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# PERFORMANCE AND ENDOCRINE RESPONSES TO DIFFERING RATIOS OF CONCURRENT STRENGTH AND ENDURANCE TRAINING

**PERFORMANCE RESPONSES TO DIFFERING RATIOS OF CONCURRENT TRAINING**

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## ABSTRACT

The present study examined functional strength and endocrine responses to varying ratios of strength and endurance training in a concurrent training regimen. 30 resistance-trained men completed 6 weeks of 3 $d \cdot wk^{-1}$ of i) strength training (ST), ii) concurrent strength and endurance training ratio 3:1 (CT3), iii) concurrent strength and endurance training ratio 1:1 (CT1) or iv) no training (CON). Strength training was conducted using whole-body, multi-joint exercises, while endurance training consisted of treadmill running. Assessments of maximal strength, lower body power, and endocrine factors were conducted pre-training and following 3 and 6 weeks. Following the intervention ST and CT3 elicited similar increases in lower body strength; furthermore, ST resulted in greater increases than CT1 and CON (all $p < 0.05$). All training conditions resulted in similar increases in upper body strength following training. ST group observed greater increases in lower body power than all other conditions (all $p < 0.05$). Following the final training session, CT1 elicited greater increases in cortisol than ST ($p = 0.008$). When implemented as part of a concurrent training regimen, higher volumes of endurance training result in the inhibition of lower body strength, whereas low volumes do not. Lower body power was attenuated by high and low frequencies of endurance training. Higher frequencies of endurance training resulted in increased cortisol responses to training. These data suggest that if strength development is the primary focus of a training intervention, frequency of endurance training should remain low.


**KEY WORDS** combined exercise, interference, cortisol, resistance training, training frequency

## INTRODUCTION

Various sports and events require contrasting physical performance phenotypes for successful performance. Training for sports and events at the extremes of the strength-endurance continuum, such as Powerlifting and ultra-endurance challenges, is relatively straight-forward compared with sports and events that require a combination of strength and endurance capabilities. In these situations athletes and coaches are often forced to combine training methods which elicit contrasting and even antagonistic physiological and performance responses (12). In the case of '*concurrent training*', the divergent stimuli of strength and endurance training can result in attenuated strength type adaptation when compared to strength training performed in isolation. This divergent physiology is known as the interference effect or phenomenon (17).

Research has indicated that any interference experienced during a concurrent strength and endurance training regimen may be dependent in part on the volume of training performed (1, 13, 24, 25, 33). Despite this, no study has specifically examined the effects of whole body, multi-joint concurrent training inventions with varying training volumes and the effect that is has on muscle force characteristics. Previous work from our laboratory (20) has indicated that the magnitude of interference experienced may be proportional to the frequency of endurance training performed; indicating overall training volume and exercise stress may indeed regulate the presence of any interference experienced.

Elevated training 'stress' has previously been proposed as a mechanism for interference (10), and is perhaps attributable to the experimental design of some published studies in this area. Often the concurrent training condition will perform double the overall training volume and total work to that of the strength training alone condition, which has previously resulted in muted strength development (6, 16, 20, 22). In contrast studies employing lower concurrent training volumes have reported no inhibited strength development as a result of concurrent training (24, 25). These findings may support the hypothesis that total work performed in a concurrent programme influences both the presence and magnitude of any interference experienced, although the underlying mechanisms are yet to be fully elucidated.

Previous research has reported a decreased testosterone:cortisol ratio following concurrent training with no such decrease in participants who performed strength training alone (2, 3, 22). This may implicate elevated endocrine responses and catabolism as a contributing factor to interference. As such, it is reasonable to suggest that the higher training volumes experienced in concurrent training regimens can result in elevated physiological stress, which is reflected in the responses of primary anabolic and catabolic hormones. This shift in the endocrine milieu in favour of catabolism may contribute to attenuated strength and hypertrophic adaptation associated with concurrent training.

Previous work from our laboratory (20) illustrates the value in exploring the role of training frequency in a systematic fashion. Furthermore no research has assessed if differing ratios of strength and endurance training can influence the degree of interference experienced as a result of adaptations in the anabolic:catabolic environment. Therefore, the purpose of this research was to investigate the strength, anthropometric and endocrine responses to a variety of concurrent strength and endurance training ratios, with incremental loads in a functional multi joint model.

## METHOD

### Experimental Approach to the Problem

A balanced, randomized, between-group study design was employed to examine the effect of differing ratios of strength and endurance training in a concurrent regimen on strength, anthropometric, and endocrine responses. A 6 week training intervention was completed, during which participants were randomly assigned to one of four experimental conditions: either i) strength training alone (ST), ii) concurrent strength and endurance training at a ratio of 3:1 (CT3), iii) concurrent strength and endurance training at a ratio of 1:1 (CT1), or iv) no training (CON). Participants in the ST group were required to perform strength training alone on all scheduled training sessions. The CT3 group completed strength training on every scheduled session with every third session immediately followed by an endurance training protocol. Elsewhere, participants designated CT1 completed an identical strength training protocol immediately followed by endurance training at every scheduled session. Those participants in the CON group performed no strength or endurance training during the entire experimental period. Due to the requirements of the separate training protocols, it was not possible to match total work performed in the respective experimental conditions. All participants were instructed to abstain from any other strength or endurance training throughout the experimental period beyond that prescribed by the investigator.

Participants completed their respective intervention 3 d·wk$^{-1}$ with ~48 h between sessions for 6 weeks resulting in a total of 18 separate training sessions in the micro cycle. In order to assess whether the frequency and ratio of strength and endurance training performed influenced strength and changes in body composition, assessments of 1 repetition maximums (1RM), countermovement jump height (CMJ), and body composition were assed pre, mid and post-intervention. To assess the effect of the designated training interventions on endocrine factors related to strength and morphological adaptation, venous blood samples were taken and subsequently analysed for circulating testosterone and cortisol concentrations. During the investigation, venous blood samples were collected immediately before (pre) and following the cessation of exercise (post) in the initial, mid and final compound training sessions of the 18 sessions performed.

**Subjects**

Prior to all experimental procedures the study was approved by the Northumbria University research ethics committee. All subjects were informed of the risks and benefits of the investigation prior to signing an approved informed consent document to participate in the study. Thirty healthy, recreationally resistance-trained men (age: 23 ± 4 y; body mass: 79.2 ± 6.7 kg; height: 179.2 ± 6.7 cm; % body fat: 16.2 ± 5.4 %; sum of assessed 1RMs: 506.0 ± 11.4 kg; CMJ: 52.5 ± 7.3 cm; $\dot{V}O_{2max:}$ 50.2 ± 5.8 ml·kg·min) volunteered to participate in the study.  Prior to commencing, participants were matched for age, body mass, body fat % and 1RM (sum off all assessed 1RMs) load (all $p > 0.05$), and then randomly assigned (via block randomisation) to one of the four experimental conditions. Each participant had completed > 2 years of strength training activities prior to the start of a study, and were considered recreationally “resistance trained”; all participants were conducting strength training ≥ 2 d·wk$^{-1}$, however none were involved in a sport-specific training programme. All participants were non-smokers, free from any endocrine or metabolic contraindications, and were not following any specialized dietary interventions. In all cases participants were asked to refrain from nutritional supplementation or pharmacological interventions for 30 days prior to and throughout the duration of any experimental intervention.

**Procedures**

***Strength training protocol***

Prior to the intervention all participants completed a familiarisation week involving each respective training session in order to habituate themselves fully with the exercise techniques employed. The strength training intervention was comprised of 3 sessions, and each was performed on separate days with ~48 h between sessions. Each session was composed of differing exercises; as such each of the sessions were designated “compound”, “pull” and “push” respectively, to best describe the nature of exercises performed. Full details of each session are presented in Table 1. The respective sessions were performed in the same order each week (i.e., compound, push then pull). Furthermore, the order of exercises within each session was consistent throughout the intervention.

During familiarisation, training intensity was set at 70% of 1 repetition maximum (1RM) for 3 sets of 10 repetitions. The first 3 weeks of the training intervention required participants to complete all sessions and exercises at 80% 1RM for 4 sets of 8 repetitions. The following and final 3 weeks of the intervention were completed at an intensity of 85% 1RM for 5 sets of 6 repetitions. These loads, volumes and rest intervals were selected as they are deemed appropriate for eliciting adaptations in strength and hypertrophy in recreationally trained non-athletes (27, 28). Additionally, strength training programmes of this nature involving exercises which stimulate large muscle masses and shorter rest periods have been shown to elicit large increases in the endocrine factors assessed within this study (21, 32). Full details of the intervention are presented in Table 1.

All strength and/or endurance-based exercise commenced at the same time of day (1000 h ± 1 h) to avoid any diurnal performance or endocrine variations (15). Participants were also advised to abstain from exercise for 24 h prior to a visit. Training load was modified accordingly for each exercise if a participant's 1RMs were observed to change at the mid-intervention assessments. Compliance was 100% for all participants.

*Table 1 about here*

***Endurance training protocol***

In all instances endurance training was conducted immediately following strength training. The endurance training protocol required participants to run on a treadmill (hp Cosmos, Pulsar, Nussdorf-Traunstein, Germany) at 1% incline at 70% of their pre-determined peak running velocity at $\dot{V}O_{2max}$ (v$\dot{V}O_{2max}$). Running velocity was modified if participant's v$\dot{V}O_{2max}$ was observed to change at the mid-intervention assessments.

***Whole body strength assessments - 1 repetition maximum (1RM)***

1RM loads were established for all strength-training exercises prior to the experimental intervention and following 3 and 6 weeks of training. For analysis purposes lower body strength was assessed via back squat and deadlift 1RM total load. To examine strength development in the upper body musculature, bench press, bent over row and military press total 1RM load was analysed. These exercises were chosen as they are considered gross motor movements that require all the major joints and muscle groups involved in the strength training intervention. All assessments were conducted in line with standardised procedures (29).

***Maximal aerobic capacity - $\dot{V}O_{2max}$***

Assessments of participant's maximal oxygen uptake and peak running velocity at $\dot{V}O_{2max}$ were conducted at baseline, after 3 weeks of training and following the 6 week training intervention. All assessments were conducted in line with standardised procedures reported elsewhere (34).

***Lower body power - countermovement jump assessment***

Lower body power was assessed via maximal countermovement jump height (CMJ) and was conducted prior to and following 3 and 6 weeks of training. Maximal CMJ was adopted as a proxy of lower body power, and was assessed using a contact mat (Just Jump, Probotics, Huntsville, AL, USA). Following familiarization, independent trials of CMJs were conducted with 3 min between each individual jump; the highest jump being recorded for data analysis. When performing the test, participants positioned themselves in the centre of the contact mat and place their hands on the iliac crest where they were to remain throughout. CMJs began from an erect standing position. When ready, participants squatted to a self-selected depth perceived as their individual optimal depth, and immediately ascended to jump vertically for maximal height.

***Body composition - air displacement plethysmography***

All participants lean mass and % body fat was assessed prior to and following 3 and 6 weeks of training. Lean mass and % body fat were assessed using air displacement plethysmography (BodPod, Life Measurements Instruments, CA, USA) (11, 26, 30). Initially the devise was calibrated using a metal cylinder of known and standardised composition. Participants were asked to disrobe to minimal clothing and place a tight fitting cap over their hair. Participants were then weighed on a calibrated scale prior to entering the chamber. Once two consistent measures of body composition were obtained % body fat and lean mass were calculated using associated software (8).

***Rate of perceived exertion***

To examine perception of physical exertion in response to the training intervention, rate of perceived exertion (RPE) was recorded during strength training. Briefly, participants were required to select a number from 6 to 20, corresponding to a statement which best described their level of exertion at that particular moment (4, 7, 31).

***Blood sampling and storage***

When blood samples were collected, participants arrived at the lab having refrained from consuming food or caffeine for 2 h prior to assessment. Venous blood samples were collected from the antecubital fossa in a branch of the basilica vein into vacutainer tubes (BD Vacutainer, NJ, USA) coated with Ethylenediaminetetraacetic acid (EDTA) to negate. Whole blood was subsequently centrifuged (accuSpin 3R, Fisher Scientific, Loughborough, UK) at 4°C and 1509 g for 10 min, after which the resultant plasma from each sample was then transferred to individual eppendorf containers for subsequent storage at -80°c. Venous blood samples were collected immediately before (pre) and following the cessation of exercise (post) in the initial, mid and final compound training sessions (additional information presented in Table 1) of the 18 sessions performed.

***Biochemical analysis***

Plasma testosterone and cortisol were measured in duplicate (testosterone; ICC = 0.89, $R$ = 0.89, Cortisol: ICC = 0.92, $R$ = 0.95) via commercially available enzyme-linked immunosorbent assay (ELISA) kits (IBL International, Hamburg, Germany). In all cases procedures were followed according to the manufacturer's instructions. For both variables, 25 ųL of each standard, control and sample were pipetted into the respective wells of the mircotire plate, after which 2000 ųL of enzyme conjugate was then pipetted into each well and the plate was covered and left to incubate at room temperature (18 - 25°c) for 60 min. After this period the incubation solution was discarded and the microplate was washed 3 times with wash buffer and distilled water solution diluted at a ratio of 1:10. 100 ųL of Tetramethylbenzidine (TMB) substrate solution was then pipetted into each well prior to a 15 min incubation period. Immediately following this incubation 100 ųL of TMB stop solution was pipetted into each well and the contents were briefly mixed by gently agitating the plate. The optical density was measured at 450 nm within 10 min of the stop solution being added using an Anthos 2010 mircoplate reader (DAZDAQ LTD, Brighton, UK (reference-wavelength 600 – 650 nm)). For testosterone there was a minimum detection limit of 0.2 nmol·L-1, inter-assay and intra-assay variation of 4.2 – 7.4 and 3.1 – 5.4 and the calibration curve revealed Pearson's correlation coefficients (*r*) = 0.99. For cortisol there was a minimum detection limit of 6.8 nmol·L-1 with an inter-assay and intra-assay variation of 2.1 – 5.0 and 2.6 – 3.5, the calibration curve revealed *r* = 0.99, respectively.

***Statistical analysis***

Data are presented as mean ± standard deviation. Values of RMs, CMJ and lean mass were transformed to a percentage change (∆%) from baseline and used for analysis. Prior to analysis, dependant variables were verified as meeting required assumptions of parametric statistics and changes in all assessed measures were analysed using mixed model repeated measures ANOVA tests. ANOVA analysed differences between 4 conditions (ST, CT3, CT1 and CON) and 3 time points (baseline, mid-intervention and post-intervention). The alpha level of 0.05 was set prior to data analysis. Assumptions of sphericity were assessed using Mauchly's test of sphericity, if the assumption of sphericity was violated Greenhouse Gessier correction was employed. If significant effects between conditions or over time were observed *post-hoc* differences were analysed with the use of Bonferroni correction. Statistical power of the study was calculated post-hoc using G*Power statistical software (v3.1.3, Düsseldorf, Germany) using the effect size, group mean, SD and sample size of the primary outcome measures, in this case being lower and upper body maximal strength and endocrine factors. Power was calculated as between 0.8 and 1 indicating sufficient statistical power (5).

## RESULTS

### *Physical performance measures*

Participant's baseline strength and endurance physical performance capabilities were similar between experimental conditions, these data are presented in Table 2.

*Table 2 about here*

### *Upper and lower body maximal strength*

A significant group x time interaction was observed ($F_{(4, 36)}$ = 4.940, $p$ = 0.003) for lower body strength development, as was an effect of time ($F_{(1, 36)}$ = 45.042, $p$ < 0.001). All training conditions elicited increases in lower body strength at the mid-intervention time point following 3 weeks of training (ST; 9.0 ± 4.5%, $p$ < 0.001. CT3; 9.8 ± 11.0%, $p$ = 0.024. CT1; 5.8 ± 3.2%, $p$ < 0.001). Similarly lower body strength improved in all training conditions from baseline to post-intervention (ST; 17.2 ± 7.2%, $p$ < 0.001. CT3; 15.0 ± 11.8%, $p$ = 0.003. CT1; 10.1 ± 4.9%, $p$ < 0.001). ST was the only condition to significantly increase lower body strength from mid to post-intervention (8.3 ± 2.8%, $p$ = 0.016, Figure 1).

*Figure 1 about here*

All training conditions improved lower body strength to a greater extent that CON at both mid and post-intervention (all $p$ < 0.05). Post-training ST improved lower body strength 7.1 ± 2.4% more than CT1 ($p$ = 0.036, Figure 1).

A significant group x time interaction ($F_{(5, 41)} = 2.895$, $p = 0.027$) and an effect of time ($F_{(2, 36)} = 31.510$, $p < 0.001$) were observed for upper body strength development. CT3 and CT1 both improved upper body strength between baseline to mid-intervention (6.2 ± 6.9%, $p = 0.024$ and 7.8 ± 4.5%, < 0.001 respectively, Figure 2). All training conditions increased upper body strength from pre to post-training (all $p < 0.05$). Upper body strength improved in all training conditions following training interventions (ST; 10.5 ± 5.2%, $p < 0.001$. CT3; 10.6 ± 10.7%, $p = 0.014$. CT1; 12.1 ± 6.9%, $p < 0.001$). ST was the only condition to improve upper body strength from mid to post-training (6.9 ± 0.1%, $p = 0.019$).

*Figure 2 about here*

All training conditions elicited significantly greater increases in upper body strength than CON at mid- and post intervention (all $p < 0.05$, Figure 2).

***Lower body power***

A significant group x time interaction ($F_{(6, 52)} = 3.236$, $p = 0.009$) and effect of time ($F_{(2, 52)} = 26.086$, $p < 0.001$) were observed for lower body power development. Both ST and CT1 increased CMJ from baseline to mid-intervention (ST; 8.7 ± 7.0%, $p = 0.003$. CT1; 3.0 ± 2.3%, $p = 0.002$). Post-intervention all training conditions elicited significant increases in CMJ from baseline (ST; 13.1 ± 7.3%, $p < 0.001$. CT3; 7.1 ± 3.7%, $p < 0.001$. CT1; 4.8 ± 2.3%, $p < 0.001$; Figure 3).

*Figure 3 about here*

Participants in the ST condition achieved significantly higher CMJ than those following CT1 (7.0 ± 3.5%) and CON (5.7 ± 4.7%) conditions after 3 weeks of training (i.e. mid-intervention) (both $p = 0.04$). Following training (i.e. post-intervention), ST elicited 6.0 ± 3.6% greater increases in CMJ than CT3, 8.3 ± 5.0% greater than CT1 and 10.9 ± 2.3% greater than CON (all $p < 0.05$).

***Strength training performance***

During the first 3 weeks of the training intervention all groups ability to maintain the required training intensity was similar ($F_{(3, 30)} = 1.063$, $p = 0.548$) and did not change significantly over time ($F_{(1, 30)} = 4.295$, $p = 0.062$). Similar results were observed in the final 3 weeks of the intervention as ability to maintain designated training load was not different between conditions ($F_{(3, 28)} = 1.301$, $p = 0.293$) or over time ($F_{(1, 28)} = 3.777$, $p = 0.052$).

***Testosterone***

No group x time interaction was reported for circulating basal testosterone concentrations ($F_{(6, 52)} = 1.820$ $p = 0.113$, Table 3). A significant group x time interaction was however observed for the testosterone response to strength training ($F_{(3, 26)} = 11.466$, $p < 0.001$). Testosterone responses to the respective training interventions also changed significantly over time ($F_{(1, 26)} = 130.683$, $p < 0.001$). Following the initial and mid sessions ST was the only condition to increase testosterone levels greater than CON (30.7 ± 5.0%, $p = 0.04$ and 37.1 ± 12.9% $p = 0.005$ respectively). CT3 was the only condition to elicit a greater increase in testosterone than CON post the final session (42.2 ± 10.5%, $p = 0.002$). ST and CT3 elicited significant increases from pre training in both the mid and final sessions (all $p$

< 0.05). Testosterone was also increased post training in the CT3 condition following the final session ($p$ = 0.01). No other increases were observed.

### Cortisol

No group x time interaction was observed for circulating basal cortisol concentrations ($F_{(6, 52)}$ = 1.540, $p$ = 0.184, Table 3). A significant a group x time interaction ($F_{(3, 26)}$ = 7.592, $p$ = 0.001) and an effect of time ($F_{(1, 26)}$ = 101.852, $p$ < 0.001) were observed for cortisol responses to the respective training interventions. Following the initial session ST was the only condition to increase cortisol levels to a greater extent than CON (84.7 ± 22.1%, $p$ = 0.014). Post training after the mid-intervention session CT1 was the only condition which resulted in significantly greater cortisol increases than CON (49.2 ± 3.1%, $p$ < 0.001). Following the final session, CT1 elicited 26.6 ± 8.4% greater cortisol increases than ST ($p$ < 0.008). All training conditions elicited significant increases in cortisol post training on all assessed sessions (all $p$ < 0.05).

### Testosterone-cortisol ratio

No group x time interactions were present for basal testosterone:cortisol ratio (T:C ratio) ($F_{(6, 52)}$ = 1.903, $p$ = 0.098) nor the T:C ratio response to training ($F_{(6, 52)}$ = 1.124, $p$ = 0.361).

*Table 3 about here*

### Lean mass

Participant's baseline lean mass was similar between experimental conditions, these data are presented in Table 4. No group x time interaction was observed for changes in participant's lean mass.

*Table 4 about here*

***Body fat %***

A significant group x time interaction was observed for body fat % ($F_{(6, 52)}$ = 4.616, $p$ = 0.001). Following the 6 week training intervention, CT1 resulted in 2.65 ± 0.04% greater decreases in body fat % than CON ($p$ < 0.001) at the post-intervention time point. No other significant effects of time or group were observed for changes in body fat %.

***Rate of perceived exertion***

A significant group x time interaction was present for RPE ($F_{(5, 52)}$ = 2.744, $p$ = 0.029). At week 5 and 6 of the training intervention RPE was significantly lower in the ST group than CT1 (both $p$ < 0.05) (Figure 4). No other interactions or effects were present.

*Figure 4 about here*

## DISCUSSION

The present study sought to prioritise strength development in concurrent training regimens with varying volumes of endurance training. The primary finding of this study was that an increase in the frequency of endurance training and total training volume within the concurrent training paradigm resulted in the attenuated development of lower body strength when compared to strength training alone. Following 6 weeks of training, ST and CT3 conditions resulted in similar increases in lower body strength, whereas the improvements of those performing both strength and endurance training collectively 3 times per week (CT1) were muted (Figure 1). These findings reflect data presented in our previous work (20), in which ST and CT3 resulted in similar increases in maximal voluntary contraction (MVC), whereas increases in the CT1 condition were significantly lower. Although no other published research has examined differing frequencies of strength and endurance training on strength-related adaptation, studies employing concurrent training frequencies of ≥ 3 $d \cdot wk^{-1}$ have typically reported some manifestation of interference characteristics (2, 14, 19, 22). Lower concurrent training frequencies (≤ 2 $d \cdot wk^{-1}$) have however resulted in similar development of strength related phenotypes following both concurrent and strength training programmes (24, 25). When combined, the findings of these studies are consistent with those of the present study. Concurrent training conducted 3 $d \cdot wk^{-1}$ (CT1) resulted in inhibited gains in maximal lower body strength, whereas performing concurrent training once per week with 2 strength alone sessions (CT3; concurrent training frequency of 1 $d \cdot wk^{-1}$) elicited similar lower body strength increases than strength-training in isolation. The findings of this study and those of previous research indicate higher training volumes and elevated physiological stress may contribute to the presence of the interference phenomenon.

In addition to the inhibition of lower body strength development lower body power development was also inhibited following 3 and 6 weeks of training in the CT1 condition when compared with strength training alone (Figure 3). Furthermore, lower volumes of endurance training also resulted in attenuated increases in lower body power, as post-intervention participants who performed strength and endurance training at a ratio of 3:1 (CT3) exhibited improvements which were 6.0 ± 3.6% ($p$ = 0.04, smallest worthwhile change = 1.2% (18)) lower than those who performed strength training alone. As previously stated, maximal lower body strength development was not different between ST and CT3 conditions (Figure 1), which may indicate that power phenotypes are more susceptible to interference than maximal strength indices. This suggestion is supported by previous research indicating that development of variables including CMJ, rate of force development (RFD) and peak torques at high velocities have been inhibited as a result of combining strength and endurance training, yet maximal strength development remained uninhibited (6, 9, 14).

Unlike lower body strength and power development, increases in upper body strength were similar following both strength training alone and both concurrent training conditions (CT3 and CT1). Furthermore, following 3 weeks of training CT1 resulted in 4.2 ± 0.8% greater increases than strength training alone (Figure 2), although this was not statistically significant ($p$ = 0.09). Previous research has also reported concurrent training does not result in the inhibition of upper body maximal strength (1, 3). Unlike the present study, which employed steady state running, previous research involved rowing (3) and arm cranking (1) as the endurance training modalities. It may be argued that whilst aerobically demanding the stimuli of arm cranking and rowing are further towards the strength end of the strength-endurance continuum than steady state running. As such, it is reasonable to suggest that concurrent training may not differently affect the upper body musculature, but rather for interference to occur the assessed musculature must experience divergent contractile activity (i.e. strength and endurance stimulus) of contrasting intensities and durations. It is reasonable to suggest that the lower body musculature was placed in a greater state of conflict than the upper body, as both training stimuli directly affected hip dominant and lower limb muscle groups and only the strength training protocol required noteworthy contributions from the upper body musculature. Due to the relatively low number of high force contractions involved in strength training and the continuous lower force contractions experienced during endurance training, different patterns of motor unit activation are required. It is possible that the divergent demands placed on the neuromuscular system by strength and endurance training elicited differing alterations in motor unit recruitment in the musculature of the lower limbs, previous research has also implicated altered neural activation during high force contractions as a potential mechanism for impaired strength development (22, 23). Morevover, the potential alterered neural recruitment during rapid and high force contractions may have contributed to the inhibition of lower body power development as a result of both high and low frequncies of concurrent training (Figure 3).

Following the final training session of the intervention CT1 elicited greater cortisol levels than ST which is consistent with previous research (2, 3). This may indicate higher frequencies of concurrent training can result in elevated physiological stress, which was also reflected in participant's perceived exertion during training (Figure 4). In additional to enhanced training stress elevations in cortisol have been implicated in catabolism and impaired hypertrophic development with concurrent training (22).

However, in the present study increases in lean mass were similar between training conditions, as such it is unlikely the observed elevations in cortisol influenced muscle morphological adaptation. The variance in the findings of the present study and those of Kraemer *et al.* (22) are perhaps due to the differing lengths of the respective training programmes. Kraemer *et al.* (22) employed a 12 week intervention whereas in the present study participants trained for 6 weeks. As the CT1 condition resulted in the inhibition of strength development following 6 weeks of training it may be speculated that had the interventions been longer CT1 may have also resulted in impaired increases in lean mass.

**PRACTICAL APPLICATIONS**

The findings of this study build on the understanding of concurrent training developed in the isolated limb model discussed in our previous work (20). The data presented here indicate that if strength development is the primary goal of an training programme, endurance-training frequency should be kept to a minimum. It should however be noted, that this minimal dose of endurance training should be sufficient to maintain any necessary endurance performance characteristics. Also the elevations in post exercise cortisol concentrations observed only in participants conducting strength and endurance training 3 times weekly indicate that overall training stress likely plays a key role in the inhibition of strength development. Therefore if a concurrent training programme must be performed it is imperative that appropriate monitoring strategies are employed to ensure training stress doesn't become too great and result in the plateau of strength development. Furthermore if development of power type characteristics is required then it appears that frequency and volume of endurance training should be minimized or omitted from the programme all together. This may be achieved via appropriate programme construction and periodization to allow power development to occur in periods in which endurance type training can be kept to a minimum.

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## Figure Legends

**Figure 1.** Mean relative changes in lower body strength (as assessed by back squat and deadlift) in response to respective training interventions in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * significant increases from baseline in all training conditions ($p < 0.05$). ** significant increase from mid-intervention in ST ($p = 0.016$). † significantly greater increases than CON in training conditions ($p < 0.05$). ‡ ST significantly greater than CT1 ($p = 0.036$).

**Figure 2.** Mean relative changes in upper body strength (as assessed by bench press, bent over row and military press) in response to respective training interventions in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * significant increases from baseline in CT3 and CT1 ($p < 0.05$). ** significant increases from baseline in all training conditions ($p < 0.05$). † Significant increase from mid-intervention in ST ($p = 0.019$). ‡ all training conditions greater than CON ($p < 0.05$).

**Figure 3.** Mean relative changes in countermovement jump height in response to respective training intervention s in the ST (n = 8), CT3 (n = 8), CT1 (n = 8) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. * ST and CT1 significantly greater than baseline ($p < 0.05$). ** ST, CT3 and CT1 significantly greater than baseline ($p < 0.001$). † ST significantly greater than CT1 and CON ($p < 0.05$). ‡ ST significantly greater than CT3, CT1 and CON (all $p < 0.05$).

**Figure 4.** Mean RPE experienced in the ST (n = 8), CT3 (n = 8) and CT1 (n = 8) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session. * ST significantly lower than CT1 ($p < 0.05$).

**Table 1.** Programme variables within periodized resistance training intervention.

| | | | |
|---|---|---|---|
| | **Week 1** | Pre-intervention assessments | |
| | **Week 2** | Familiarisation | |
| | Sets | 3 | |
| | Repetitions | 10 | |
| | % 1RM | 70 | |
| | Rest (s) | 90 | |
| | **Weeks 3 – 5** | Training | |
| | Sets | 4 | |
| | Repetitions | 8 | |
| | % 1RM | 80 | |
| | Rest (s) | 120 | |
| | **Week 6** | Mid-intervention assessments | |
| | **Week 7 – 9** | Training | |
| | Sets | 5 | |
| | Repetitions | 6 | |
| | % 1RM | 85 | |
| | Rest (s) | 120 | |
| | **Week 10** | Post-intervention assessments | |
| **Sessions** | Compound | Pull | Push |
| | back squat, bench press, bent over row, dead lift and military press | high pull, lat pull down, seated row, standing dumbbell reverse fly and seated hamstring curls | incline bench press, front squat, push press, seated leg press and dumbbell chest flys |

**Table 2.** Participant's baseline maximal strength, lower body power and maximal aerobic capacity.

| **Lower body maximal strength – 1RMs (kg)** | | | | |
|---|---|---|---|---|
| | ST | CT3 | CT1 | CON |
| Back squat | 117.8 ± 7.7 | 120.3 ± 11.8 | 122.4 ± 8.9 | 118.5 ± 12.5 |
| Deadlift | 136.3 ± 7.9 | 142.6 ± 12.4 | 139.7 ± 6.7 | 136.9 ± 9.5 |
| Total | 254.1 ± 11.5 | 262.9 ± 14.2 | 262.1 ± 10.6 | 255.4 ± 11.4 |
| **Upper body maximal strength – 1RMs (kg)** | | | | |
| | ST | CT3 | CT1 | CON |
| Bench press | 99.1 ± 9.2 | 105.9 ± 7.1 | 107.4 ± 12.4 | 101.6 ± 8.8 |
| Bent over row | 80.0 ± 5.3 | 77.5 ± 6.6 | 82.5 ± 5.8 | 80.5 ± 7.4 |
| Military press | 61.6 ± 6.1 | 67.5 ± 5.8 | 65.5 ± 7.9 | 60.3 ± 5.1 |
| Total | 240.6 ± 11.9 | 250.9 ± 12.8 | 255.4 ± 14.0 | 242.4 ± 13.6 |
| **Lower body power – CMJ (cm)** | | | | |
| | ST | CT3 | CT1 | CON |
| | 52.7 ± 10.3 | 52.8 ± 7.7 | 50.7 ± 7.5 | 53.9 ± 5.1 |
| **Maximal aerobic capacity – $\dot{V}O_{2max}$ (ml·kg·min)** | | | | |
| | ST | CT3 | CT1 | CON |
| | 52.1 ± 7.0 | 47.4 ± 4.9 | 49.5 ± 6.3 | 51.9 ± 7.8 |

**Note:** ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period.

**Table 3.** Effects of respective training interventions on testosterone, cortisol and testosterone:cortisol (T:C) ratio.

| Condition | Training Session | | | | | |
|---|---|---|---|---|---|---|
| | Initial | | Mid | | Final | |
| | Pre | Post | Pre | Post | Pre | Post |
| **ST** | | | | | | |
| Testosterone (nmol·L$^{-1}$) | 17.2 ± 4.0 | 23.4 ± 5.4*† | 16.4 ± 2.7 | 23.7 ± 4.2*† | 19.6 ± 10.0 | 27.3 ± 13.6 |
| Cortisol (nmol·L$^{-1}$) | 262.6 ± 86.6 | 495.6 ± 150.0*† | 254.4 ± 124.3 | 408.5 ± 145.3* | 269.5 ± 116.0 | 389.1 ± 99.7* |
| T:C Ratio (x10$^{3}$) | 76.2 ± 46.3 | 53.5 ± 28.0 | 77.5 ± 36.0 | 63.4 ± 20.8 | 88.7 ± 69.7 | 77.67 ± 50.1 |
| **CT3** | | | | | | |
| Testosterone (nmol·L$^{-1}$) | 13.0 ± 1.6 | 17.6 ± 2.2* | 15.4 ± 3.7 | 20.1 ± 4.2* | 19.5 ± 4.6 | 27.1 ± 5.6*† |
| Cortisol (nmol·L$^{-1}$) | 260.5 ± 114.6 | 522.0 ± 325.7* | 284.7 ± 103.6 | 460.5 ± 134.6* | 262.8 ± 90.9 | 428.7 ± 137.0* |
| T:C Ratio (x10$^{3}$) | 60.7 ± 31.5 | 50.3 ± 42.1 | 58.4 ± 16.6 | 48.4 ± 13.6 | 81.0 ± 28.5 | 68.6 ± 22.7‡ |
| **CT1** | | | | | | |
| Testosterone (nmol·L$^{-1}$) | 18.7 ± 7.5 | 24.4 ± 11.7 | 19.5 ± 5.2 | 24.5 ± 8.0 | 17.3 ± 4.3 | 21.9 ± 4.6 |
| Cortisol (nmol·L$^{-1}$) | 278.2 ± 64.9 | 471.6 ± 186.9* | 331.4 ± 17.1 | 499.9 ± 48.3*† | 368.3 ± 51.8 | 507.8 ± 45.2*†Æ |
| T:C Ratio (x10$^{3}$) | 71.4 ± 33.9 | 57.6 ± 30.4 | 59.0 ± 15.1 | 49.1 ± 14.9 | 47.8 ± 12.5 | 43.0 ± 6.4 |
| **CON** | | | | | | |
| Testosterone (nmol·L$^{-11}$) | 16.1 ± 1.4 | 16.8 ± 1.1 | 16.2 ± 1.5 | 17.6 ± 1.4 | 18.5 ± 3.0 | 17.7 ± 2.1 |
| Cortisol (nmol·L$^{-1}$) | 291.6 ± 65.0 | 311.5 ± 47.8 | 305.5 ± 91.1 | 320.6 ± 96.2 | 306.6 ± 115.8 | 330.2 ± 101.9 |
| T:C Ratio (x10$^{3}$) | 58.1 ± 16.4 | 55.0 ± 9.0 | 57.0 ± 18.1 | 59.1 ± 17.8 | 58.4 ± 20.8 | 63.5 ± 26.0 |

* significantly greater than pre ($p < 0.05$), † significantly greater than CON ($p < 0.05$), ‡ significantly greater than post mid-session ($p < 0.05$), Æ increase significantly greater than ST ($p < 0.05$).

**Table 4.** Participant's basal lean mass.

| Lean mass (kg) | | | |
|---|---|---|---|
| ST | CT3 | CT1 | CON |
| 68.4 ± 6.8 | 66.1 ± 8.1 | 70.2 ± 3.7 | 66.9 ± 8.7 |

**Note:** ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period

Figure 1

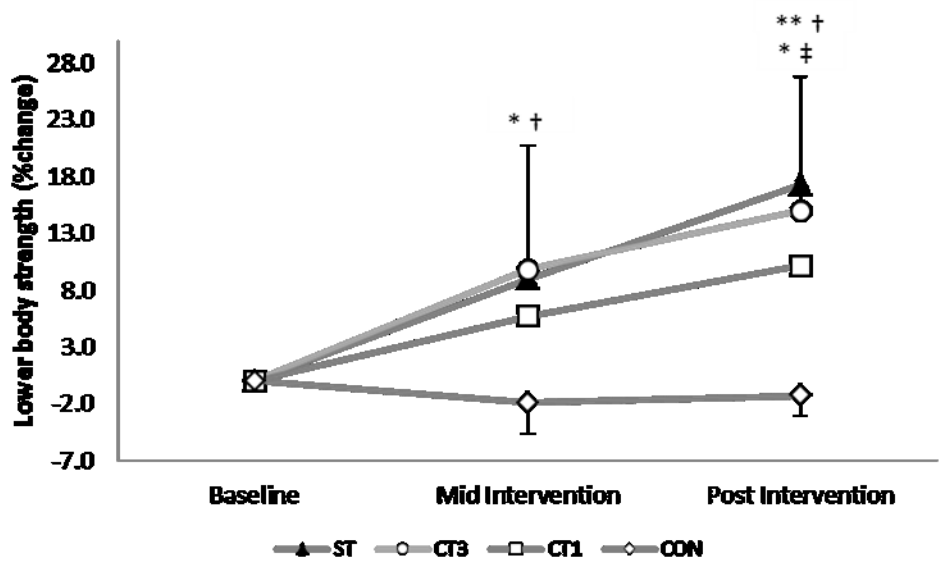
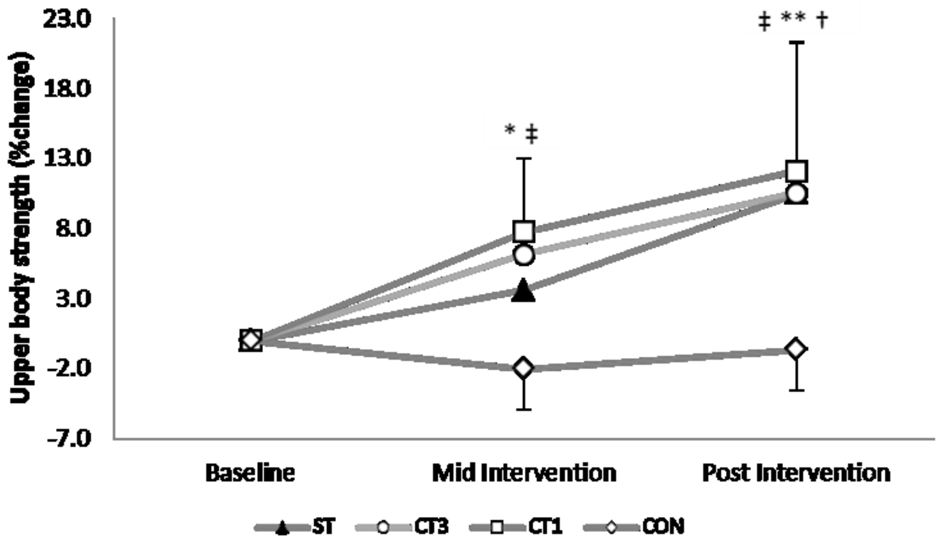
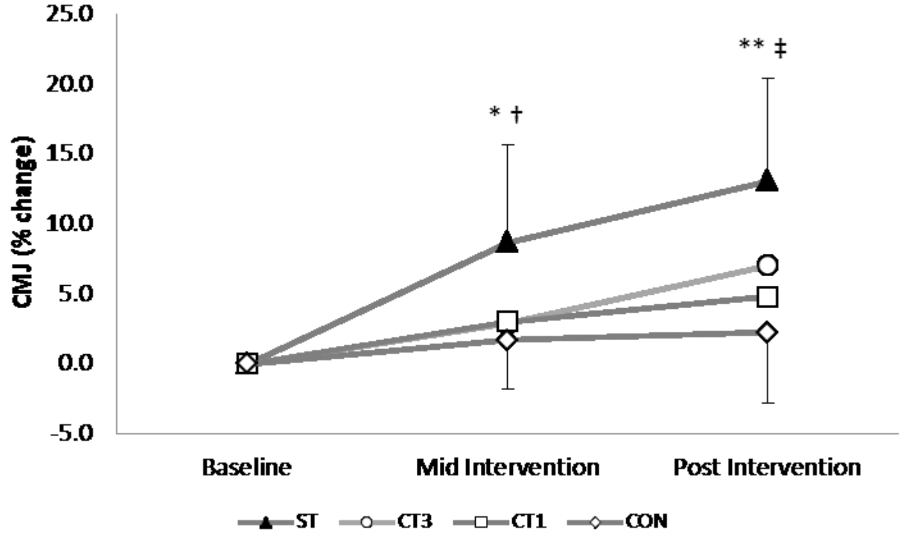

** †
* ‡
* †
28.0
23.0
18.0
13.0
8.0
3.0
-2.0
-7.0
Lower body strength (%change)
Baseline
Mid Intervention
Post Intervention
ST
CT3
CT1
CON

Figure 2

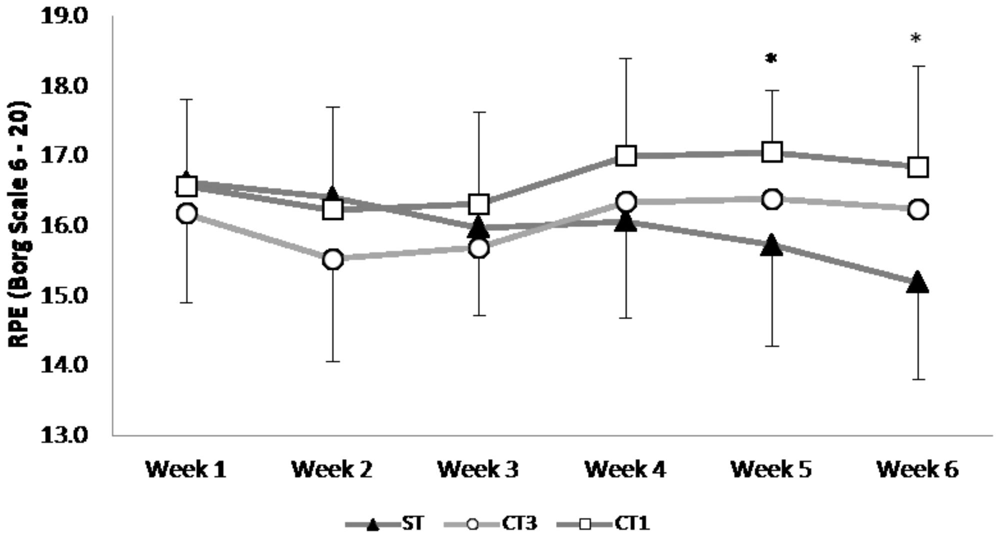


23.0
18.0
13.0
8.0
3.0
-2.0
-7.0
Upper body strength (%change)
* ‡
‡ ** †
Baseline
Mid Intervention
Post Intervention
ST
CT3
CT1
CON

Figure 3


25.0
20.0
15.0
10.0
5.0
0.0
-5.0
CMJ (% change)
* †
** ‡
Baseline
Mid Intervention
Post Intervention
ST
CT3
CT1
CON

1 Figure 4


19.0
18.0
17.0
16.0
15.0
14.0
13.0
RPE (Borg Scale 6 - 20)
*
*
Week 1
Week 2
Week 3
Week 4
Week 5
Week 6
ST
CT3
CT1

2