Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0b013e3182903221

PERFORMANCE AND NEUROMUSCULAR ADAPTATIONS FOLLOWING DIFFERING RATIOS OF CONCURRENT STRENGTH AND ENDURANCE TRAINING

RESPONSES TO DIFFERING RATIOS OF CONCURRENT TRAINING

THOMAS. W JONES[1], GLYN HOWATSON[1,2], MARK RUSSELL[1] and DUNCAN N. FRENCH[1]

[1] *Department of Sport and Exercise Science, Northumbria University, Newcastle upon Tyne, United Kingdom*

[2] *Water Research Group, School of Environmental Sciences and Development, North West University, Potchefstroom, South Africa*

Dr Duncan N. French
Department of Sport and Exercise Sciences
Northumbria University
Northumberland Building
Newcastle upon Tyne
NE1 8ST
tel: 01912437018
duncan.french@northumbria.ac.uk

ABSTRACT

The *interference effect* attenuates strength and hypertrophic responses when strength and endurance training are conducted concurrently; however, the influence of training frequency upon 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 $d\cdot wk^{-1}$ 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) in an isolated limb model. Assessments of maximal voluntary contraction via isokinetic dynamometry leg extensions (MVC), limb girth and neuromuscular responses via electromyography (EMG) were conducted at baseline, mid-intervention and post-intervention. Following training, ST and CT3 conditions elicited greater MVC increases than CT1 and CON conditions ($P \leq 0.05$). ST resulted in significantly greater increases in limb girth than both CT1 and CON conditions ($P = 0.05$ and 0.004 respectively). 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 following 6 weeks of $3\text{-}d\cdot^{-1}$ 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 is the fact performance in many sports and athletics 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 two 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 the majority of studies tending to employ 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 inhibiting effects of endurance training (1, 19, 21, 35, 36, 40, 49, 51) on the desired physiological adaptations to strength training. However this non inhibition tends to occur when training frequency remains low (typically < 3-d·wk^{-1}) (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 appears 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 employed. Participants were randomly assigned to an experimental condition: of either i) strength training (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). 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 ~48 h between sessions for 6 weeks resulting in a total of 18 separate training sessions. In order 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 assed pre, mid and post intervention. 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 yrs; 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 prior to the start of the study, however none where involved in a specific or structured training programme.

All participants were non-smokers, none were following specialized dietary interventions, and each was required to refrain from nutritional supplementation for 30 days prior to 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 via a document approved by the University Institutional Review Board prior to 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, N.Y.). 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 stabiliser pad while the thigh was secured to prevent any unwanted movement of the upper leg. Participants performed extension of the knee through 135° of flexion and extension. Dominant limb was determined using methods consistent with those described by Hebbal and Mysorekar. The strength training protocol required participants to perform 5 sets of 6 repetitions (reps) at 80±5% of their individual isometric MVC with 3 min rest intervals between sets. This training intensity has been reported to appropriate for eliciting adaptations in strength and hypertrophy in recreationally trained non-athletes (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 post-training.

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

All training and testing was conducted at the same time of day (± 1 h) for each individual participant to avoid any diurnal performance variations. Participants were also required to repeat their dietary intake the evening before and 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 ten warm up repetitions at ~50% MVC. This was followed by two maximal repetitions to ensure participants quadriceps were fully activated and potentiated. Following a 3 min rest participants were given 3 attempts to achieve their individual maximal torque output. If participants peaked on their third attempt following 3 min rest 2 subsequent attempts were given to ensure 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 extensions at 60±5% of their initial baseline MVC at frequency of 1 muscle action·s^{-1} and a velocity of 60° 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, two consecutive failures resulted in test cessation. Tempo was standardised via electronic metronome throughout the test.

Limb Girth Measurements

Limb girth of the participant's dominant thigh was assessed pre, mid and post training. Limb girths were assessed using a limb girth specific tape measure. The measuring tape was placed horizontally around the 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 standardised procedures (34).

Electromyography

Surface EMG was recorded over Vastus Lateralis (VL) and Bicep Femoris (BF) using paired electrodes (22 mm diameter, model; Kendall, Tyco Healthcare Group, Mansfield, MA, USA) 2 cm apart. VL electrodes were placed at ⅔ 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 then wiped clean with a sterile swab. Each site was marked with indelible ink to ensure a consistent placement of electrodes could be assured during the experimental period.

EMG was amplified (1000x), band pass filtered 10 - 1,000Hz (D360, Digitimer, Hertfordshire, UK) and sampled at 5,000Hz (CED Power 1401, Cambridge Electronics Design, Cambridge, UK). EMG recordings were normalised to individual sessional MVC. Neuromuscular responses were recorded during MVC determination and throughout the endurance performance test.

Statistical Analysis

Data are presented as mean ± standard deviation. Values of MVC, TTE and limb girth were transformed to percentage (%) change from baseline and used for analysis. 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). EMG data was normalized using MVC values from each individual training/assessment session. All subsequent statistical analysis was conducted on converted data. Prior to analysis dependant variables were verified as meeting required assumptions of parametric statistics and changes in all assessed measures were analyzed using 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 LSD correction. Statistical power of the study was calculated post-hoc, power was calculated as between 0.8 and 1 indicating sufficient statistical power (11).

Elsewhere statistical analysis which reports uncertainty of outcomes as 90% confidence intervals (CI), generating probabilistic magnitude-based inferences about the true value of outcomes were also employed (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 which focuses on absolute effect instead of noneffect interpretation (48). A common criticism of this method is that is 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 recognise sample variability (48), and provide athletes, applied practitioners and scientists with the practical meaningfulness of the results. Dependant variables including MVC, limb girth and TTE were analysed 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 employed in similar investigations (10, 16, 17). This method allows practical inferences to be drawn using the approach identified by Batterham and Hopkins (2006). Quantitative chances of benefit were assessed qualitatively: <1% indicated almost certainly none; 1% to 5% indicated very unlikely; 5% to 25% indicated unlikely; 25% to 75% indicated possibly; 75% to 95% indicated likely; 95% to 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 (7).

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 post-intervention in both ST and CT3 conditions (P <0.001), no time effects were observed from baseline to post intervention 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% greater than CON condition (P = 0.01). No other significant differences were observed at this time point. Post-training 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). CT3 condition also resulted in significantly greater increases in MVC than CT1 and CON conditions post intervention (*P* = 0.024 and <0.001 respectively). Practical effects of respective training interventions on MVC are detailed in Table 1.

Figure 1 about here

Table 1 about here

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

Table 2 about here

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. ST and CT3 conditions induced significant increases of 1.7±0.4% and 1.7±0.9% in limb girth at mid intervention, respectively. Post training further increases of 3.7±2.3% and 2.5±1.2% were observed (all *P* <0.05).

Limb girth adaptions from baseline to post intervention 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 2.4±1.7% greater increases in limb girth than CON post training intervention (P = 0.04). Practical effects of respective training interventions on limb girth are detailed in table 3.

Figure 2 about here

Table 3 about here

EMG

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).

Figure 3 about here

DISCUSSION

The focus of the present research was to prioritise muscular strength development as the primary objective, and to examine the impact of additional endurance components upon it. The results of this study demonstrate that 6 weeks of 3-d·wk^{-1} 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 employed training interventions with greater frequencies than that employed 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-d·wk^{-1}) of endurance training remain low interference may be avoided (13, 14, 20, 26, 33, 36, 38).

Elsewhere however, Gergley reported that 9 weeks of concurrent training (2-d·wk^{-1}) resulted in compromised strength development (18). 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 (2, 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 which were deemed “most likely beneficial” for improving strength following training. Furthermore ST was the only condition which was “most likely beneficial” for improving limb girth. CT1 was only deemed “possibly beneficial” for improving limb girth, this may indicate the attenuated strength responses were due to 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 (5, 6, 47). It is possible this may be due to 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-d·wk^{-1}) 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 due to 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 wk of 3-d·wk^{-1}) it is unlikely that the attenuated strength and muscular growth can be attributed to overtraining. Dudley and Djamil also reported inhibited strength responses were unlikely to be due to overtraining in a short duration low frequency programme (14).

In the present study training was conducted in an isolated limb employing the same biomechanical movement pattern for both strength and endurance training. Gergley suggested that if the primary objective of a training programme 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 employed similar training frequencies but multi joint 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 employed 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 due to lack of hypertrophic adaptation. CT3 and CT1 conditions resulted in 1.2±0.8% and 2.3±1.6% lower limb girth increases than ST alone, this was coupled with 5.4±3.7% and 22.7±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 analysed 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 signalling pathways responsible for hypertrophy (22, 47). It has also been demonstrated that the molecular signalling pathways responsible for endurance based adaptations inhibit the activation of pathways responsible for protein synthesis, thus strength and hypertrophic adaptations (3, 4, 39).

Concurrent training is typically associated with impaired strength and hypertrophy however, various research has indicated 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±2.3% greater increases in TTE than strength training alone. Davis et al. 2008 (13) reported similar findings as concurrent training increased TTE by 8.1% more than strength training alone. This was further illustrated as at mid and post-intervention 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 trained 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 programmes to minimise interference (15, 33).

In the current 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 appear 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 appears that increased volumes of endurance training results in amplified inhibition of strength and muscular growth responses. As such practitioners involved in sports and events which require both strength and endurance capabilities should carefully monitor the volume of endurance training prescribed if interference is to be avoided.

REFERENCES

1. Abernethy PJ and Quigley BM. Concurrent strength and endurance training of the elbow extensors. *The Journal of Strength & Conditioning Research* 7: 234, 1993.
2. Balabinis CP, Psarakis CH, Moukas M, Vassiliou MP, and Behrakis PK. Early phase changes by concurrent endurance and strength training. *The Journal of Strength & Conditioning Research* 17: 393, 2003.
3. Baar K. Training for endurance and strength: lessons from cell signaling. *Medicine & Science in Sports & Exercise* 38: 1939, 2006.
4. Baar K. The signaling underlying FITness. *Applied Physiology, Nutrition, and Metabolism* 34: 411-419, 2009.
5. Baker D. The effects of an in-season of concurrent training on the maintenance of maximal strength and power in professional and college-aged rugby league football players. *The Journal of Strength & Conditioning Research* 15: 172, 2001.
6. Baker DG and Newton RU. Adaptations in upper-body maximal strength and power output resulting from long-term resistance training in experienced strength-power athletes. *The Journal of Strength & Conditioning Research* 20: 541, 2006.
7. Batterham AM and Hopkins WG. Making meaningful inferences about magnitudes. 2006.
8. Bell G, Syrotuik D, Martin T, Burnham R, and Quinney H. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *European journal of applied physiology* 81: 418-427, 2000.
9. Chromiak JA and Mulvaney DR. A review: The effects of combined strength and endurance training on strength development. *J Appl Sport Sci Res* 4: 55-60, 1990.
10. Cockburn E, Stevenson E, Hayes PR, Robson-Ansley P, and Howatson G. Effect of milk-based carbohydrate-protein supplement timing on the attenuation of exercise-induced muscle damage. *Applied Physiology, Nutrition, and Metabolism* 35: 270-277, 2010.
11. Cohen J. Statistical power analysis. *Current directions in psychological science* 1: 98-101, 1992.
12. Craig BW, Lucas J, Pohlman R, and Stelling H. The effects of running, weightlifting and a combination of both on growth hormone release. *The Journal of Strength & Conditioning Research* 5: 198, 1991.

13. Davis WJ, Wood DT, Andrews RG, Elkind LM, and Davis WB. Concurrent training enhances athletes' strength, muscle endurance, and other measures. *The Journal of Strength & Conditioning Research* 22: 1487, 2008.

14. Dudley GA and Djamil R. Incompatibility of endurance-and strength-training modes of exercise. *Journal of Applied Physiology* 59: 1446-1451, 1985.

15. Dudley GA and Fleck SJ. Strength and endurance training are they mutually exclusive? *Sports Medicine* 4: 79-85, 1987.

16. Gee TI, French DN, Howatson G, Payton SJ, Berger NJ, and Thompson KG. Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later? *European journal of applied physiology* 111: 2653-2662, 2011.

17. Gee TI, Olsen PD, Fritzdorf SWG, White DJ, Golby J, and Thompson KG. Recovery of Rowing Sprint Performance After High Intensity Strength Training. *International Journal of Sports Science and Coaching* 7: 109-120, 2012.

18. Gergley JC. Comparison of two lower-body modes of endurance training on lower-body strength development while concurrently training. *The Journal of Strength & Conditioning Research* 23: 979, 2009.

19. Gravelle BL and Blessing DL. Physiological adaptation in women concurrently training for strength and endurance. *The Journal of Strength & Conditioning Research* 14: 5, 2000.

20. Häkkinen K, Alen M, and Komi P. Changes in isometric force-and relaxation-time, electromyographic and muscle fibre characteristics of human skeletal muscle during strength training and detraining. *Acta Physiologica Scandinavica* 125: 573-585, 1985.

21. Häkkinen K, Alen M, Kraemer W, Gorostiaga E, Izquierdo M, Rusko H, Mikkola J, Häkkinen A, Valkeinen H, and Kaarakainen E. Neuromuscular adaptations during concurrent strength and endurance training versus strength training. *European journal of applied physiology* 89: 42-52, 2003.

22. Hawley JA. Molecular responses to strength and endurance training: Are they incompatible? This paper article is one of a selection of papers published in this Special Issue, entitled 14th International

Biochemistry of Exercise Conference-Muscles as Molecular and Metabolic Machines, and has undergone the Journal's usual peer review process. *Applied Physiology, Nutrition, and Metabolism* 34: 355-361, 2009.

23. Hebbal GV and Mysorekar VR. Evaluation of some tasks used for specifying handedness and footedness. *Perceptual and motor skills* 102: 163, 2006.
24. Hennessy LC and Watson AWS. The interference effects of training for strength and endurance simultaneously. *The Journal of Strength & Conditioning Research* 8: 12, 1994.
25. Hermens HJ, Freriks B, Disselhorst-Klug C, and Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. *Journal of Electromyography and Kinesiology* 10: 361-374, 2000.
26. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *European journal of applied physiology and occupational physiology* 45: 255-263, 1980.
27. Holloszy JO and Booth FW. Biochemical adaptations to endurance exercise in muscle. *Annual Review of Physiology* 38: 273-291, 1976.
28. Hopkins W. A spreadsheet for analysis of straightforward controlled trials. *Sportscience* 7: 2-7, 2003.
29. Hopkins WG. Probabilities of clinical or practical significance. *Sportscience* 6: 201, 2002.
30. Kotzamanidis C, Chatzopoulos D, Michailidis C, Papaiakovou G, and Patikas D. The effect of a combined high-intensity strength and speed training program on the running and jumping ability of soccer players. *J Strength Cond Res* 19: 369-375, 2005.
31. Kraemer WJ, Patton JF, Gordon SE, Harman EA, Deschenes MR, Reynolds K, Newton RU, Triplett NT, and Dziados JE. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *Journal of Applied Physiology* 78: 976-989, 1995.
32. Leveritt M and Abernethy PJ. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *Journal of Strength and Conditioning Research* 13: 47-51, 1999.
33. Leveritt M, Abernethy PJ, Barry BK, and Logan PA. Concurrent strength and endurance training: a review. *Sports Medicine* 28: 413-427, 1999.
34. Lohman TG, Roche AF, and Martorell R. *Anthropometric standardization reference manual.* Human Kinetics Books Champaign, 1988.
35. McCarthy J, Agre JC, Graf B, Pozniak MA, and Vailas AC. Compatibility of adaptive responses with combining strength and endurance training. *Medicine and science in sports and exercise* 27: 429, 1995.

36. McCarthy J, Pozniak MA, and Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Medicine & Science in Sports & Exercise* 34: 511, 2002.

37. McDonagh MJN and Davies CTM. Adaptive response of mammalian skeletal muscle to exercise with high loads. *European journal of applied physiology and occupational physiology* 52: 139-155, 1984.

38. Mikkola JS, Rusko HK, Nummela AT, Paavolainen LM, and Häkkinen K. Concurrent endurance and explosive type strength training increases activation and fast force production of leg extensor muscles in endurance athletes. *Journal of strength and conditioning research/National Strength & Conditioning Association* 21: 613, 2007.

39. Nader GA. Concurrent strength and endurance training: from molecules to man. *Medicine & Science in Sports & Exercise* 38: 1965, 2006.

40. Nelson AG, Arnall DA, Loy SF, Silvester LJ, and Conlee RK. Consequences of combining strength and endurance training regimens. *Physical Therapy* 70: 287-294, 1990.

41. Paavolainen L, Häkkinen K, Hämäläinen I, Nummela A, and Rusko H. Explosive-strength training improves 5-km running time by improving running economy and muscle power. *Journal of Applied Physiology* 86: 1527-1533, 1999.

42. Paton CD and Hopkins WG. Combining explosive and high-resistance training improves performance in competitive cyclists. *The Journal of Strength & Conditioning Research* 19: 826, 2005.

43. Peterson MD, Rhea MR, and Alvar BA. Maximizing strength development in athletes: a meta-analysis to determine the dose-response relationship. *Journal of Strength and Conditioning Research* 18: 377-382, 2004.

44. Peterson MD, Rhea MR, and Alvar BA. Applications of the Dose-Response for Muscular Strength Development: Areview of Meta-Analytic Efficacy and Reliability for Designing Training Prescription. *The Journal of Strength & Conditioning Research* 19: 950, 2005.

45. Rhea MR, Oliverson JR, Marshall G, Peterson MD, Kenn JG, and Ayllón FN. Noncompatibility of power and endurance training among college baseball players. *The Journal of Strength & Conditioning Research* 22: 230, 2008.

46. Rønnestad BR, Hansen EA, and Raastad T. Effect of heavy strength training on thigh muscle cross-sectional area, performance determinants, and performance in well-trained cyclists. *European journal of applied physiology* 108: 965-975, 2010.

47. Rønnestad BR, Hansen EA, and Raastad T. High volume of endurance training impairs adaptations to 12 weeks of strength training in well-trained endurance athletes. *European journal of applied physiology*: 1-10, 2011.

48. Rowlands DS, Rössler KK, Thorp RM, Graham DF, Timmons BW, Stannard SR, and Tarnopolsky MA. Effect of dietary protein content during recovery from high-intensity cycling on subsequent performance and markers of stress, inflammation, and muscle damage in well-trained men. *Applied Physiology, Nutrition, and Metabolism* 33: 39-51, 2007.

49. Sale D, MacDougall J, Jacobs I, and Garner S. Interaction between concurrent strength and endurance training. *Journal of Applied Physiology* 68: 260-270, 1990.

50. Shaw BS, Shaw I, and Brown GA. Comparison of resistance and concurrent resistance and endurance training regimes in the development of strength. *The Journal of Strength & Conditioning Research* 23: 2507, 2009.

51. Volpe SL, Walberg-Rankin J, Rodman KW, and Sebolt DR. The effect of endurance running on training adaptations in women participating in a weight lifting program. *The Journal of Strength & Conditioning Research* 7: 101, 1993.

ACKNOWLEDGEMENTS

The authors would like to thank all individuals who volunteered to participate in the study. The results of the present study do not constitute any endorsement from the NSCA.

Table 1. Effect of respective training interventions on increases in MVC.

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 post intervention		
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

Note: 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.

Table 2. Effect of respective training interventions on increases in TTE.

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 post intervention		
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

Note: 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.

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 post intervention		
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

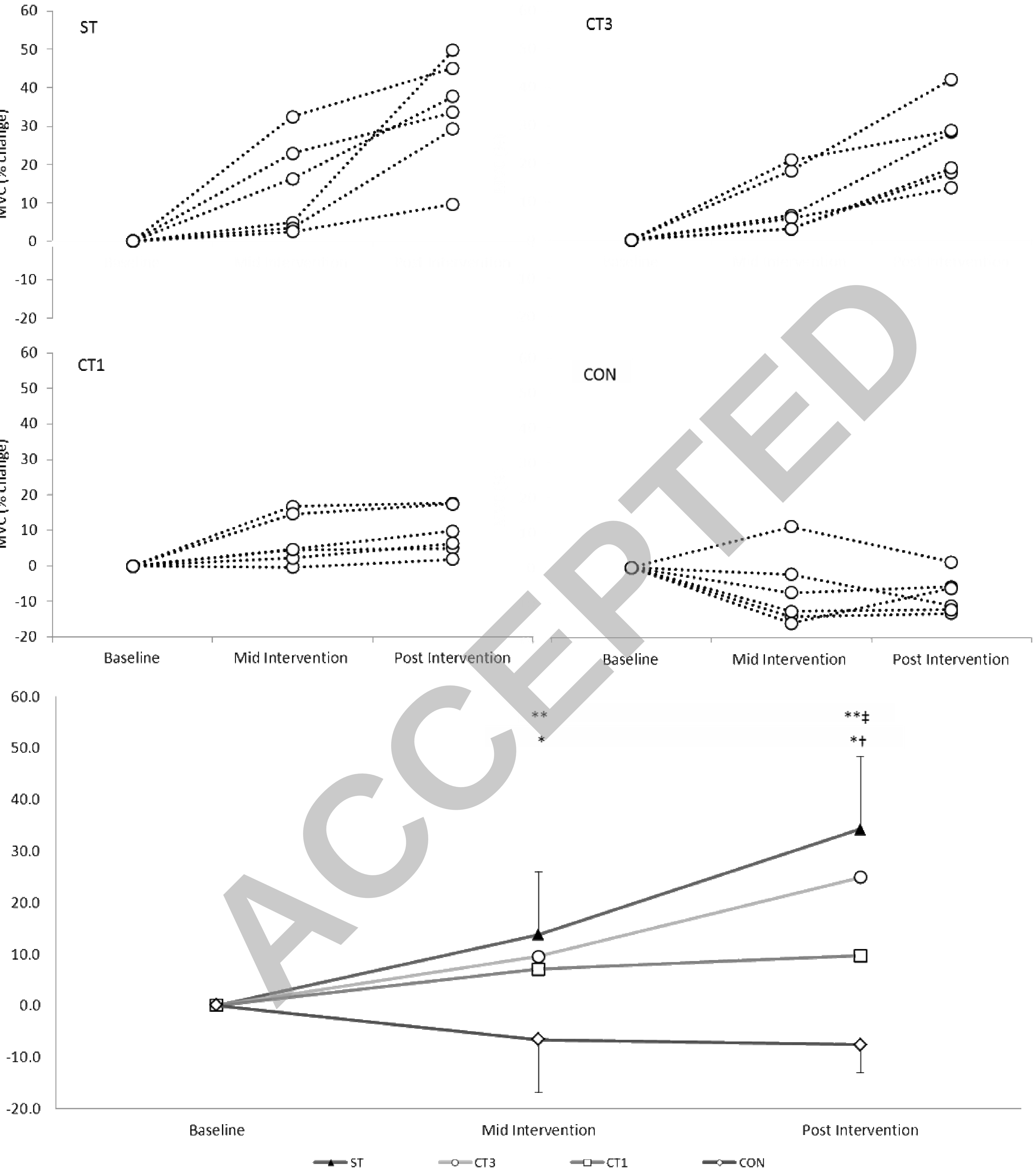
Note: Mean effect refers to the first named stage of intervention minus the second named stage of intervention. For the ±90% CI, add and subtract this number to the mean effect to obtain the 90% confidence intervals for the true difference. ST, strength training alone performed every session; CT3, strength 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.

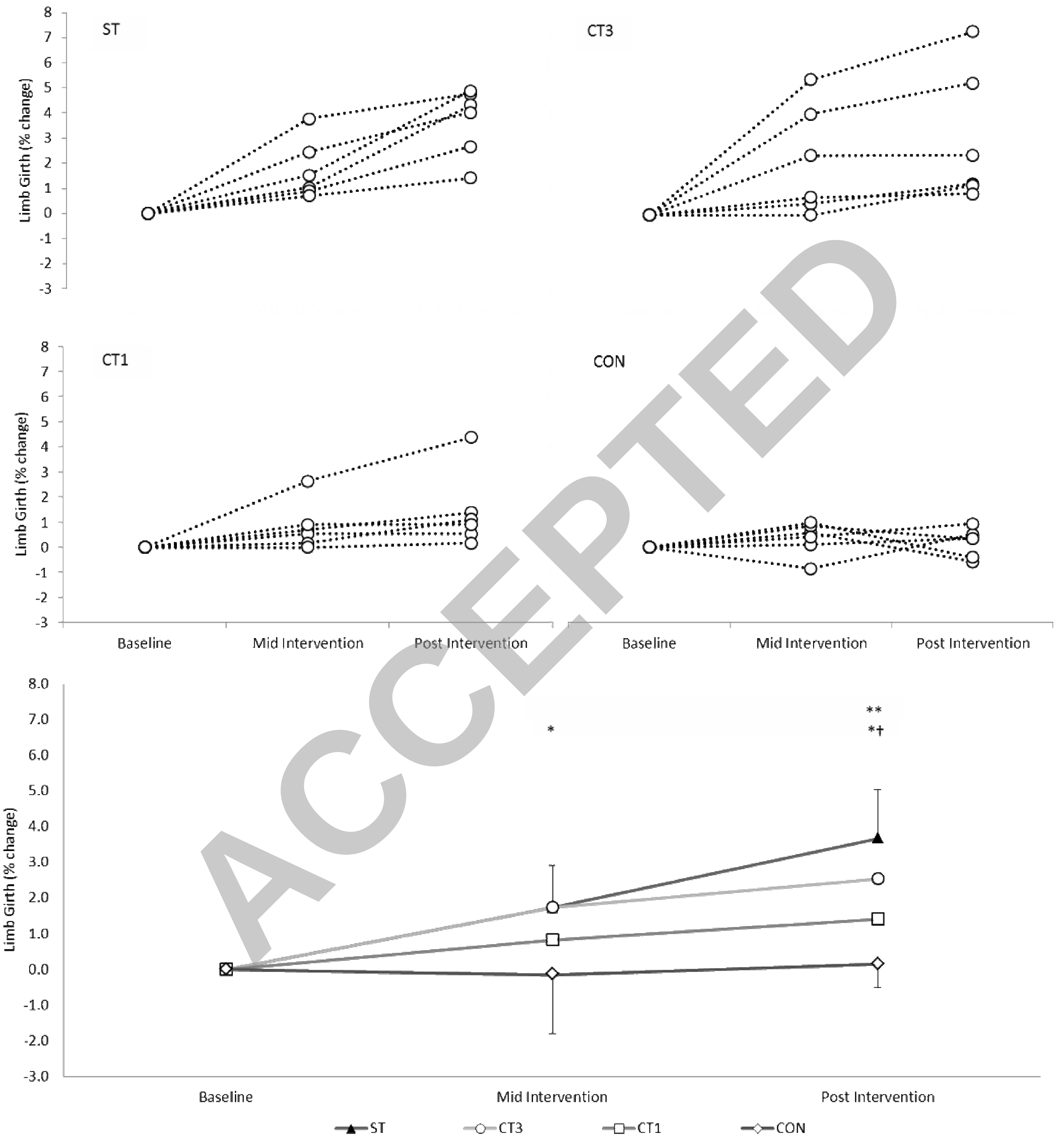
Figure Legends

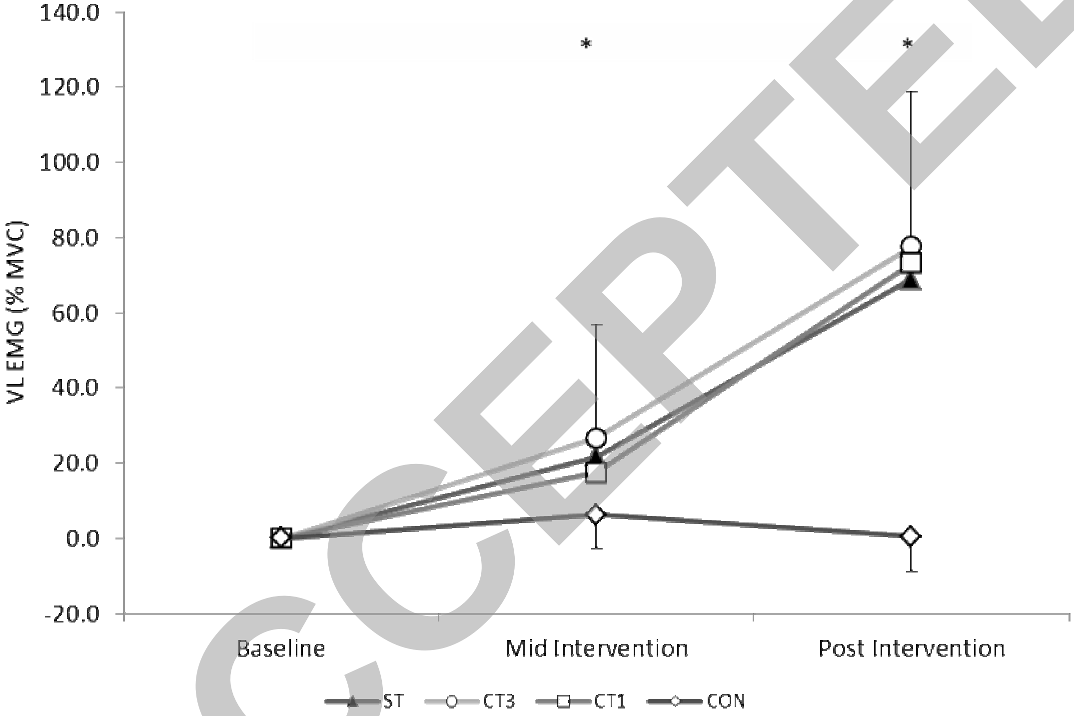
Figure 1. Individual and mean relative peak torque in unilateral leg extensions of the right leg in response to respective training interventions in the ST (n = 6), CT3 (n = 6), CT1 (n = 6) and CON (n = 6) conditions. ST, strength training alone performed every session; CT3, strength performed every session, strength and endurance training performed every third session; 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.

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).

Figure 3. Relative increases in neuromuscular activity during MVC as assessed by EMG in the VL 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. * significantly higher than baseline in training groups (*P* <0.05).


ST
CT3
CT1
CON
MVC (% change)
60
50
40
30
20
10
0
-10
-20
Baseline
Mid Intervention
Post Intervention
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
-20.0
**
*
**‡
*†
ST
CT3
CT1
CON


ST
CT3
CT1
CON
Limb Girth (% change)
8
7
6
5
4
3
2
1
0
-1
-2
-3
Baseline
Mid Intervention
Post Intervention
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
*
**
*†
ST
CT3
CT1
CON


140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
VL EMG (% MVC)
*
*
Baseline
Mid Intervention
Post Intervention
ST
CT3
CT1
CON