of 25% MVC contractions, it is unlikely that a greater increase in muscle temperature could explain the impairment in muscle endurance when subjects were dehydrated.

One objective of this study was to examine the effectiveness of rapid fluid replacement by using a rehydration program with mineralized water similar to those used under field conditions. As in many previous studies, the volume of water ingested after passive dehydration was equal to that lost. All subjects exhibited a negative fluid balance as a result of urine losses (285 $\pm$ 54 mL). Our results clearly demonstrate that nearly full fluid replacement with mineralized water was not effective in restoring muscle endurance. This finding is consistent with that of Torranin et al. (29), who reported a 13% decrease in isometric endurance time after rehydration after a 3.9% body weight loss by passive dehydration. In the present study, a 2.6% reduction in PV persisted after rehydration, which could, at least partly, account for the lack of recovery in muscle endurance after rapid rehydration. However, because Eu trials did not include sauna exposure with maintenance of body water balance, it is difficult to ascertain whether alterations in muscle performance between Eu and Rhy trials were due to the difference in body water balance or to exposure to the passive heat, *per se*. The effectiveness of rehydration after exercise-induced dehydration is improved by the addition of chloride salt of sodium (23). Whether the rapid replacement of water and electrolyte losses induced by passive heat exposure may be improved by the ingestion of electrolyte-enriched fluids with a beneficial effect on muscle strength and endurance remains to examine.

In conclusion, we have shown that passive dehydration impairs muscle resistance to fatigue. EMG spectral changes associated with fatigue occurred earlier when subjects were dehydrated than during the control trial. Hypohydration induced an accelerated rate of RMS increase and MPF decrease. However, for all trials, exhaustion occurred for similar levels of RMS, MPF, blood lactate, and bicarbonate. There is no clear evidence to date that the accelerated decrease in spectral parameters could be attributed to biochemical modifications and the role of increased perception of effort when subjects were dehydrated should be clarified. Because rapid rehydration failed to restore muscle endurance, sauna-induced dehydration does not appear to be a desirable practice to achieve rapid weight loss before weight-class sporting events.

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