Performance and Neuromuscular Adaptations Following Differing Ratios of Concurrent Strength and Endurance Training

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Abstract

Jones, TW, Howatson, G, Russell, M, and French, DN. Performance and neuromuscular adaptations following differing ratios of concurrent strength and endurance training. *J Strength Cond Res* 27(12): 3342–3351, 2013—The interference effect attenuates strength and hypertrophic responses when strength and endurance training are conducted concurrently; however, the influence of training frequency on these responses remain unclear when varying ratios of concurrent strength and endurance training are performed. Therefore, the purpose of the study was to examine the strength, limb girth, and neuromuscular adaptations to varying ratios of concurrent strength and endurance training. Twenty-four men with >2 years resistance training experience completed 6 weeks of 3 days per week of (a) strength training (ST), (b) concurrent strength and endurance training ratio 3:1 (CT3), (c) concurrent strength and endurance training ratio 1:1 (CT1), or (d) no training (CON) in an isolated limb model. Assessments of maximal voluntary contraction by means of isokinetic dynamometry leg extensions (maximum voluntary suppression [MVC]), limb girth, and neuromuscular responses through electromyography (EMG) were conducted at baseline, mid-intervention, and postintervention. After training, ST and CT3 conditions elicited greater MVC increases than CT1 and CON conditions ($p \leq 0.05$). Strength training resulted in significantly greater increases in limb girth than both CT1 and CON conditions ($p = 0.05$ and 0.004, respectively). The CT3 induced significantly greater limb girth adaptations than CON condition ($p = 0.04$). No effect of time or intervention was observed for EMG ($p > 0.05$). In conclusion, greater frequencies of endurance training performed increased the magnitude of the interference response on strength and limb girth responses after 6 weeks of 3 days a week of training. Therefore, the frequency of endurance training should remain low if the primary focus of the training intervention is strength and hypertrophy.

Key Words combined exercise, interference, EMG, resistance training, training frequency

Introduction

It has been well documented that adaptations to exercise are highly dependent on the type of activity performed (27,37) as the fact performance in many sports and athletic events is dependent on various physical performance phenotypes (30,42). As strength and endurance training represent differing ends of the physiological spectrum, it is unsurprising that research has demonstrated the potential incompatibility of these 2 modes of exercise (8,12,14,24,26,31). This incompatibility manifests itself in the form of muted strength, power, and hypertrophic responses when strength and endurance training are conducted concurrently compared to when performed in isolation (26,31,49).

The incompatibility of strength and endurance training has been investigated on various occasions, with most studies tending to use similar research designs. These typically include a strength training condition, a concurrent training condition, and, on occasion, an endurance or control condition (21,36,50). More recently, research has investigated the effects of implementing strength training within a group of endurance-trained athletes (38,46,47). What remains to be understood, however, is if the frequency and ratio of strength and endurance training performed can further influence the degree of interference experienced.

Sports and events such as team games (e.g., basketball, rugby union and league), sprint kayak, and rowing require strength development and/or maintenance yet also demand endurance-type capabilities for optimal performance. As such, it is inevitable that concurrent training will be performed at particular stages during an athlete's training cycle. As such, a greater understanding of the interactions between strength and endurance training would provide useful insight for applied practitioners involved in the aforementioned sports and events.

The so-called "interference effect" (26) is neither conclusive nor exhaustive, as various investigators have reported no

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inhibiting effects of endurance training (1,19,21,35,36,40,49,51) on the desired physiological adaptations to strength training. However, this noninhibition tends to occur when training frequency remains low (typically <3 days per week) (1,12,19,21,35,36,49,51). As such, it may be prudent to ask if the ratio of strength and endurance training performed may influence the magnitude of interference expressed.

It seems that an increased frequency of endurance training can result in attenuated strength and power responses (12,24,31), whereas lower frequencies do not (1,35,49). Consequently, it makes the expectation tenable that magnitude of interference experienced is dependent on the volume of endurance training performed, a question which has not been addressed in scientific literature. Therefore, the purpose of the present study was to investigate the strength, limb girth, and neuromuscular responses to a variety of concurrent strength and endurance training ratios, with incremental loads in an isolated limb model.

Method

Experimental Approach to the Problem

A balanced, randomized, between-group study design was used. Participants were randomly assigned to an experimental condition: of either (a) strength training (ST), (b) concurrent strength and endurance training at a ratio of 3:1 (CT3), (c) concurrent strength and endurance training at a ratio of 1:1 (CT1), or (d) no training (CON). All strength and endurance training was conducted in an isolated limb model and focused on the quadriceps muscle group.

Participants in the ST group performed 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. Participants designated CT1 completed strength training immediately followed by endurance training at every scheduled session. Those assigned to CON performed no strength or endurance training during the 6-week experimental period. All participants were instructed to perform no strength training other than that prescribed by the investigator throughout the experimental period.

The total duration of the study was 6 weeks. Participants completed their respective intervention 3 times per week with approximately 48 hours between sessions for 6 weeks, resulting in a total of 18 separate training sessions. To assess whether the frequency and ratio of strength and endurance training performed may influence the degree of strength and muscular growth responses experienced during concurrent strength and endurance training, assessments of maximal voluntary contraction (MVC) and limb girth of the trained leg were conducted preintervention, mid-intervention, and postintervention. To determine the influence of neural and neuromuscular factors on strength responses, neuromuscular activity was assessed by electromyography (EMG) during MVC determination. Muscular endurance was determined by a time to exhaustion (TTE) protocol, which was performed at the aforementioned stages of the training intervention.

Subjects

Twenty-four healthy recreationally resistance-trained men (25 ± 3 years; 82.3 ± 10.0 kg; 179 ± 7 cm; 214.2 ± 42.3 Nm) volunteered to participate in the study; participants were matched at baseline for age, body mass, and initial MVC (all $p > 0.05$). All participants had completed >2 years of strength training before the start of the study, however, none where involved in a specific or structured training program.

All participants were nonsmokers, none were following specialized dietary interventions, and each was required to refrain from nutritional supplementation for 30 days before and throughout the investigation. After being informed of the benefits and potential risks of the investigation, each participant completed a health-screening questionnaire and provided written informed consent by means of a document approved by the University Institutional Review Board before any participation in the study. All experimental procedures were ratified by the academic Schools Research Ethics Committee in accordance with the Declaration of Helsinki.

Procedures

Strength and Endurance Training Protocols. All training and assessments consisted of unilateral leg extensions of the dominant leg performed on an isokinetic dynamometer (Cybex Norm, Cybex International, New York, NY, USA). Participants were seated in the dynamometer with the hip, knee, and ankle of the dominant leg set at joint angles as advised by the manufacturer's guidelines. The ankle of the dominant leg was firmly strapped to the knee adapter and stabilizer pad, whereas the thigh was secured to prevent any unwanted movement of the upper leg. Participants performed extension of the knee through 135° angle of flexion and extension. Dominant limb was determined using methods consistent with those described by Hebbal and Mysorekar (23). The strength training protocol required participants to perform 5 sets of 6 repetitions (reps) at 80 ± 5% of their individual isometric MVC with 3 minutes rest intervals between sets. This training intensity has been reported to appropriate for eliciting adaptations in strength and hypertrophy in recreationally trained nonathletes (43,44). Training intensity was incremented progressively in that MVC was determined at the start of each training session to reflect increases in strength. Mid-intervention participants in training groups MVC increased by 8.1 ± 3.8%, increases of 20.9 ± 11.9% were observed posttraining.

The endurance training protocol consisted of 30 minutes of repeated isokinetic unilateral leg extensions at 30 ± 5% individual MVC for that session. Frequency was set at 1 second per muscle action. Tempo was standardized through electronic metronome throughout the trial.

All training and testing were conducted at the same time of the day (±1 hour) for each individual participant to avoid any diurnal performance variations. Participants were also required to repeat their dietary intake the evening before and on the day of each training session and trial.

Muscle Strength Measurements. Participants were habituated with all testing procedures of voluntary force production of the muscle groups tested. Assessment of MVC required participants to first perform 10 warm-up repetitions at approximately 50% MVC. This was followed by 2 maximal repetitions to ensure participants' quadriceps were fully activated and potentiated. After a 3-minute rest, participants were given 3 attempts to achieve their individual maximal torque output. If participants peaked on their third attempt after the 3 minutes rest, 2 subsequent attempts were given to ensure that the maximum isometric torque for that visit was defined.

Endurance Performance Measurements. Participant's muscular endurance capabilities were assessed using a TTE performance test. Participants performed repeated unilateral leg

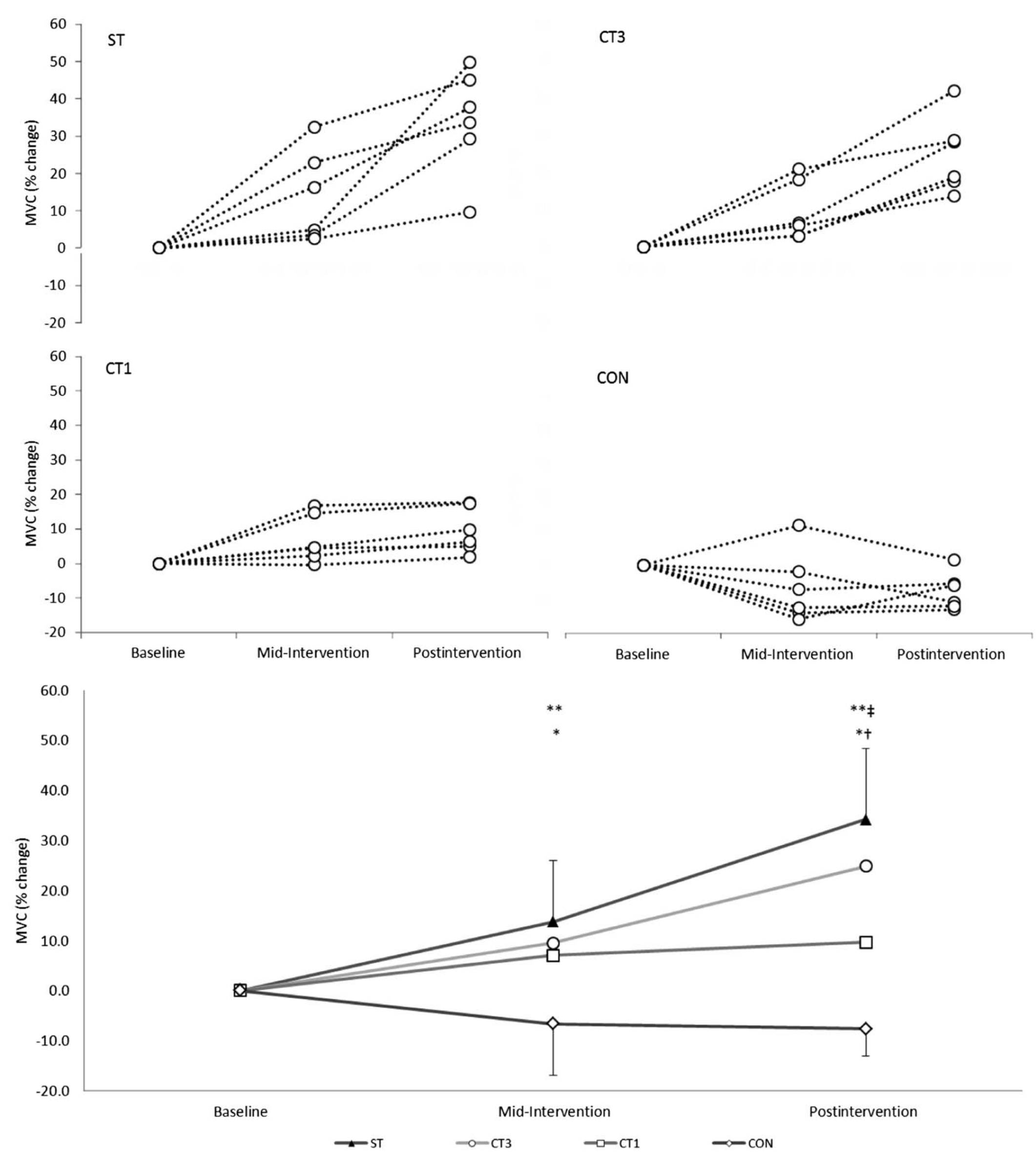

Figure 1. Individual and mean relative peak torque in unilateral leg extensions of the right leg in response to respective training interventions in the ST ($n = 6$), CT3 ($n = 6$), CT1 ($n = 6$), and CON ($n = 6$) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; MVC, maximum voluntary suppression; CT1, strength and endurance training performed every session; CON, no strength or endurance training performed during experimental period. *significantly greater than baseline in ST condition ($p < 0.05$); **ST significantly greater than CON ($p < 0.05$); †ST and CT3 significantly greater than baseline; ‡ST and CT3 significantly greater than CT1 and CON.

TABLE 1. Effect of respective training interventions on increases in maximum voluntary suppression.*

Condition	Mean effect ± 90% CI	Qualitative inference
Change from baseline to mid-intervention		
ST	12.3 ± 10.9	Likely beneficial
CT3	7.1 ± 11.3	Unclear
CT1	4.9 ± 6.8	Unclear
CON	−6.9 ± 9.3	Unlikely beneficial
Change from baseline to postintervention		
ST	30.4 ± 13.2	Most likely beneficial
CT3	24.6 ± 8.5	Most likely beneficial
CT1	7.2 ± 6.1	Likely beneficial
CON	−10.6 ± 10.9	Very unlikely beneficial

*Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. 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.

extensions at 60 ± 5% of their initial baseline MVC at frequency of 1 muscle action per second and a velocity of 60° angle per second until 60 ± 5% of initial MVC could no longer be maintained. The criteria for failure were set as failure to complete reps at 60 ± 5% of initial MVC and/or 1 muscle action per second, 2 consecutive failures resulted in test cessation. Tempo was standardized by means of electronic metronome throughout the test.

Limb Girth Measurements. Limb girth of the participant's dominant thigh was assessed before, mid, and after training. Limb girths were assessed using a limb girth–specific tape measure. The measuring tape was placed horizontally around the thigh mid-way between the midpoint of the inguinal crease and proximal border of the patella. The proximal border of the patella was marked, while the participant extended their knee. This was in accordance with standardized procedures (34).

Electromyography. Surface EMG was recorded over vastus lateralis and bicep femoris (BF) using paired electrodes (22-mm diameter model; Kendall, Tyco Healthcare Group, Mansfield, MA, USA) 2 cm apart. Vastus lateralis electrodes were placed at two-thirds on the line from the anterior superior spina iliaca superior to the lateral side of the patella (25). Electrodes for the BF were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia. A reference electrode was placed over the patella (25). All sites were shaved, abraded, and then wiped clean with a sterile swab. Each site was marked with indelible ink to ensure that a consistent placement of electrodes could be assured during the experimental period.

Electromyography was amplified (×1,000), band pass filtered 10–1,000 Hz (D360; Digitimer, Hertfordshire, UK), and sampled at 5,000 Hz (CED Power 1401; Cambridge Electronics Design, Cambridge, UK). Electromyography recordings were normalized to individual sessional MVC. Neuromuscular responses were recorded during MVC determination and throughout the endurance performance test.

TABLE 2. Effect of respective training interventions on increases in time to exhaustion.*

Condition	Mean effect ± 90% CI	Qualitative inference
Change from baseline to mid-intervention		
ST	43.7 ± 55.2	Unclear
CT3	21.3 ± 14.4	Very likely beneficial
CT1	17.6 ± 10.5	Very likely beneficial
CON	19.3 ± 17.4	Unclear
Change from baseline to postintervention		
ST	27.6 ± 39.8	Unclear
CT3	26.1 ± 16.2	Very likely beneficial
CT1	35.6 ± 19.5	Very likely beneficial
CON	6.1 ± 25.3	Unclear

*Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. 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.

Statistical Analyses

Data are presented as mean ± *SD*. Values of MVC, TTE, and limb girth were transformed to percentage change from baseline and used for analyses. Initial pilot work indicated that the aforementioned measures demonstrated tight test-retest reliability for measures of MVC (ICC = 0.99, $r = 0.99$), TTE (ICC = 0.99, $r = 0.98$), and limb girth (ICC = 0.99, $r = 0.99$). Electromyography data were normalized using MVC values from each individual training/assessment session. All subsequent statistical analysis was conducted on converted data. Before analysis dependent variables were verified as meeting required assumptions of parametric statistics and changes in all assessed measures were analyzed using repeated measures analysis of variance tests. Analysis of variance analyzed differences between 4 conditions (ST, CT3, CT1, and CON) and 3 time points (baseline, mid-intervention, and postintervention). The alpha level of 0.05 was set before data analysis. Assumptions of sphericity were assessed using Mauchly's test of sphericity, and if the assumption of sphericity was violated, the Greenhouse Gessier correction was used. If significant effects between conditions or over time were observed, post hoc differences were analyzed with the use of Least Significant Difference (LSD) correction. Statistical power of the study was calculated post hoc, and power was calculated as between 0.8 and 1, indicating sufficient statistical power (11).

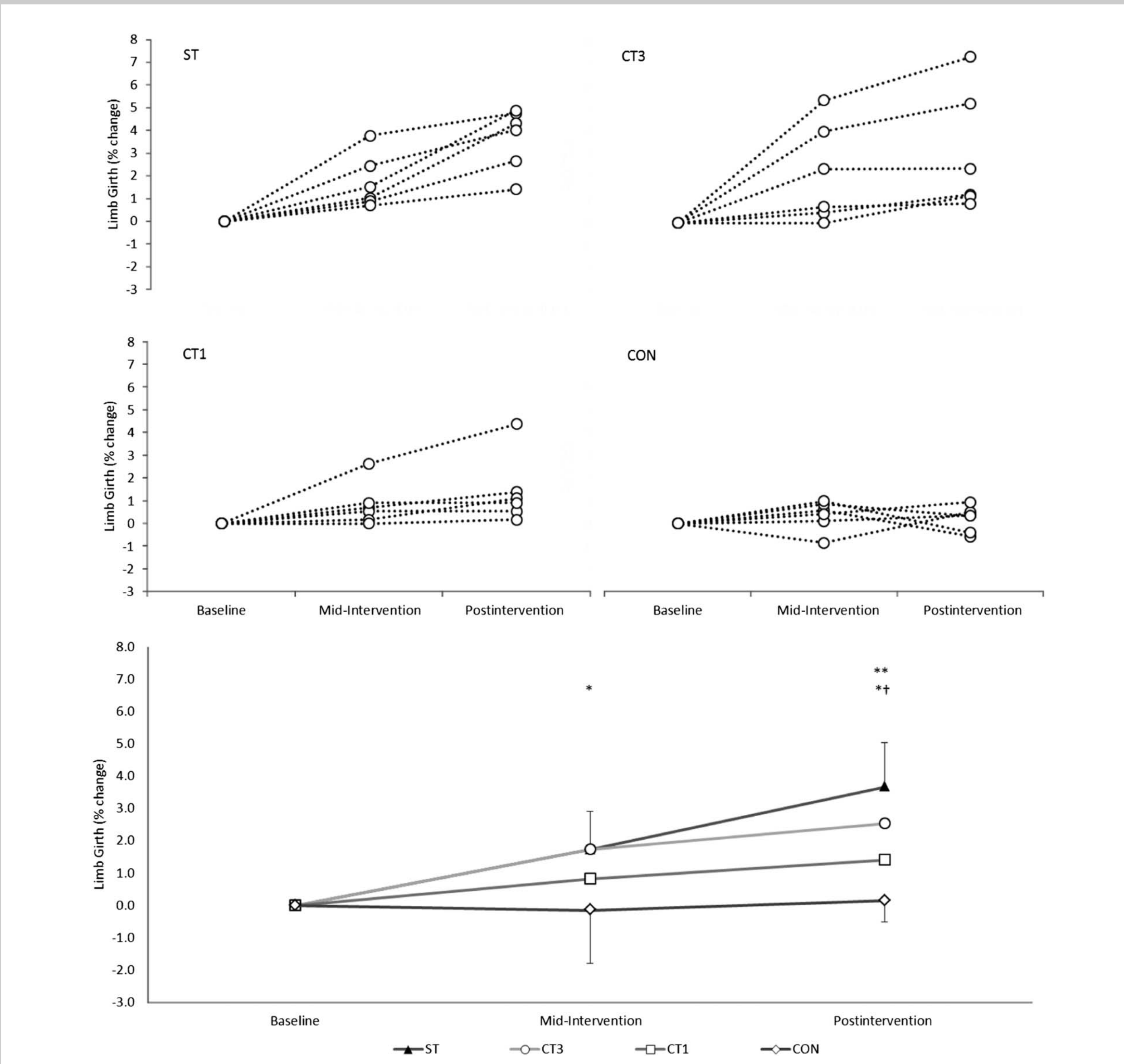

Figure 2. Individual and mean relative changes in right mid-thigh limb girth in response to respective training interventions in the ST ($n = 6$), CT3 ($n = 6$), CT1 ($n = 6$), and CON ($n = 6$) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength 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 CT3 significantly greater than baseline ($p < 0.05$); **ST greater than CT1 and CON ($p < 0.05$); †CT3 greater than CON ($p < 0.05$).

Elsewhere, statistical analysis which reports uncertainty of outcomes as 90% confidence intervals (CIs), generating probabilistic magnitude-based inferences about the true value of outcomes were also used (7). This analysis method allows the emphasis of magnitudes of effects and precision of estimates, rather than the traditional p value based null hypothesis testing that focuses on absolute effect instead of noneffect interpretation (48). A common criticism of this method is that it does not deal with the real world significance of an outcome (7). The aforementioned method defines the smallest physiological or practical effect allowing qualification of the probably of a worthwhile effect with inferential descriptors to aid interpretation (48). Magnitude inferences recognize sample variability (48), and provide athletes, applied practitioners, and scientists with the practical meaningfulness of the results. Dependent variables, including MVC, limb girth, and TTE were analyzed using a published spread sheet (28) to determine the effect of the designated training intervention as the difference in change within each group.

To calculate the possibility of benefit, the smallest worthwhile effect for each dependant variable was the smallest standardized change in the mean–0.2 times the between-subject *SD* for baseline values of all participants (7). This analysis method has previously been used in similar investigations (10,16,17). This method allows practical inferences to be drawn using the approach identified by Batterham and Hopkins (7). Quantitative chances of benefit were assessed qualitatively: <1% indicated almost certainly none; 1–5% indicated very unlikely; 5–25% indicated unlikely; 25–75% indicated possibly; 75–95% indicated likely; 95–99% indicated very likely; and >99% indicated almost certainly (29). These inferences are also free from type I and II errors, as they are probabilistic rather than definitive statements.

Results

Performance Measures

Significant effects of time ($p < 0.001$, $F = 15.15$) and group ($p < 0.001$, $F = 7.71$) were observed for strength responses. There was a significant effect across time from baseline to mid-training (12.4 ± 3.9%) for MVC values in the ST group ($p = 0.016$). Significant increases were present from baseline to postintervention in both ST and CT3 conditions ($p < 0.001$), no time effects were observed from baseline to postintervention in CT1 and CON conditions ($p = 0.152$ and 0.58, respectively).

At the mid-training point, MVC in ST condition increased 19.0 ± 2.4% more than that in CON condition ($p = 0.01$). No other significant differences were observed at this time point. Posttraining ST resulted in 22.7 ± 5.9% and 41.0 ± 2.4% greater MVC increases than CT1 and CON conditions ($p = 0.005$ and <0.001, respectively; Figure 1). The CT3 condition also resulted in significantly greater increases in MVC than CT1 and CON conditions postintervention ($p = 0.024$ and <0.001, respectively). Practical effects of respective training interventions on MVC are detailed in Table 1.

A significant time effect was observed for muscular endurance responses ($p < 0.001$, $F = 10.23$). The CT3 elicited significant improvements of 21.1 ± 4.2% in TTE mid-training ($p = 0.008$). Posttraining intervention CT3 also resulted in TTE improvements of 26.1 ± 6.7% ($p = 0.048$). The CT1 condition increased TTE posttraining by 35.5 ± 11.1% ($p = 0.14$). Practical effects of respective training interventions on endurance performance are detailed in Table 2.

Limb Girth

Significant effects of time ($p < 0.001$, $F = 17.38$) and group ($p = 0.024$, $F = 2.78$) were observed for muscular growth responses. The ST and CT3 conditions induced significant increases of 1.7 ± 0.4% and 1.7 ± 0.9% in limb girth at mid-intervention, respectively. Posttraining, further increases of 3.7 ± 2.3% and 2.5 ± 1.2% were observed (all $p < 0.05$).

Limb girth adaptations from baseline to postintervention were 2.3 ± 0.5% greater in participants who followed ST condition than those who followed CT1 and 3.6 ± 0.1% than those designated CON ($p = 0.05$ and 0.004, respectively; Figure 2). It was also observed that CT3 condition elicited

Table 3. Effect of respective training interventions on increases in limb girth.*

Condition	Mean effect ± 90% CI	Qualitative inference
Change from baseline to mid-intervention		
ST	2.0 ± 1.2	Likely beneficial
CT3	2.0 ± 2.5	Likely beneficial
CT1	1.2 ± 0.9	Possibly beneficial
CON	1.1 ± 9.5	Unclear
Change from baseline to postintervention		
ST	4.3 ± 1.2	Most likely beneficial
CT3	2.8 ± 3.1	Likely beneficial
CT1	1.0 ± 0.9	Possibly beneficial
CON	1.2 ± 3.7	Unclear

*Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. 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.

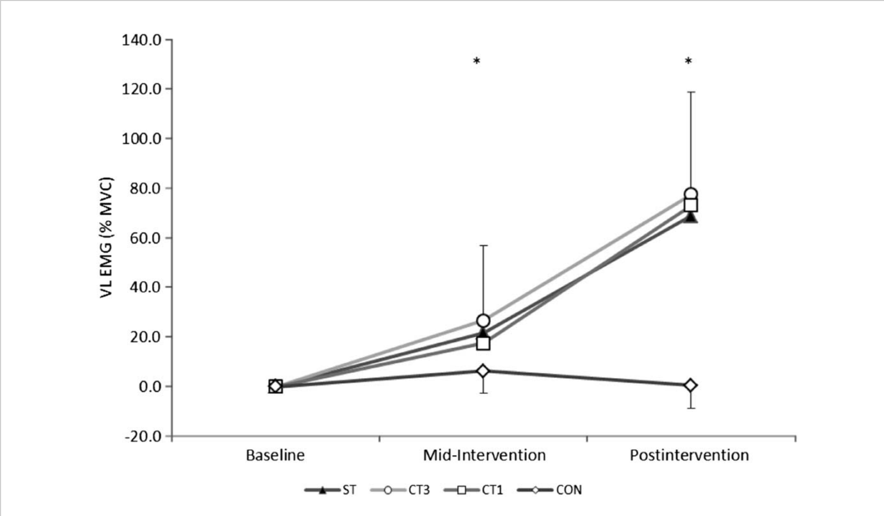

Figure 3. Relative increases in neuromuscular activity during maximum voluntary suppression as assessed by electromyography in the vastus lateralis in response to respective training interventions in the ST ($n = 6$), CT3 ($n = 6$), CT1 ($n = 6$), and CON ($n = 6$) conditions. VL, vastus lateralis; EMG, electromyography; 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; *significantly higher than baseline in training groups ($p < 0.05$).

2.4 ± 1.7% greater increases in limb girth than CON posttraining intervention ($p = 0.04$). Practical effects of respective training interventions on limb girth are detailed in Table 3.

Electromyography

Neuromuscular responses during MVC increased significantly over time for all conditions other than CON (all $p < 0.05$, $F = 12.45$). No effect of training intervention was observed (Figure 3).

Discussion

The focus of the present research was to prioritize muscular strength development as the primary objective and to examine the impact of additional endurance components on it. The results of this study demonstrate that 6 weeks of 3 days per week strength training was successful in eliciting improvements in both strength and limb girth. It was also observed that concurrent strength and endurance training improves muscular endurance. When an endurance element was added to training, the degree of strength and muscular growth responses were blunted in proportion to the frequency of endurance training. As such, our findings may indicate frequency of endurance training performed during a concurrent training strategy may influence the degree of interference experienced.

The fact that the addition of endurance training results in muted strength and hypertrophic responses is consistent with previous research (12,14,24,26,31); however, many of the studies which have reported interference characteristics used training interventions with greater frequencies than that used in the present study. It has been suggested that if the training period is too long and/or training frequency is too high, the overall training stress becomes to great and strength development plateaus (13,21,38). However, when volume, intensity, and frequency (<3 days per week) of endurance training remain low, interference may be avoided (13,14,20,26,33,36,38).

Elsewhere, however, Gergley (18) reported that 9 weeks of concurrent training (2 days per week) resulted in compromised strength development. Like our findings, this demonstrates that interference may still occur when training frequency remains low and may be dependent on the relative doses of strength and endurance training performed. Previous authors have suggested that concurrent training may be beneficial for developing strength and muscular growth in the early phases of training (6,21). Similar data exist in the present study, as mid-intervention limb girth had increased by 1.7 ± 0.4% in ST condition and 1.7 ± 0.9% in CT3.

From a practical perspective, it was only the ST and CT3 conditions that were deemed "most likely beneficial" for improving strength after training. Furthermore, ST was the only condition that was "most likely beneficial" for improving limb girth. The CT1 was only deemed "possibly beneficial" for improving limb girth, this may indicate that the attenuated strength responses were due to the lack of morphological adaptation.

Recreationally, resistance trained individuals were recruited to participate in the present study in which we observed clear interference in both strength and limb girth. Training history and current training status of participants is a common variant in concurrent training research (36,50). It seems that athletes and highly trained populations may be more susceptible to interference than untrained individuals (4,5,47). It is possible this may be because of overtraining as highly trained individuals experience a far greater training load and volume than those who are recreationally trained. Many studies that have reported no interference, when training frequency remains low (<3 days per week), recruited untrained individuals (1,12,35,49,51). This may partly explain why we observed interference, as all participants had prior experience of strength training, although none could be described as highly trained.

As frequency and volume of training seems to be a key indicator of interference various researchers have suggested the muted strength and hypertrophic responses may be because of overtraining (18,21,24,40). This may be particularly relevant in untrained individuals, as they are more susceptible to physiological stress than those with a history of training (21). As training frequency and duration remained relatively low in the present study (6 weeks of 3 days per week), it is unlikely that the attenuated strength and muscular growth can be attributed to overtraining. Dudley and Djamil (14) also reported inhibited strength responses were unlikely to be because of overtraining in a short duration low-frequency program.

In the present study, training was conducted in an isolated limb using the same biomechanical movement pattern for both strength and endurance training. Gergley suggested that if the primary objective of a training program is developing strength in a specific muscle, group endurance training should be avoided in that muscle group as specificity of movement pattern may amplify interference (18). As such, this may explain why in the present study clear interference was reported, whereas other studies which have used similar training frequencies but multijoint resistance training and cycling or running endurance protocols observed no interference (1,12,19,21,35,36,49,51).

No differences in neuromuscular responses were observed between training interventions during the present study; this is in agreement with previous research stating neuromuscular characteristics are not fully inhibited by concurrent training (36,38,41). However, neuromuscular factors, including altered patterns in neural recruitment (9,15,18,31), neuromuscular fatigue (13,32,33), and inability to develop adequate force to induce strength development due to endurance training (15,45,47) have previously been proposed mechanisms behind the interference effect. The relatively short duration of training used here may account for the similar neural responses between groups. More longitudinal studies have reported greater variance in neuromuscular responses (20,35).

As neuromuscular responses were similar between the prescribed training interventions (evident from EMG data), it may be suggested that the attenuated improvements in strength were primarily because of lack of hypertrophic adaptation. The CT3 and CT1 conditions resulted in 1.2 $\pm$ 0.8% and 2.3 $\pm$ 1.6% lower limb girth increases than ST alone, this was coupled with 5.4 $\pm$ 3.7% and 22.7 $\pm$ 16.1% lower increases in MVC. This indicates that in the present study, the inclusion of endurance training may have impaired muscular growth, which in turn resulted in attenuated strength responses. This concurs with other conclusions that the muted strength responses associated with concurrent training can be attributed to lack of hypertrophy (8,9,15,18,31,33,47).

As strength and endurance training initiate various contrasting biochemical, endocrine, and molecular responses, there are potential mechanisms for the interference effect, which have not been analyzed here. The interference phenomenon may be attributed to an increased catabolic hormonal state caused by increased training frequency and volume of endurance training (8,31). More recent research has indicated endurance training induced low muscle glycogen and may impair intracellular signaling pathways responsible for hypertrophy (22,47). It has also been demonstrated that the molecular signaling pathways responsible for endurance-based adaptations inhibit the activation of pathways responsible for protein synthesis, thus the strength and hypertrophic adaptations (2,3,39).

Concurrent training is typically associated with impaired strength and hypertrophy, however, various research have indicated that concurrent training is an effective means of improving muscular endurance (13,46,47). This was also observed in the present study, as concurrent training conditions were shown to improve muscular endurance. Concurrent training conducted 3 times weekly (CT1) resulted in 7.6 $\pm$ 2.3% greater increases in TTE than strength training alone. Davis et al. (13) reported similar findings, as concurrent training increased TTE by 8.1% more than strength training alone. This was further illustrated at mid-intervention and postintervention; it was only the concurrent conditions that were deemed "very likely beneficial" for improving muscular endurance. The benefit of ST and CON on TTE was deemed "unclear."

Although concurrent training was observed to be an effective means of improving muscular endurance, our data demonstrate that when strength and endurance training are performed concurrently greater volumes of endurance training result in an amplified inhibition of strength and muscular growth. Lower volumes of endurance exercise did not result in a noteworthy inhibition of strength or muscular growth. As such, it may be suggested that frequency and volume of endurance training performed is a key determinant of the interference effect.

Practical Applications

Strength and conditioning practitioners often have limited access to their athletes, and, as such, it is key that training elicits the necessary responses to maximize adaptations and performance (13). At present, little guidance exists for designing concurrent training programs to minimize interference (15,33).

In the present study, short-term, low-frequency, isolated limb concurrent strength and endurance training resulted in attenuated strength and hypertrophic responses. However, these data also indicated that the ratio of strength and endurance training performed influences the degree of interference experienced. As all prescribed training interventions had no effect on neuromuscular adaptations, improvements in strength in the present study seems to be attributable structural adaptation.

The practical significance of these data lies in the fact that if during short-term isolated training, strength and hypertrophy are the primary aims frequency and volume of endurance components should conceivably remain low as it seems that increased volumes of endurance training results in amplified inhibition of strength and muscular growth responses. As such, practitioners involved in sports and events that require both strength and endurance capabilities should carefully monitor the volume of endurance training prescribed if interference is to be avoided.

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