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

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ABSTRACT

The present study aimed to examine a wide profile of acute biochemical and neuromuscular responses to strength (STR) and hypertrophy (HYP) resistance exercise (RE). Seven trained males completed a STR workout (4 x 6 repetitions, 85% one repetition maximum [1RM], 5 min rest periods), a HYP workout (4 x 10 repetitions, 70% 1RM, 90s rest periods) and a control condition (CON) in a randomised cross-over design. Peak force (PF), rate of force development (RFD) and muscle activity were quantified pre- and post-exercise during an isometric squat protocol. Blood samples were taken 20, 10 and 0 minutes pre- and 0, 10 and 60 minutes post-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 following 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 following both workouts and a handful of these changes displayed significant correlations with the PF reductions observed following 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 practioners to look beyond the classification of RE workouts when aiming to elicit specific physiological responses.

Keywords: 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 one repetition maximum-1RM), low volumes (2-6 sets, ≤6 repetitions) and long-rest intervals (3-5 minutes) in order to increase phosphocreatine resynthesis and maximise motor unit (MU) recruitment. Whilst these workouts are known to result in hypertrophic adaptations, they are often prescribed with the intention of emphasising neural adaptations (1) which may be desirable for sports in which relative strength is important. HYP-type workouts in contrast are characterised by high volumes (3-6 sets, 8-

12 repetitions), moderate intensities (<85% 1RM) and short rest intervals (30-90s) in order to maximise anabolic responses (2) that result in mainly hypertrophic adaptations (3). 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 (4).

In terms of acute responses to RE there is a number of studies which have examined acute fatigue elicited by a range of workouts (add e.g. refs here). Fatigue is generally classified as being central or peripheral in origin (ad ref). Central fatigue relates to a reduction in MU activation by the central nervous system (CNS) whilst peripheral fatigue refers to reduced action potential (AP) generation and neurotransmitter release, as well as impaired force-generating capacity of muscle due to changes (e.g. metabolic) that take place at or distal to the neuromuscular junction (6). Although a number of studies have examined acute metabolic and neuromuscular fatigue following 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 (5). However, based on the notion that adaptations occur in order 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 following 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 (7). Although a large number of studies have examined the BL and endocrine responses to different RE workouts (8), few studies have compared the changes in H^+ and other key ions (e.g. potassium, calcium) following STR and HYP workouts involving multi-joint 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 (9). Furthermore, few studies have corrected for plasma volume (PV) changes following RE (40); 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 following different RE approaches may be paramount in order to 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 (3). Specifically, it has been theorised 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 fibre degradation which have all been linked to muscle hypertrophy (11). Whilst these factors may be important when aiming to maximise the hypertrophic response, the relative training intensity is also known to be key (3). Although Fry (12) 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 (39). Given that these findings are at odds with the current recommendations by the ACSM (14), the present classification system may create some confusion as to what constitutes a STR- and HYP-type RE.

A lack of clear information also exists regarding the acute neural fatigue responses that may underpin chronic adaptations to the nervous system. Significant reductions in muscle activity have been reported following high-intensity/low-volume workouts alongside reductions in force production (15-17). Although these observations have often been used to support the notion that STR-type RE provides a greater stimulus to the nervous system (1), a number of studies have not observed differences between high and low intensity workouts with respect to their effects on the nervous system (18-19). The lack of clarity most likely results from the utilisation of distinctly different performance measures (e.g. single vs. multi-joint) 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 (8); 5 x 10RM (20)). Whilst 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 (17), it is suggested that the strength-endurance continuum may provide a more effective means of visualising 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 as the loads become heavier and the repetitions become fewer. This suggestion seems logical and it could allow explaining inconsistent findings from acute studies, however, there is always going to be a practical categorisation of workouts into strength, hypertrophy or endurance-type RE and therefore an understanding of the boundaries of these discrete workouts within the strength-endurance continuum is vital. The aim of the current 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 few studies to examine neuromuscular responses and multiple ion changes together in vivo, particularly following RE involving large muscle mass. Such an approach is intended to provide an insight into the physiological processes involved in the fatigue experienced following STR and HYP-type RE.

METHODS

Experimental Approach to the Problem

In order to examine the acute biochemical and neuromuscular responses to STR and HYP-type workouts, subjects visited the laboratory on five separate occasions. During the first session subjects were screened and familiarised with the tests and procedures. Subjects' one repetition maximum (1RM) back squat strength was measured on the second visit in order to determine the training intensities. Subjects then completed 2 experimental workouts and a control (CON) condition in a randomised cross-over design separated by at least 72 hours. Volume was not equated between the experimental workouts in order 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 prior to 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 analysed 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 ABOUT HERE #

Subjects

Seven resistance trained males 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 due to their experience in structured strength training (minimum 12 months) and their proficiency in the back squat exercise. During familiarisation, if 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 effect energy metabolism or RE performance. The Faculty's Ethics Committee approved the details of the study including consent documentation and information provided to subjects prior to 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 over the age of 18 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 (21) and briefly involved a series of submaximal warm-up sets followed by five 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 customised power rack with adjusted safety stoppers and were performed at least 72 hours prior to the experimental sessions.

Acute Resistance Exercise Bouts

Prior to each experimental protocol a standardised warm-up was completed which involved 5 minutes of cycling on a stationary ergometer and dynamic mobility exercises. The hypertrophy (HYP) protocol involved 4 sets of 10 repetitions of the parallel back squat at 70% of 1RM with 90s rest intervals. The strength (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 warm-up and NPT's. 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 (14). 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 multi-joint exercise is known to produce greater metabolic and hormonal responses (5). 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. Subjects were encouraged to lift at a self-selected velocity and 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 following 3-4 hours of fasting. Fingertip blood samples (150µL) were taken 20 (pre20), 10 (pre10) and 0 (pre0) mins before and 0 (post0), 10 (post10) and 60 (post60) mins following exercise. To arterialise blood samples and to achieve greater blood flow subject's hands were placed in warm water (43^{o}c) for 30s prior to each sample; dried and cleaned using alcotip swabs, and then pierced using a sterile lancet. The samples were immediately analysed for pH, blood lactate concentration (BL), potassium (K^{+}), calcium (Ca^{2+}), sodium (Na^{+}), chloride (Cl^{-}), haemoglobin (Hb) and haematocrit (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]) (22). 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 of Dill and Costill (23). To control for the influence of postural changes, subjects were seated for 20 mins 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 (10).

Neuromuscular Performance

In order to investigate the effects of the workouts on neuromuscular performance, maximal isometric strength and concurrent electromyographic (EMG) activity were measured for the leg muscles pre- and post-exercise; this required synchronisation between the force plate (BioWare 3.20; Kistler, Winterthur) and EMG software (EMGworks 4.0; Delsys, MA). Subjects performed three maximal isometric back squats pre- and post-exercise using a modified squat rack positioned over a Kistler force platform (9281B, 40 x 60cm) sampling at 1000 Hz;. Subjects were instructed to push upwards against a fixed bar as hard and as fast as possible for 4s whilst assuming a knee angle of 100^{o} (FIGURE 2). Pilot studies conducted prior to the investigation demonstrated that a knee angle of 100^{o} produced the highest level of between- (CV = 1.52%, ICC = 0.961) and within-session (CV = 1.17%, ICC = 0.976) reproducibility for peak force 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 standardised at shoulder-width. Loud verbal encouragement was provided to maintain subject

motivation for each trial. Numerous measures of mechanical performance were identified pre- and post-exercise including measures of peak force (PF) and rate of force development (RFD). Peak force production was determined from the resultant ground reaction forces and several measures of rate of force development (RFD) were calculated including the time taken to produce 250N, 500N and 750N from 50N 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 (0.05s, 0.1s, 0.15s, 0.2s, and 0.25s) 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 peak force (PF) during the pre- and post-exercise measurements.

FIGURE 2 ABOUT HERE #

Surface EMG activity was recorded during the isometric assessments for the key leg muscles: vastus medialis (VM), rectus femoris (RF), biceps femoris (BF) and lateral gastrocnemius (LG). Skin preparation involved shaving and cleaning the skin surface with alcohol swabs. Two active bipolar electrodes (Delysys Inc., Boston, MA) with a 10mm fixed inter-electrode distance were placed over the muscle belly parallel to the underlying muscle fibres and a reference electrode was placed on the lateral condyle of the femur. A telemetry unit (Myomonitor IV; Delysys Inc., Boston, MA) was used to collect the data at 1000 Hz (CMRR > 80Db, gain = 1000, input impedance = 10 MΩ). The data was filtered using a bandpass filter (cut-off frequencies: 20-450Hz) and to reduce movement artefact, 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 0.5s period corresponding to PF production and for the initial 0.25s of the force-time curve.

FIGURE 3 ABOUT HERE #

Statistical Analysis

Means and standard deviations (SD) of the experimental variables were initially calculated. The changes over time between protocols were analysed using a general linear model (SPSS version

18.0) analysis of variance with repeated measures (protocol x 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 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 utilised 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 36.21 ± 2.68% ($p \leq 0.001$) greater than that performed during the STR workout, the mean intensity however, was 15.02 ± 0.05% higher ($p \leq 0.001$) in the STR workout. The mean duration of each set increased gradually for the STR (22.41 ± 4.80s) and HYP (32.11 ± 5.55s) 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 1601.62 ± 263.56N to 1348.27 ± 364.31N) in PF ($p \leq 0.05$) when compared to the CON condition. The force-time curve shifted greatly to the right following both experimental protocols (FIGURE 4B), this was demonstrated by significant reductions in several measures of rate of force development (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 0.05s (from 3476.50 ± 1645.85N/s to 2782.55 ± 1413.17N/s) and 0.1s (from 4585.74 ± 2210.19N/s to 3465.30 ± 1702.38N/s) of the force-time curve as well as significant ($p \leq 0.05$) increases in the time required to produce 500N (from 0.11 ± 0.06s to 0.16 ± 0.11s) when compared

with the CON condition. In contrast, the STR workout was characterised by significant ($p \leq 0.05$) reductions in the rate of force production during the initial 0.2s of the force-time curve (from 4415.11 ± 1166.17N/s to 3507.27 ± 1410.08N/s) and significant ($p \leq 0.05$) increases in the time required to produce 250N (from 0.04 ± 0.01s to 0.05 ± 0.01s) when compared to the CON condition. Again, no significant differences were observed between the experimental conditions for any RFD variable.

FIGURE 4 ABOUT HERE #

Although the descriptive data for VM highlighted a tendency for mean RMS and AREMG to decrease following 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 following the three 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.

FIGURE 5 ABOUT HERE #

Pre- and post-exercise comparisons were mainly conducted between baseline (pre20) and immediately post exercise (post0) as 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 to the CON condition, this was true for corrected and uncorrected values when compared to baseline (pre20). In terms of the differences between the two 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 to 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 ABOUT HERE #

Although uncorrected values revealed significant ($p \leq 0.05$) changes in a number of electrolytes from pre0 to post0 following the STR and HYP workouts when compared to the CON condition, there were no significant changes in any ion after correcting for changes in PV. When the values at post0 were compared to 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 to 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^+ following the HYP workout were significantly greater than those following the STR workout ($p \leq 0.05$). When the corrected data was analysed both the STR and HYP workouts demonstrated significantly greater decreases in Ca^{2+} than the CON condition ($p \leq 0.05$), in addition, solitary changes in Ca^{2+} following the STR workout and K^+ following the HYP workout were also observed when compared to 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 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 ABOUT HERE #

Nutritional Intake

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

DISCUSSION

Despite the classification of the two 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 two 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 two 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/or RFD, however, marked differences in the mechanical or EMG responses were again not observed between the two workouts.

Neuromuscular Responses

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 fibre distribution (16, 17). 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 great care needs to be exercised due to the low number of subjects used in the present study, 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 (15, 17)[15, 17] and HYP-type RE (17, 24). The reduction in voluntary isometric force following the STR (-14.90%) and HYP (-16.39%) workouts were similar and in line with those reported previously (15, 17). 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 (17). 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 to the CON condition, these reductions encompassed 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 following similar HYP workouts (25) and have been attributed to low frequency fatigue which relates to the reduction in force production from low frequency stimulation. Whilst 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 motor unit (MU) activation by the central nervous system and/or peripheral mechanisms relating to metabolite accumulation and impaired excitation-contraction coupling (6). A number of previous investigations have reported acute reductions in EMG activity following STR-type workouts (16, 17). Whilst these previous findings are often used in support of the view that STR-type RE emphasises mainly neural adaptations (1, 21) changes in EMG activity cannot be attributed entirely to neural factors since a handful of peripheral factors (e.g. muscle blood flow) are also known to influence the recorded signal (26). If neural factors did contribute to the reductions in mechanical performance observed in the present 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) which do not support the popular perception that high loads result in greater neural fatigue (18, 19). 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 (19). Whilst 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 following STR workouts have examined higher intensities (≥90% 1RM) and lower volumes (15, 17). Despite the fact that the present and previous studies have incorporated high intensities and long-rest intervals into their STR workouts (e.g. 4 sets of 5RM [21]), 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.

On the other hand, increases in EMG activity have been previously reported alongside reductions in force production following moderate intensity RE performed in an occluded (27) and non-occluded (17) 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 MU's during fatiguing low load training. Higher levels of force are known to be required to activate higher threshold MU's based on the size principle of MU recruitment (28) but the above studies suggest an alternative pathway to recruit high threshold MU's in the absence of near maximal loads. . Finally, a number of other previous studies have observed either reductions (24) or no changes (25, 29) in muscle activity immediately following HYP workouts which obviously is not in agreement with the above. Even though all these conflicting findings prevent accurate conclusions regarding the neural responses to HYP-type RE, the present EMG data is not at odds with the theory that fatigue following HYP workouts is mainly peripheral in origin (19).

Whilst 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 the present 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. Whilst the repeatability of EMG amplitude during single-joint isometric assessments has been reported previously, little is known about the reproducibility of these measures during multi-joint protocols. Although factors relating to body position, motivation, electrode placement and familiarisation were controlled during the present protocol, differences in training history, fibre type and subtle changes in synergist contribution may have accounted for the variability observed in the present study. Although multi-joint 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 (25).

Biochemical Responses

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 following the HYP workout when compared to STR and CON conditions and the magnitude of the increases were similar to those reported previously (2). These large changes are believed to result from the higher volumes and shorter rest intervals as well as the large muscle mass recruited during the back squat exercise. Although STR workouts are typically not prescribed to elicit significant metabolic stress (5), the BL and H^+ changes following the STR workout were significantly greater than those observed for the CON condition and were greater in magnitude than those reported previously for BL (2, 8). 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 (14) for strength-type RE (2-6 sets, ≤6 repetitions) and towards 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 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 (8), the greatest force decrements were observed following the workout that resulted in the greatest increases in BL and H^+ concentration. Whilst it was once thought that BL and the accompanying acidosis were key players in muscular fatigue, a number of observations based on isolated muscle fibres have demonstrated that these changes alone do not severely impair muscular function (30). Although it seems unlikely that the observed disturbances in acid-base homeostasis were solely responsible for the reductions in mechanical performance, a handful of papers present the possibility that exercise-induced acidosis may still limit whole-body performance (31) especially when interacting with other factors that simultaneously change during exercise. Whilst 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 (5, 11) 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 following the present HYP protocol therefore lend support to the use of similar HYP workouts when aiming to maximise 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 transsarcolemmal K^{+} gradient is the dominant process around which other ions interact to contribute to fatigue (9). Whilst a number of mechanisms have been offered to explain the negative effects of these ion interactions, much of the research has utilised isolated/skinned muscle fibres 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 (32). Whilst 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 multi-joint RE.

Interpretation of the present ion data is complicated by the transient fluid shifts in (haemodilution) and out (haemoconcentration) of the intravascular space. Both workouts produced short-term haemoconcentration and the PV changes observed were within the range previously reported following RE (33). Although significantly greater PV changes have been previously observed for HYP compared to STR-type RE following multi-exercise workouts (33), these differences were not replicated in the present study. Examination of the uncorrected biochemical changes from pre0 to post0 revealed significant changes in Ca^{2+}, Na^{+} and Cl^{-} immediately post 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 to the CON condition, these changes may be indicative of ion fluxes that resulted from the effects of exercise rather than the effects of haemoconcentration. The contrasting observations may highlight that the pre0 values were influenced by postural changes associated with the warm-up and isometric squat procedures. Whilst 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 action potentials (AP) along the sarcolemma and down the transverse tubules in order 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 post-exercise due to 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/L^{-1}), Na^{+} (145-156 mmol/L^{-1}), Ca^{2+} (1.28 mmol/L^{-1}) and Cl^{-} (104.5-105 mmol/L^{-1}) following intense exercise of differing modalities (32, 34, 35). Correction for PV changes revealed significant reductions in plasma Na^{+} immediately following both workouts which most likely reflect its influx into the sarcoplasm during depolarisation. Although K^{+} efflux and Cl^{-} influx are known to occur during the repolarisation phase of each AP, correction for PV changes revealed significant reductions in Cl^{-} and a small but significant reduction in K^{+} following the HYP workout. Although information on electrolyte changes following different whole-body RE workouts is not available, greater increases in K^{+} may have been expected following 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 (36). Despite the fact that K^{+} responses following exercise are known to be affected by the proportion of active muscle mass, the post0 K^{+} concentrations (uncorrected) were lower than previously observed following unilateral knee extension exercise (35). It is possible that a number of factors affected the measured concentration of K^{+}, these include: the intensity, duration and modality of exercise (36), the sampling method (arterial vs. venous) and timings as well as the magnitude of haemoconcentration. 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 post 0) may suggest that there was a gradual reuptake and redistribution of circulating K^{+} during the rest intervals followed by a slight undershoot. Whilst such a notion is consistent with some previous studies (34, 36), 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 due to variations in Na^+/K^+ pump concentration (32).

In summary it is clear that intensity, volume and rest interval manipulation mainly influenced the acid-base response to the two 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 low sample size of the present 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 following the present HYP workout, this conclusion is consistent with previous research that has attributed peripheral factors to reductions in performance following HYP workouts (17, 19, 24). Although greater BL and pH changes were observed following the HYP workout, peripheral fatigue factors cannot be excluded as a reason for the force reductions following the STR workout. Whilst the significant biochemical responses are in agreement with previous studies that have observed significant peripheral responses following STR workouts (2, 17), these peripheral responses may not reach the magnitude of those brought about HYP workouts as studies using more neural techniques have shown (18, 19). Whilst 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 multi-joint force production. Based on the fact that significant correlations were observed between electrolyte changes and reductions in mechanical performance following the HYP workout, it could be argued that the disturbances may have partially contributed to the additional reductions in voluntary force production following 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 fibre conduction velocity and subsequent EMG output are mediated by a sensory feedback loop relating to metabolic and ion fluxes (37). 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 is in agreement with previous research (38) 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 following 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. Whilst the greater changes in BL and pH following 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 do not preclude that 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 maximise gains in muscle size, this is based on the growing body of research which indicates that metabolic stress is a mediator for muscle hypertrophy. 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. However, a more accurate conclusion is that the current findings through of 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. The present findings provide 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 visualisation 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 as well as additional factors relating to an athlete's training history and nutritional status.

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FIGURES

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

Figure 2 Maximal isometric squat protocol utilising a customised power rack and force platform

Figure 3 Example force-time curve and raw electromyographic activity during the maximal isometric squat test (note the change in axis range). Dotted vertical lines indicate time intervals of 50, 100, 150, 200, 250ms relative to the start of contraction. RF = Rectus Femoris, VM = Vastus Medialis, LG = Lateral Gastrocnemius

Figure 4 (a) Comparison of the mean (SD) peak force following 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 following the STR workout

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

Table 1 The mean (SD) corrected and uncorrected biochemical responses at pre20 and post0 for the strength (STR), hypertrophy (HYP) and control (CON) conditions for blood lactate (BL), pH, potassium (K^+), calcium (Ca^{2+}), sodium (Na^+) and chloride (Cl^-).

Blood Parameter	Uncorrected			Corrected	
	pre20	post0	change	post0	change
BL ($mmol/L^{-1}$)					
STR	1.07 (0.38)	7.49 (2.56)	↑ **6.41 (2.75)** ^{c}	6.66 (2.31)	↑ **5.59 (2.45)** ^{c}
HYP	0.83 (0.13)	10.91 (3.06)	↑ **10.09 (3.08)** $^{*, c}$	9.67 (2.45)	↑ **8.84 (2.46)** $^{*, c}$
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)** ^{c}		
HYP	7.43 (0.02)	7.29 (0.04)	↓ **0.14 (0.03)** $^{*, c}$		
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)** ^{c}
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)** ^{c}
HYP	1.18 (0.04)	1.23 (0.04)	↑ **0.05 (0.03)** $^{*, c}$	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)** ^{c}	120.8 (12.21)	↓ **13.91 (12.79)** ^{c}
HYP	134.57 (1.27)	137.43 (1.13)	↑ **2.86 (1.35)** $^{*, c}$	122.34 (5.79)	↓ **12.23 (6.64)** ^{c}
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)** ^{c}	89.57 (8.43)	↓ **13.43 (9.38)** ^{c}
HYP	102.57 (0.79)	100.71 (1.89)	↓ **1.86 (1.35)** ^{c}	89.69 (5.17)	↓ **12.88 (4.72)** ^{c}
CON	103.71 (1.11)	102.71 (1.25)	↓ **1.00 (1.00)**	103.86 (4.62)	↑ **0.15 (4.24)**

* significant difference between strength and hypertrophy, ^{c} significant different from control

Table 2 Correlations (one-tailed) between the mean changes (∆) in plasma ion concentrations (from pre20 to post0) and the mean change in peak force production (∆PF). Correlations were performed for corrected values with the exception of pH.

	∆ PF	
	STR	**HYP**
∆ **pH**	0.505	0.577
∆ **Ca^{2+}**	0.334	0.416
∆ **Na^{+}**	0.307	0.835**
∆ **K^{+}**	0.620	0.082
∆ **Cl^{-}**	0.346	0.807*

*correlation significant at the $p<0.05$ level; **correlation significant at the $p<0.01$ level