Do the acute biochemical and neuromuscular responses justify the classification of strength- and hypertrophy-type resistance exercise?

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Abstract

This study aimed to examine a wide profile of acute biochemical and neuromuscular responses to strength (STR) and hypertrophy (HYP) resistance exercise (RE). Seven trained men completed an STR workout (4 x 6 repetitions, 85% 1 repetition maximum [1RM], 5-minute rest periods), an HYP workout (4 x 10 repetitions, 70% 1RM, 90-second rest periods), and a control condition (CON) in a randomized crossover design. Peak force (PF), rate of force development (RFD), and muscle activity were quantified before and after exercise during an isometric squat protocol. Blood samples were taken 20, 10, and 0 minutes before and 0, 10, and 60 minutes after exercise to measure the concentration of blood lactate (BL), pH, and a number of electrolytes that were corrected for plasma volume changes. No differences were observed between the workouts for changes in PF, RFD, or muscle activity. Repeated contrasts revealed a greater ($p \leq 0.05$) increase in BL concentration and reduction in pH after the HYP protocol than the STR or CON conditions. There were similar but significant ($p \leq 0.05$) changes in the concentration of a number of electrolytes after both workouts, and a handful of these changes displayed significant correlations with the PF reductions observed after the HYP condition. Although the STR and HYP workouts were significantly different in terms of intensity, volume, and rest, these differences were only observable in the acid-base responses. The present findings reinforce the need for practitioners to look beyond the classification of RE workouts when aiming to elicit specific physiological responses.

Key words electrolyte, fatigue, muscle activity, plasma volume

Introduction

Resistance exercise (RE) is considered the primary modality when strength development is the training goal, and RE workouts are usually divided into strength (STR), hypertrophy (HYP), and muscular endurance–type schemes. STR-type workouts typically involve high intensities (≥85% of 1 repetition maximum [1RM]), low volumes (2–6 sets, ≤6 repetitions), and long rest intervals (3–5 minutes) to increase phosphocreatine resynthesis and maximize motor unit (MU) recruitment. Although these workouts are known to result in hypertrophic adaptations, they are often prescribed with the intention of emphasizing neural adaptations (6), which may be desirable for sports in which relative strength is important. HYP-type workouts in contrast are characterized by high volumes (3–6 sets, 8–12 repetitions), moderate intensities (<85% 1RM), and short rest intervals (30–90 seconds) to maximize anabolic responses (31) that result in mainly hypertrophic adaptations (9,29). Although the classification of these workouts suggests differences in the type (neural vs. muscular) and magnitude of adaptations when prescribed over a period of time, documented scientific evidence in support of these differences is far from unequivocal (33).

In terms of acute responses to RE, there are a number of studies that have examined acute fatigue elicited by a range of workouts (2,3,17,18,24,25,28). Fatigue is generally classified as being central or peripheral in origin (5,36). Central fatigue relates to a reduction in MU activation by the central nervous system (CNS), whereas peripheral fatigue refers to reduced action potential (AP) generation and neurotransmitter release, as well as impaired force-generating capacity of muscle because of the changes (e.g., metabolic) that take place at or are distal to the neuromuscular junction (36). Although a number of studies have examined acute metabolic and neuromuscular fatigue after different RE workouts, the link between acute responses and long-term adaptations remains far from clear, and therefore a limited understanding exists regarding the physiological mechanisms underlying long-term adaptations to resistance training (12). However, based on the notion that adaptations occur to become accustomed to unfamiliar stressors, research that examines the locus of fatigue may help researchers to understand the training stimuli resulting from different RE approaches.

Currently, an ongoing debate exists regarding the precise peripheral factors responsible for the fatigue experienced after high-intensity RE. Metabolic factors have historically been thought to play a role in peripheral fatigue with a large body of research focusing on the detrimental effects of blood lactate (BL) and the associated H^+ accumulation as well as the negative effects of inorganic phosphate on the force-generating capacity of muscle (9). Although a large number of studies have examined the BL and endocrine responses to different RE workouts (19), few studies have compared the changes in H+ and other key ions (e.g., potassium, calcium) after STR and HYP workouts involving multijoint exercises, such as the back squat. This is particularly surprising since multiple ion interactions have been implicated in the failure of force generation by muscle (10). Furthermore, few studies have corrected for plasma volume (PV) changes after RE (22); as a result, the mechanisms responsible for certain biochemical changes are often not clear.

As suggested earlier, better knowledge of the metabolic factors contributing to the fatigue experienced after different RE approaches may be paramount to better understand the training stimuli that result from different RE approaches. In line with this suggestion, evidence now suggests that disturbances in acid-base homeostasis or muscle hypoxia may also be one of the early physiological processes involved in eliciting hypertrophic adaptations (29). Specifically, it has been theorized that disturbances in the muscular environment relating to BL and pH changes may indirectly cause increases in the concentration of growth hormone and testosterone, growth factors, or increased fiber degradation, which have all been linked to muscle hypertrophy (16). Although these factors may be important when aiming to maximize the hypertrophic response, the relative training intensity is also known to be the key (29). Although Fry (15) suggests that optimum muscle hypertrophy occurs in the range of 80–95% of 1RM, it has been shown that exercise intensities as low as 30% 1RM are equally effective at stimulating muscle protein synthesis when performed to volitional fatigue (8). Given that these findings are at odds with the current recommendations by the ACSM (27), the present classification system may create some confusion as to what constitutes an STR- and HYP-type RE.

A lack of clear information also exists regarding the acute neural fatigue responses that may underpin chronic adaptations in the nervous system. Significant reductions in muscle activity have been reported after high-intensity/low-volume workouts alongside reductions in force production (17,18,25). Although these observations have often been used to support the notion that STR-type RE provides a greater stimulus to the nervous system (6), a number of studies have not observed differences between high- and low-intensity workouts with respect to their effects on the nervous system (3,28). The lack of clarity most likely results from the utilization of distinctly different performance measures (e.g., single vs. multijoint) and measurement techniques (e.g., electromyography vs. twitch interpolation), which may differ in their ability to detect physiological and mechanical changes. Interpretation of the present literature is also complicated by the overriding need to equate training volume and the use of the term “heavy RE” to describe distinctly different load-repetition variations (e.g., 20 x 1RM (17); 5 x 10RM (23)). Although many of these workouts have incorporated elements of STR- or HYP-type regimens (e.g., high intensities), other unexpected responses (e.g., metabolite accumulation), depending on the volume and rest interval prescription, are not excluded.

Based on the theory that the acute responses elicited by RE workouts are a function of the interaction among intensity, volume, and rest interval duration (25), it is suggested that the strength-endurance continuum may provide a more effective means of visualizing the training responses to RE. This is the notion by which workouts involving higher numbers of repetitions elicit mainly peripheral responses (peripheral fatigue), whereas more neural responses (central fatigue) would be elicited because the loads become heavier and the repetitions become fewer. Although this concept may somewhat explain the inconsistent findings from previous acute studies, there is always going to be a practical categorization of workouts into strength, hypertrophy, or endurance-type RE. An understanding of the boundaries of these discrete workouts within the strength-endurance continuum is therefore vital. The aim of this study was therefore to examine a wide profile of acute biochemical and neuromuscular responses to STR- and HYP-type workouts (according to their classification). One of the novel aspects was the examination of biochemical responses relating to acid-base and electrolyte homeostasis and the correction of these for PV changes. This is one of the few studies to examine neuromuscular responses and multiple ion changes together in vivo, particularly after RE involving large muscle mass. Such an approach is intended to provide an insight into the physiological processes involved in the fatigue experienced after STR- and HYP-type RE.

Methods

Experimental approach to the problem

To examine the acute biochemical and neuromuscular responses to STR- and HYP-type workouts, subjects visited the laboratory on 5 separate occasions. During the first session, subjects were screened and familiarized with the tests and procedures. Subjects' 1RM back squat strength was measured on the second visit to determine the training intensities. Subjects then completed 2 experimental workouts and a control (CON) condition in a randomized crossover design separated by at least 72 hours. Volume was not equated between the experimental workouts to allow the workouts to be more reflective of actual training practice. For each testing session, subjects underwent 3–4 hours fasting and then completed a neuromuscular performance test (NPT), and fingertip blood samples were drawn before and after each experimental condition (Figure 1). An attempt was made to investigate the degree of fatigue elicited by the 2 experimental workouts by measuring the peak force (PF), rate of force development (RFD), and lower-body muscle activity during the NPT. Changes in a number of biochemical variables were also measured to provide an insight into the peripheral responses associated with the workouts. All subjects were advised to undergo 24 hours of rest before each session and were instructed to abstain from any maximal exercise for the duration of the study. In addition, subjects were required to complete a food diary 24 hours before all experimental sessions and were instructed to consume identical food and drink during these periods. The diet diaries were analyzed using CompEat Pro software (v.5.8; Nutrition Systems). All experimental sessions took place at the same time of day to control for diurnal variations.

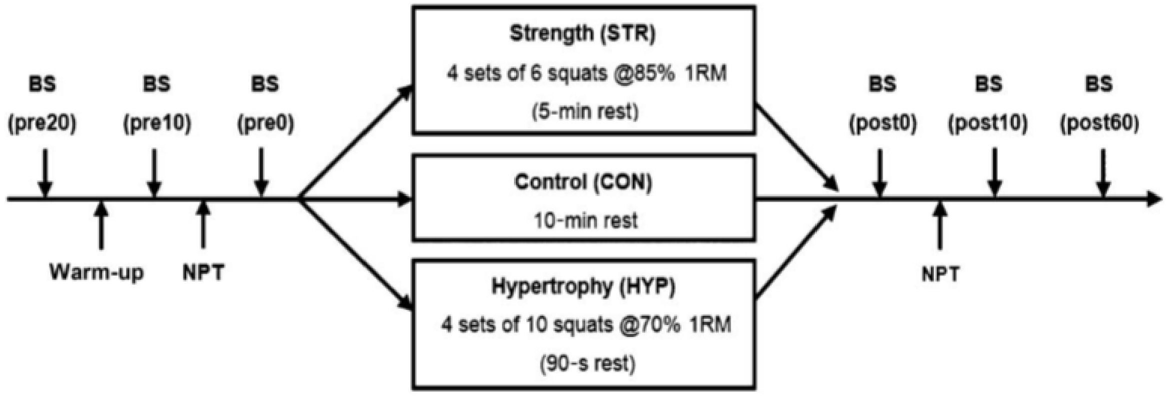

Figure 1 Schematic representation of the testing procedures. BS = blood samples, NPT = neuromuscular performance test.

Subjects

Seven resistance trained men between the ages of 18 and 27 volunteered to take part in the study (age: 23.57 ± 2.72 years; height: 182.01 ± 2.16 cm; body mass: 92.23 ± 15.13 kg; 1RM squat: 142.86 ± 16.66 kg; 1RM body mass ratio: 1.56 ± 0.15). The subjects were chosen because of their experience in structured strength training (minimum 12 months) and their proficiency in the back squat exercise. During familiarization, if the subjects were unable to complete multiple repetitions (.8) of the parallel back squat with a weight equal to their own body mass on the bar, they were excluded from the study. Furthermore, subjects who did not display correct technique (i.e., weight distribution, torso and knee alignment) were not permitted to take part. No subjects were taking any medications or supplements known to affect the energy metabolism or RE performance. The Faculty's Ethics Committee approved the details of the study including consent documentation and information provided to subjects before commencement. In accordance with the institutional review board's policies for use of human subjects in research, all subjects were informed of the benefits and possible risks associated with participation and were informed of the right to withdraw at any point. All subjects were age older than 18 years and gave written informed consent to indicate their voluntary participation.

Procedures

Strength Testing. Baseline strength levels were determined by assessing 1RM strength for the back squat exercise. Procedures to measure 1RM strength were identical to those previously described (11) and briefly involved a series of submaximal warm-up sets followed by 5 maximal lifting attempts until each subject's 1RM was identified. Periods of rest (approximately 4–5 minutes) were permitted between trials in an attempt to maintain maximal performance. Successful attempts required subjects to descend to the point where the tops of the thighs were parallel to the floor and squat depth was visually assessed by the same experienced researcher. All 1RM testing sessions took place in the same exercise laboratory using a customized power rack with adjusted safety stoppers and were performed at least 72 hours before the experimental sessions.

Acute Resistance Exercise Bouts. Before each experimental protocol, a standardized warm-up was completed, which involved 5 minutes of cycling on a stationary ergometer and dynamic mobility exercises. The HYP protocol involved 4 sets of 10 repetitions of the parallel back squat at 70% of 1RM with 90-second rest intervals. The STR protocol included 4 sets of 6 repetitions at 85% of 1RM with 5-minute rest intervals. The CON condition required subjects to rest for 10 minutes, performing only the warmup and NPTs. The training sessions were selected based on their frequent use during training practice and their conformity with the current recommendations for STR-and HYP-type RE (27). Volume load (reps x sets x intensity) was not equated between workouts to allow them to be more reflective of those used during training practice. The parallel back squat is frequently prescribed by coaches, and this sort of multijoint exercise is known to produce greater metabolic and hormonal responses (12). During training, pins were adjusted to allow each subject to descend where the tops of the thighs were parallel to the floor. Subjects were provided with strong verbal encouragement throughout the workouts to ensure that the prescribed number or repetitions were completed; however, the subjects were not pushed to the point of failure. Subjects were encouraged to lift at a self-selected velocity, and the total time for each set was recorded using a Polar S610i (Polar, Kempele, Finland) heart rate monitor to provide an indication of the pace of lifting.

Blood Sampling. Subjects reported to the laboratory after 3–4 hours of fasting. Fingertip blood samples (150 mL) were taken 20 (pre20), 10 (pre10), and 0 (pre0) minutes before and 0 (post0), 10 (post10), and 60 (post60) minutes after exercise. To arterialize blood samples and to achieve greater blood flow, subject's hands were placed in warm water (43°c) for 30 seconds before each sample; dried and cleaned using alcotip swabs, and then pierced using a sterile lancet. The samples were immediately analyzed for pH, BL concentration, potassium (K^+), calcium (Ca^{2+}), sodium (Na^+), chloride (Cl^-), hemoglobin (Hb), and hematocrit (Hct) using the portable GEM Premier 4000. This device has previously demonstrated good coefficient of variation (CV%) values for inter- and intra-day measurements (e.g., K^+: 1.6% [inter-day] and 0.9% [intra-day]) (4). To evaluate the impact of PV shifts on the concentration on different biochemical parameters, changes in PV were estimated from Hb and Hct using the equations by Dill and Costill (14). To control for the influence of postural changes, subjects were seated for 20 minutes before the first sample and were instructed to remain seated between each sample when possible. The concentration of a number of biochemical variables (BL, K^+, Ca^{2+}, Na^+, Cl^-) were subsequently corrected for PV changes using the methods of Kraemer and Brown (21).

Neuromuscular Performance. To investigate the effects of the workouts on neuromuscular performance, maximal isometric strength and concurrent electromyographic (EMG) activity were measured for the leg muscles before and after exercise; this required synchronization between the force plate (BioWare 3.20; Kistler, Winterthur, Switzerland) and EMG software (EMGworks 4.0; Delsys, Boston, MA, USA). Subjects performed 3 maximal isometric back squats before and after exercise using a modified squat rack positioned over a Kistler force platform (9281B, 40 x 60 cm) sampling at 1,000 Hz. Subjects were instructed to push upward against a fixed bar as hard and as fast as possible for 4 seconds while assuming a knee angle of 1008 (Figure 2). Pilot studies conducted before the investigation demonstrated that a knee angle of 1008 produced the highest level of between-session (CV = 1.52%, ICC = 0.961) and within-session (CV = 1.17%, ICC = 0.976) reproducibility for PF and was closely monitored using a clinical goniometer. Hip angle was controlled using a wooden plank fixed in front of the knees, and stance width was standardized at shoulder width. Loud verbal encouragement was provided to maintain subject motivation for each trial. Numerous measures of mechanical performance were identified before and after exercise, including measures of PF and RFD. Peak force production was determined from the resultant ground reaction forces, and several measures of RFD were calculated including the time taken to produce 250 N, 500 N, and 750 N from 50 N and the time required to achieve 30 and 60% PF from 10% of PF. The rate of force production was also identified for different time periods (0.05, 0.1, 0.15, 0.2, and 0.25 seconds) by recording the slope gradient during the initial portion of each force-time curve (Figure 3). All measures of mechanical performance were reported for the trial corresponding to the highest PF during the pre- and post-exercise measurements.

Figure 2 Maximal isometric squat protocol utilizing a customized power rack and force platform.

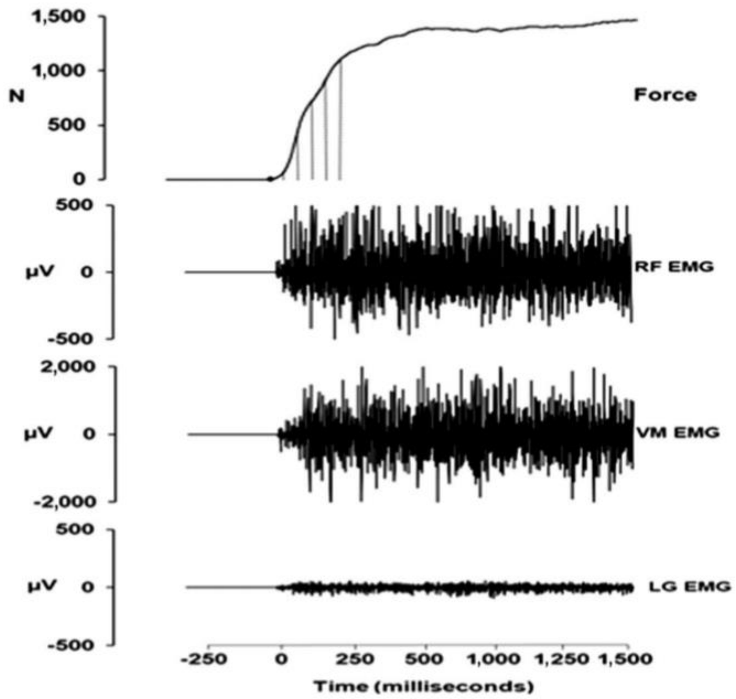

Figure 3 Example force-time curve and raw electromyographic (EMG) activity during the maximal isometric squat test (note the change in axis range). Dotted vertical lines indicate time intervals of 50, 100, 150, 200, 250 milliseconds relative to the start of contraction. RF = rectus femoris, VM = vastus medialis, LG = lateral gastrocnemius.

Surface EMG activity was recorded during the isometric assessments for the key leg muscles: vastus medialis (VM), rectus femoris, biceps femoris, and lateral gastrocnemius. Skin preparation involved shaving and cleaning the skin surface with alcohol swabs. Two active bipolar electrodes (Delsys Inc.) with a 10-mm fixed interelectrode distance were placed over the muscle belly parallel to the underlying muscle fibers and a reference electrode was placed on the lateral condyle of the femur. A telemetry unit (Myomonitor IV; Delsys Inc.) was used to collect the data at 1,000 Hz (CMRR > 80Db, gain = 1000, input impedance = 10 MΩ). The data were filtered using a bandpass filter (cut-off frequencies: 20–450 Hz), and to reduce movement artifact, wires connecting the electrodes to the unit were held in place by tubular net bandages. The raw EMG signals were processed using average rectified EMG (AREMG), root mean square (RMS), and median frequency (MF) for a 0.5-second period corresponding to PF production and for the initial 0.25 seconds of the force-time curve.

Statistical Analyses

Mean and SD values of the experimental variables were initially calculated. The changes over time between protocols were analyzed using a general linear model (SPSS version 18.0; SPSS, Chicago, IL, USA) analysis of variance with repeated measures (protocol 3 time). If significant interactions were present, differences between the experimental protocols were identified using repeated contrast tests. A one-way analysis of variance was used to ensure that there were no pre-exercise differences in the dependent variables between the conditions. Statistical significance was set at the $p \leq 0.05$ level. Although caution should be taken when interpreting correlational analyses with small samples, we used the Pearson product-moment correlations to add a descriptive view of the relationships between selected variables.

Results

Volume and Duration of Resistance Exercise

All subjects completed their prescribed number of repetitions. In line with the study design, the total volume-load performed in the HYP protocol was shown to be 26.60 ± 1.45% ($p \leq 0.001$) greater than that performed during the STR workout, and the mean intensity (% 1RM), however, was 17.65 ± 0.00% higher ($p \leq 0.001$) in the STR workout. The mean duration of each set increased gradually for the STR (22.41 ± 4.80 seconds) and HYP (32.11 ± 5.55 seconds) conditions, and the mean duration was significantly greater for the HYP workout for all sets performed ($p \leq 0.05$).

Acute Neuromuscular Response

Both the STR and HYP protocols resulted in large reductions of 15–18% in voluntary force measured during the maximal isometric leg strength protocol as shown in Figure 4A. There were no significant differences between the STR and HYP conditions in terms of the decrements in PF production; however, only the HYP workout demonstrated a significant drop (from 1,601.62 ± 263.56 N to 1,348.27 ± 364.31 N) in PF ($p \leq 0.05$) when compared with the CON condition. The force-time curve shifted greatly to the right after both experimental protocols (Figure 4B), and this was demonstrated by significant reductions in several measures of RFD for the STR and HYP. For example, the HYP workout elicited a significant ($p \leq 0.05$) drop in the rate of force production during the initial 0.05 seconds (from 3,476.50 ± 1,645.85 $N \cdot s^{-1}$ to 2,782.55 ± 1,413.17 $N \cdot s^{-1}$) and 0.1 seconds (from 4,585.74 ± 2,210.19 $N \cdot s^{-1}$ to 3,465.30 ± 1,702.38 $N \cdot s^{-1}$) of the force-time curve and significant ($p \leq 0.05$) increases in the time required to produce 500 N (from 0.11 ± 0.06 seconds to 0.16 ± 0.11 seconds) when compared with the CON condition. In contrast, the STR workout was characterized by significant ($p \leq 0.05$) reductions in the rate of force production during the initial 0.2 seconds of the force-time curve (from 4,415.11 ± 1,166.17 $N \cdot s^{-1}$ to 3,507.27 ± 1,410.08 $N \cdot s^{-1}$) and significant ($p \leq 0.05$) increases in the time required to produce 250 N (from 0.04 ± 0.01 seconds to 0.05 ± 0.01 seconds) when compared with the CON condition. Again, no significant differences were observed between the experimental conditions for any RFD variable.

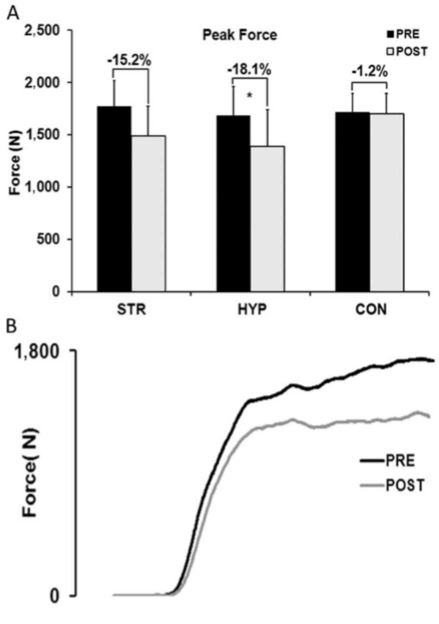

Figure 4 (A) Comparison of the mean (SD) peak force after the strength (STR), hypertrophy (HYP), and control (CON) conditions during the maximal isometric squat (the data labels reflect the percent change from pre to post) *Significant ($p \leq 0.05$) difference from CON condition. (B) A typical shift in the force-time curve after the STR workout.

Although the descriptive data for VM highlighted a tendency for mean RMS and AREMG to decrease after the STR and HYP protocols, there were no significant differences in EMG amplitude or MF within or between the testing conditions for any of the key lower leg muscles. Large variability in individual responses was particularly apparent, both in the magnitude and direction of the EMG changes after the 3 testing conditions.

Acute Metabolic Response

Analysis of the PV changes immediately post-exercise for the STR (-8.05 ± 11.45%), HYP (-8.02 ± 6.54%), and CON (-3.32 ± 6.67%) conditions revealed significantly greater changes for the STR and HYP than CON condition ($p \leq 0.05$). No significant differences were observed for any biochemical variable at pre20, pre10, or pre0 between any of the testing conditions.

Pre- and post-exercise comparisons were mainly conducted between baseline (pre20) and immediately after exercise (post0) because the baseline values were not influenced by PV shifts resulting from the warm-up and maximal isometric leg strength test. The comparisons revealed that both experimental conditions elicited an increase in BL concentration alongside decreases in pH (Table 1). More specifically, the STR and HYP workouts elicited a significantly ($p \leq 0.05$) greater change in BL concentration and pH at post0 when compared with the CON condition, and this was true for corrected and uncorrected values when compared with baseline (pre20). In terms of the differences between the 2 workouts, the HYP workout resulted in significantly greater increases ($p \leq 0.05$) in BL and pH than the STR workout at the same time point for both corrected and uncorrected values when compared with baseline (pre20). In terms of the recovery from exercise, the HYP condition remained significantly different from the STR and CON for BL and pH at post10 (Figure 5).

Table 1 The mean (SD) corrected and uncorrected biochemical responses at pre20 and post0 for the STR, HYP, and CON conditions for BL, pH, K^+, Ca^{2+}, and CL^-.*

	Uncorrected			Corrected	
Blood parameter	Pre20	Post0	Change	Post0	Change
BL ($mmol·L^{-1}$)					
STR	1.07 (0.38)	7.49 (2.56)	↑ **6.41 (2.75)†**	6.66 (2.31)	↑ **5.59 (2.45)†**
HYP	0.83 (0.13)	10.91 (3.06)	↑ **10.09 (3.08)†‡**	9.67 (2.45)	↑ **8.84 (2.46)†‡**
CON	0.97 (0.48)	1.14 (0.57)	↓ 0.17 (0.33)	1.15 (0.55)	↑ 0.18 (0.34)
pH					
STR	7.44 (0.02)	7.36 (0.04)	↓ **0.08 (0.04)†**		
HYP	7.43 (0.02)	7.29 (0.04)	↓ **0.14 (0.03)†‡**		
CON	7.44 (0.02)	7.43 (0.01)	↓ 0.01 (0.02)		
K^+ ($mmol·L^{-1}$)					
STR	4.49 (0.27)	4.64 (0.33)	↑ 0.16 (0.24)	4.14 (0.61)	↓ 0.34 (0.45)
HYP	4.46 (0.33)	4.51 (0.33)	↑ 0.06 (0.32)	4.02 (0.35)	↓ **0.44 (0.36)†**
CON	4.47 (0.23)	4.43 (0.21)	↓ 0.04 (0.15)	4.48 (0.34)	↑ 0.01 (0.22)
Ca^{2+} ($mmol·L^{-1}$)					
STR	1.19 (0.04)	1.19 (0.04)	↑ 0.00 (0.03)	1.06 (0.15)	↓ **0.13 (0.13)†**
HYP	1.18 (0.04)	1.23 (0.04)	↑ **0.05 (0.03)†‡**	1.10 (0.05)	↓ 0.09 (0.06)
CON	1.18 (0.05)	1.18 (0.05)	↑ 0.00 (0.03)	1.20 (0.08)	↑ 0.02 (0.07)
Na^+ ($mmol·L^{-1}$)					
STR	134.71 (1.11)	135.71 (1.38)	↑ **1.00 (0.82)†**	120.8 (12.21)	↓ **13.91 (12.79)†**
HYP	134.57 (1.27)	137.43 (1.13)	↑ **2.86 (1.35)†‡**	122.34 (5.79)	↓ **12.23 (6.64)†**
CON	134.57 (0.98)	134.71 (1.11)	↑ 0.14 (0.69)	136.21 (5.77)	↑ 1.64 (5.60)
Cl^- ($mmol·L^{-1}$)					
STR	103.00 (1.53)	100.71 (1.98)	↓ **2.29 (0.95)†**	89.57 (8.43)	↓ **13.43 (9.38)†**
HYP	102.57 (0.79)	100.71 (1.89)	↓ **1.86 (1.35)†**	89.69 (5.17)	↓ **12.88 (4.72)†**
CON	103.71 (1.11)	102.71 (1.25)	↓ 1.00 (1.00)	103.86 (4.62)	↑ 0.15 (4.24)

*BL = blood lactate; STR – strength; HYP = hypertrophy; CON = control
†Significantly different from control
‡Significant difference between STR and HYP

Although uncorrected values revealed significant ($p \leq 0.05$) changes in a number of electrolytes from pre0 to post0 after the STR and HYP workouts when compared with the CON condition, there were no significant changes in any ion after correcting for changes in PV. When the values at post0 were compared with those at baseline (pre20), however, the uncorrected and corrected values both revealed significant changes in a number of electrolytes (Table 1). For the uncorrected values, the STR and HYP workouts demonstrated significant ($p \leq 0.05$) changes in Na^+ and Cl^- when compared with the CON. In addition, the HYP resulted in a significantly greater ($p \leq 0.05$) increase in Ca^{2+} than the CON condition (at the same time points), and the changes in Ca^{2+} and Na^+ after the HYP workout were significantly greater than those after the STR workout ($p \leq 0.05$). When the corrected data were analyzed, both the STR and HYP workouts demonstrated significantly greater decreases in Cl^- than the CON condition ($p \leq 0.05$); in addition, solitary changes in Ca^{2+} after the STR workout and K^+ after the HYP workout were also observed when compared with the CON condition ($p \leq 0.05$). In terms of the relationship between different dependent variables, a handful of significant correlations were observed between reductions in voluntary force (from pre20 to post0) and the absolute change (Δ) in

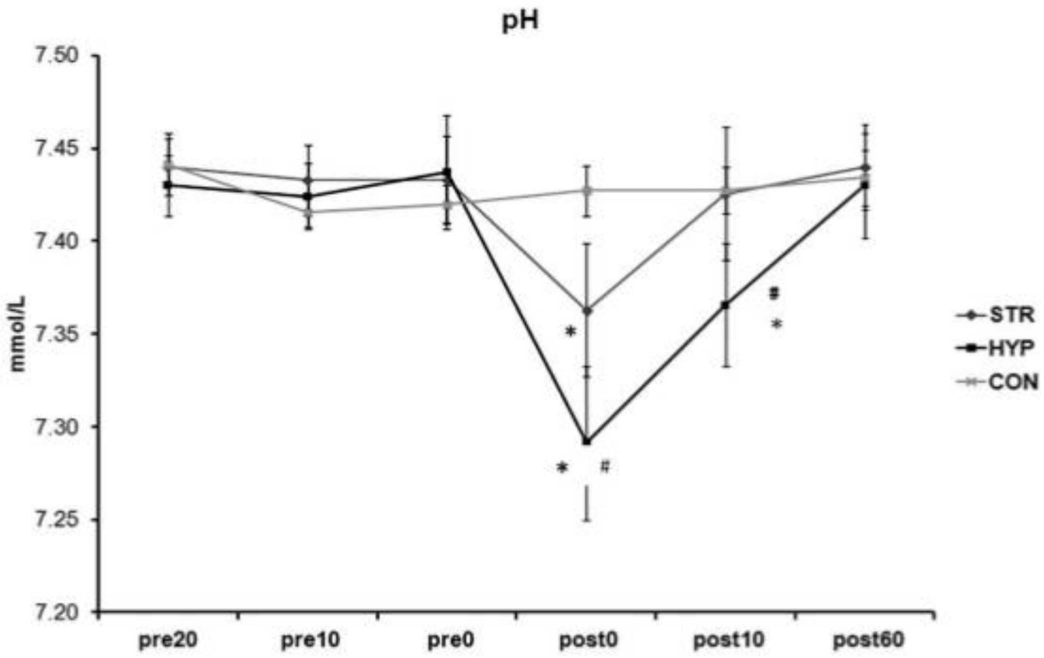

Figure 5 Mean (SD) time-course of pH changes for 20 minutes before (pre20), 10 minutes before (pre10), immediately before (pre0), immediately after (post0), 10 minutes after (post10), and 60 minutes after (post60) the strength (STR), hypertrophy (HYP) and Control (CON) conditions.
*Significantly different from control condition; #Significantly different from STR condition.

Na^+ and Cl^-; however, these correlations were observed for the HYP workout only (Table 2). No significant relationships were observed between the biochemical responses and the changes in EMG amplitude or frequency characteristics.

Table 2 Correlations (one-tailed) between the mean changes (Δ) in plasma ion concentrations (from pre20 to post0) and the mean change in peak force production (ΔPF).*

	ΔPF	
	STR	HYP
Δ pH	0.505	0.577
Δ Ca^{2+}	0.334	0.416
Δ Na^+	0.307	0.835†
Δ K^+	0.620	0.082
Δ Cl^-	0.346	0.807‡

*Correlations were performed for correct values with the exception of pH. PF = peak force; STR = strength; HYP = hypertrophy.
†Correlation significant at the $p < 0.01$ level.
‡Correlation significant at the $p \leq 0.05$ level.

<u>Nutritional Intake</u>

No significant differences were observed between protocols for total energy intake or the macronutrient composition of subject's diets for the 24-hour period before the experimental sessions.

Discussion

Despite the classification of the 2 workouts, relatively few differences were observed between the STR and HYP conditions in terms of their acute biochemical and neuromuscular responses. Although the similar acute responses do not exclude the possibility that the 2 workouts may still result in different long-term adaptations, it is clear that intensity, volume, and rest interval manipulation mainly influenced the magnitude of the acid-base disturbances. As was expected, the HYP workout resulted in the greatest increases in BL and reductions in pH; however, the additional finding was the increase in the concentration of a number of electrolytes and the fact that there were few significant differences between the 2 workouts. In terms of the neuromuscular responses, both the STR and HYP workouts resulted in acute neuromuscular fatigue as evidenced by reductions in voluntary force production and RFD; however, marked differences in the mechanical or EMG responses were again not observed between the 2 workouts.

The magnitude of the neuromuscular fatigue is believed to be dependent on a range of factors including workout volume and intensity, time under tension, the training history of subjects, and their muscle fiber distribution (18,25). Despite the fact that the protocols were significantly different in terms of volume, intensity, and total resting time, the post-protocol markers of mechanical performance were very similar. Although caution should be exercised in drawing definitive conclusions based on the small sample size, both workouts resulted in notable reductions in voluntary force production and shifts in the isometric force-time curve; in this respect, the current data are in agreement with previous studies that have examined STR-type (18,25) and HYP-type RE (24,25). The reduction in voluntary isometric force after the STR (214.90%) and HYP (216.39%) workouts were similar and in line with those reported previously (17,25). Given that STR and HYP workouts are typically prescribed to elicit different acute responses and long-term adaptations, differences in the decline in mechanical performance may have been expected; however, similar decrements in voluntary force and RFD have been observed previously between STR and HYP workouts (25). In this respect, the findings may suggest that differences in the neuromuscular responses to different stimuli are not detectable in mechanical performance.

Although both workouts demonstrated reductions in RFD when compared with the CON condition, these reductions encompassed that the early and late phases of the force rise for the HYP workout but were confined to the late phase for the STR workout. Reductions in rapid force production have been observed previously after similar HYP workouts (1) and have been attributed to low-frequency fatigue that relates to the reduction in force production from low-frequency stimulation. Although the present findings are not at odds with this suggestion, little scientific evidence exists to link different portions of the force-time curve to different physiological phenomenon.

Reductions in mechanical performance could result from central mechanisms relating to decreased MU activation by the CNS and/or peripheral mechanisms relating to metabolite accumulation and impaired excitation-contraction coupling (36). A number of previous investigations have reported acute reductions in EMG activity after STR-type workouts (18,25). Although these previous findings are often used in support of the view that STR-type RE emphasizes mainly neural adaptations (6,11), changes in EMG activity cannot be attributed entirely to neural factors because a handful of peripheral factors (e.g., muscle blood flow) are also known to influence the recorded signal (13). If neural factors did contribute to the reductions in mechanical performance observed in this study, they did not manifest themselves as surface EMG changes as neither workout resulted in significant changes. However, our findings are partly in agreement with a number of studies based on more clinical methods (e.g., Interpolated Twitch Technique) that do not support the popular perception that high loads result in greater neural fatigue (3,28). These findings have been taken to suggest that chronic adaptations resulting from HYP-type RE may result from stress being placed on both the central and peripheral components of the neuromuscular system (28). Although the limitations of surface EMG prevent an accurate interpretation of the present findings, the current combination of intensity, volume, and rest intervals should also be considered. Previous studies that have observed reductions in EMG activity after STR workouts have examined higher intensities (≥90% 1RM) and lower volumes (17,25). Despite the fact that this study and previous ones have incorporated high intensities and long rest intervals into their STR workouts (e.g., 4 sets of 5RM (11)), there exists the possibility that elevated neural responses may be confined to workouts involving near-maximal loads (≥90% 1RM), lower volumes (≤3 reps per set), and long rest intervals. From a practical perspective, this underlines a key limitation with the current classification of STR- and HYP-type RE and is something that may be more accurately demonstrated by using the strength-endurance continuum.

However, post-exercise increases in EMG activity have been previously reported alongside reductions in force production after moderate-intensity RE performed in an occluded (34) and nonoccluded (25) state. Although there is no direct link between these increases and specific portions of the MU pool, these EMG changes provide some information about possible recruitment of higher threshold MUs during fatiguing low-load training. Higher levels of force are known to be required to activate higher threshold MUs based on the size principle of MU recruitment (20), but the above studies suggest an alternative pathway to recruit high threshold MUs in the absence of near maximal loads. Finally, a number of other previous studies have observed either reductions (23) or no changes (1,2) in muscle activity immediately after HYP workouts, which obviously is not in agreement with the above. Although all these conflicting findings prevent accurate conclusions regarding the neural responses to HYP-type RE, the present EMG data are not at odds with the theory that fatigue after HYP workouts is mainly peripheral in origin (28).

Although the present data may be taken to suggest that the present STR and HYP workouts resulted in similar initial neural responses, there exists the possibility that neural deficits were not detectable based on the techniques used in this study. Interpretation of the present EMG data is complicated by the variability in individual responses, which was evident in the magnitude and the direction of the changes. Although the repeatability of EMG amplitude during single-joint isometric assessments has been reported previously, little is known about the reproducibility of these measures during multijoint protocols. Although factors relating to body position, motivation, electrode placement, and familiarization were controlled during the present protocol, differences in training history, fiber type, and subtle changes in synergist contribution may have accounted for the variability observed in this study. Although multijoint isometric assessments are becoming increasingly popular in an attempt to increase the ecological validity of research findings, this is not the first study to question the sensitivity of such measures (1).

In terms of the specific biochemical changes that may contribute to RE fatigue, previous research has tended to focus on a relatively narrow range of responses, particularly those relating to BL and H^+ accumulation. In line with many of these studies, the present data highlight significantly greater increases in BL and H^+ immediately after the HYP workout when compared with STR and CON conditions, and the magnitude of the increases were similar to those reported previously (31). These large changes are believed to result from the higher volumes and shorter rest intervals and the large muscle mass recruited during the back squat exercise. Although STR workouts are typically not prescribed to elicit significant metabolic stress (12), the BL and H^+ changes after the STR workout were significantly greater than those observed for the CON condition and were greater in magnitude than those reported previously for BL (31,19). The elevated responses in the STR workout occurred despite the extended rest intervals and most likely result from the fact that the current STR workout lies at the top end of the recommendations (27) for STR-type RE (2–6 sets, ≤6 repetitions) and toward the bottom end of the recommendations for HYP-type RE (3–6 sets, 8–12 repetitions). Although the present findings suggest that both STR and HYP workouts elicit significant metabolic stress, it is important to highlight that the present findings are not necessarily indicative of "true" strength workouts that incorporate lower numbers of repetitions (i.e., 1–4). Thus, it is again suggested that the strength-endurance continuum may provide a more accurate means of explaining the elevated metabolic responses associated with higher volume STR workouts.

In line with previous investigations (19), the greatest force decrements were observed after the workout that resulted in the greatest increases in BL and H^+ concentration. Although it was once thought that BL and the accompanying acidosis were key players in muscular fatigue, a number of observations based on isolated muscle fibers have demonstrated that these changes alone do not severely impair muscular function (40). Although it seems unlikely that the observed disturbances in acid-base homeostasis were solely responsible for the reductions in mechanical performance, a handful of articles present the possibility that exercise-induced acidosis may still limit whole-body performance (32), especially when interacting with other factors that simultaneously change during exercise. Although the BL and pH changes are now believed to have less of an impact on acute performance during high-intensity exercise, a growing body of literature (12,16) provides evidence to suggest that the build-up of BL and the accompanying declines in pH are one of the early physiological processes involved in hypertrophic adaptations. From a practical perspective, the greater changes in BL and pH after the present HYP protocol therefore lend support to the use of similar HYP workouts when aiming to maximize gains in muscle size.

In view of these developments, the latest research into biochemical aspects of fatigue has focused on the interactional effects of multiple ions. Although separate theories exist regarding the detrimental and protective effects of Ca^{2+}, and Cl^-, current understanding now suggests that the rundown of the trans-sarcolemmal K^+ gradient is the dominant process around which other ions interact to contribute to fatigue (10). Although a number of mechanisms have been offered to explain the negative effects of these ion interactions, much of the research has used isolated/skinned muscle fibers and advanced sampling methods (e.g., microdialysis). Although observations regarding the rate of ion efflux and uptake from working muscle have been previously inferred from arterial and venous samples together with measures of muscle blood flow, evidence suggests that ion shifts at the sarcolemma should be considered separate from those between the muscle and general circulation (26). Although only speculative inferences can be made regarding the effect of blood ion changes on whole-body performance, the findings provide a preliminary insight into the ion changes associated with multijoint RE.

Interpretation of the present ion data is complicated by the transient fluid shifts in (hemodilution) and out (hemoconcentration) of the intravascular space. Both workouts produced short-term hemoconcentration and the PV changes observed were within the range previously reported after RE (38). Although significantly greater PV changes have been previously observed for HYP compared with STR-type RE after multiexercise workouts (38), these differences were not replicated in this study. Examination of the uncorrected biochemical changes from pre0 to post0 revealed significant changes in Ca^{2+}, Na^+, and Cl^- immediately after exercise that were accountable to the changes in PV. In contrast, examination of the biochemical changes from "resting baseline" (pre20) to post0 revealed significant changes regardless of PV corrections when compared with the CON condition, these changes may be indicative of ion fluxes that resulted from the effects of exercise rather than the effects of hemoconcentration. The contrasting observations may highlight that the pre0 values were influenced by postural changes associated with the warm-up and isometric squat procedures. Although the findings highlight the methodological difficulties associated with quantifying fluid shifts during whole-body exercise, the results support the need to quantify fluid shifts for a better understanding of the mechanisms responsible for biochemical changes.

Muscle contraction requires the propagation of APs along the sarcolemma and down the transverse tubules to activate Ca^{2+} release from the sarcoplasmic reticulum. Despite the fact that Na^+ and K^+ move in opposite directions during each AP, an increase in the uncorrected concentration of all plasma constituents was expected immediately after exercise because of the uptake of fluid by muscle. The uncorrected K^+, Ca^{2+} , and Na^+ concentration increased in the expected manner; however, the changes were relatively minor and the concentrations were lower than previously reported for K^+ (4.6–9 $mmol{\cdot}L^{-1}$), Na^+ (145–156 $mmol{\cdot}L^{-1}$), Ca^{2+} (1.28 $mmol{\cdot}L^{-1}$), and Cl^- (104.5–105 $mmol{\cdot}L^{-1}$) after intense exercise of differing modalities (26,30). Correction for PV changes revealed significant reductions in plasma Na+ immediately after both workouts, which most likely reflect its influx into the sarcoplasm during depolarization. Although K^+ efflux and Cl^- influx are known to occur during the repolarization phase of each AP, correction for PV changes revealed significant reductions in Cl^- and a small but significant reduction in K^+ after the HYP workout. Although information on electrolyte changes after different whole-body RE workouts is not available, greater increases in K^+ may have been expected after the HYP workout based on the higher number of repetitions; however, evidence also exists to suggest that exercise intensity is the main determinant of the rate of K^+ loss (37). Despite the fact that K^+ responses after exercise are known to be affected by the proportion of active muscle mass, the post0 K^+ concentrations (uncorrected) were lower than previously observed after unilateral knee extension exercise (30). It is possible that a number of factors affected the measured concentration of K^+, and these include the intensity, duration and modality of exercise (37), the sampling method (arterial vs. venous), and timings as well as the magnitude of hemoconcentration. Although the balance of K^+ efflux, reuptake, and redistribution are not apparent from the present findings, the reduction in the corrected K^+ values (from pre20 to post0) may suggest that there was a gradual reuptake and redistribution of circulating K^+ during the rest intervals followed by a slight undershoot. Although such a notion is consistent with some previous studies (30,37), it is equally viable that the plasma K^+ concentrations also reflect blood that has perfused inactive muscle, the modifying effects of other ions (e.g., Ca^{2+}, Cl^-, H^+), the discrepancy between interstitial and circulating blood, or differences in the training status of subjects possibly because of variations in Na^+/K^+ pump concentration (26).

In summary, it is clear that intensity, volume, and rest interval manipulation mainly influenced the acid-base response to the 2 workouts. In addition, both workouts resulted in disturbances in electrolyte homeostasis by inducing reductions in Na^+ and Cl^- and to a lesser extent changes in K^+ and Ca^{2+}. Although the small sample size of this study should be considered when interpreting the findings, it seems possible that peripheral factors relating to BL and H^+ accumulation contributed to the fatigue experienced after the present HYP workout, and this conclusion is consistent with previous research that has attributed peripheral factors to reductions in performance after HYP workouts (23,25,28). Although greater BL and pH changes were observed after the HYP workout, peripheral fatigue factors cannot be excluded as a reason for the force reductions after the STR workout. Although the significant biochemical responses observed as a result of the STR workout are in agreement with previous studies that have also observed significant peripheral responses after STR workouts (25,31), these peripheral responses may not reach the magnitude of those brought about by HYP workouts as studies using more neural techniques have shown (3,28). Although a causative link between individual ion shifts and the reductions in mechanical performance is beyond the scope of the present data, it seems unlikely that disturbances in electrolyte homeostasis were exclusively responsible for the reductions in multijoint force production. Based on the fact that significant correlations were observed between electrolyte changes and reductions in mechanical performance after the HYP workout, it could be argued that the disturbances may have partially contributed to the additional reductions in voluntary force production after the HYP workout; however, consideration should be given to the lack of differences between the STR and HYP conditions. In terms of the relationship between surface EMG output and biochemical changes, it has been previously suggested that MU recruitment pattern, muscle fiber conduction velocity, and subsequent EMG output are mediated by a sensory feedback loop relating to metabolic and ion fluxes (7). Although BL and H+ responded in the expected manner, the acid-base or electrolyte changes were not related to changes in EMG amplitude or frequency characteristics. In this respect, the data are in agreement with previous research (35) that does not support a role for metabolic factors in the mediation of surface EMG output. Although the examination of a wide profile of biochemical responses did not provide any further information regarding the peripheral factors contributing to the fatigue experienced after RE, a role for multiple ion interactions in the reduction of whole-body performance should not be discounted based on the present findings. Future studies that examine endocrine responses alongside acid-base and electrolyte changes may provide a more detailed understanding regarding the potential involvement of these biochemical factors in the morphological adaptations to RE.

Practical applications

Given that coaches often prescribe STR- and HYP-type RE to elicit distinctly different acute and chronic responses, more differences in the acute physiological and mechanical responses may have been expected. Although the greater changes in BL and pH after the HYP workout support the use of moderate intensities and high volumes to elicit mainly peripheral responses, the present findings demonstrate that the use of high intensities and long rest intervals does not preclude the occurrence of an increased level of peripheral fatigue. Although it is yet to be determined if the acute responses observed in this study produce similar long-term neuromuscular adaptations, the present findings support the use of similar HYP regimens for those wishing to maximize gains in muscle size, and this is based on the growing body of research that indicates that metabolic stress is a mediator for muscle hypertrophy. However, given that the present STR and HYP workouts did not lead to a clearly differentiated source of fatigue, the current findings may be taken to question the future prescription of similar workouts when aiming to elicit distinctly different neuromuscular stimuli. A more accurate conclusion is that the current findings through the magnitude of fatigue observed reinforce the need for coaches to look beyond the classification of workouts when prescribing RE with the aim of eliciting specific neuromuscular responses. Despite the fact that the workouts were significantly different in terms of volume, intensity, and total rest, the findings highlight that higher repetition STR workouts represent more of a "hybrid" between classical STR- and HYP-type RE. This provides further evidence to suggest that the classification of STR- and HYP-type RE is an oversimplification and may give the wrong message to coaches regarding the acute responses to different RE workouts. It is therefore suggested that the "repetition maximum continuum" may provide a more useful visualization of training responses rather than the separate classifications used in the present literature. Above all, coaches should be mindful that the training stimulus elicited by RE workouts is a complex function of the intensity, volume, and rest interval combination and additional factors relating to an athlete's training history and nutritional status.

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