Concurrent training: a meta-analysis examining interference of aerobic and resistance exercises.

ARTICLE *in* THE JOURNAL OF STRENGTH AND CONDITIONING RESEARCH · OCTOBER 2011

Impact Factor: 1.86 · DOI: 10.1519/JSC.0b013e31823a3e2d · Source: PubMed

6 AUTHORS, INCLUDING:

Jacob M Wilson
The University of Tampa

Pedro J Marín
Universidad Europea Miguel de Cervantes

Stephanie M. C. Wilson
University of Florida

Journal of Strength and Conditioning Research Publish Ahead of Print
DOI: 10.1519/JSC.0b013e31823a3e2d

Running head: CONCURRENT TRAINING

Concurrent Training: A Meta Analysis Examining Interference of Aerobic and Resistance Exercise

Jacob M. Wilson Ph.D., CSCS,*D[1]

Pedro J. Marin, Ph.D.[2,3]

Matthew R. Rhea, Ph.D.[4]

Stephanie M.C. Wilson, M.S., R.D., L.D.N. [1, 5]

Jeremy, P., Loenneke, M.S. [6]

Jody C. Anderson, Ph.D., ATC, PT, SCS[1]

[1]The University of Tampa, Department of Health Sciences and Human Performance, Tampa, FL

[2]Laboratory of Physiology, European University Miguel de Cervantes, Valladolid, Spain.

[3] Research Center on Physical Disability, ASPAYM Castilla y León, Valladolid Spain.

[4]Human Movement Program, A. T. Still University, Mesa, AZ

[5] St. Joseph's Hospital, Tampa, FL

[6] Department of Health and Exercise Science. The University of Oklahoma, Norman, Oklahoma, USA.

*Corresponding author: Dr. Jacob M. Wilson

Contact Number: (813) 257-6314

Email: jmwilson@ut.edu

ABSTRACT: The primary objective of this investigation was to identify which components of endurance training (e.g. modality, duration, frequency) are detrimental to resistance training outcomes. Methods: A meta-analysis of 21 studies was performed with a total of 422 effect sizes. Criteria for study inclusion were (a) compare strength training alone to strength plus endurance training (concurrent), or to compare combinations of concurrent training, (b) the outcome measures include at least one measure of strength, power, or hypertrophy and (c) the data necessary to calculate effect sizes must be included or available. Results: The mean ES for hypertrophy for strength training was 1.23, for endurance training was 0.27, and for concurrent training was 0.85, with strength and concurrent training being significantly greater than endurance training only. The mean ES for strength development for strength training was 1.76, for endurance training was 0.78, and for concurrent training 1.44. Strength and concurrent training were significantly greater than endurance. The mean ES for power development for strength training only was 0.91, for endurance training was 0.11, and for concurrent training 0.55. Significant differences were found between all three groups. For moderator variables, resistance training concurrently with running, but not cycling, resulted in significant decrements in both hypertrophy and strength. Correlational analysis identified significant negative relationships between frequency (-.26 to -.35) and duration (-.29 to -.75) of endurance training for hypertrophy, strength, and power. Significant relationships (*P*< 0.05) between ES for decreased body fat and % maximal heart rate (*r*: -0.60) were also found. Our results indicate that interference effects of endurance training are a factor of the modality, frequency, and duration of the endurance training selected.

Key Words: Concurrent training; Strength training; endurance training; exercise; power; hypertrophy; VO2max; resistance training

INTRODUCTION

Several sports require the need for endurance, power, muscular size and strength. For example, in a single hockey game an athlete may be required to sprint past their opponent for a lose puck (explosive power), deliver a hard body check (strength and muscularity), and kill two power plays in overtime (endurance). The inclusion of resistance training (to gain strength, hypertrophy and power) combined with aerobic exercise (to enhance endurance) in a single program is known as concurrent training. Generally, concurrent training studies have 3 groups: one with exclusive resistance training, one with endurance training only, and the last performing both resistance training and endurance training in the same program. Concurrent training, relative to resistance training alone, has been shown to result in decrements in strength (13, 21, 25, 29), hypertrophy (25, 29, 39) and power (21, 24, 26, 29, 31). However, additional studies have found little to no decrements in strength training gains with the addition of endurance training (4, 38, 39, 48, 49). Moreover, recent data has demonstrated large inter-individual variation in responses to changes in maximal voluntary contraction following concurrent training (-12% to 87%). These data indicate that some individuals experience strength decrements following concurrent training, while others experience substantial gains (27).

Several explanations have been offered to explain the concurrent training or interference effects seen. One of the more popular theories is the chronic interference hypothesis, which postulates that the addition of endurance training results in overreaching/overtraining as well as stimulates competing adaptations over a long-term training program (33). Overreaching is currently thought to be caused by high volume, high intensity, or high frequency training bouts (22), particularly when bouts of exercise result in large amounts of skeletal muscle damage (22). It is likely that elements of endurance training, which exacerbate overreaching, would in theory result in greater interference effects.

As far as competing adaptations are concerned, traditional resistance exercise trains skeletal muscle in short duration activities in which force is maximal or at least near maximal levels. In contrast, endurance training requires individuals to exert relatively low force outputs and maintain those outputs over long durations. Logically the adaptations for resistance and endurance exercise are vastly different and in many cases conflict with one another (23, 33). From a molecular standpoint, endurance exercise preferentially increases net protein synthesis in the mitochondrial subfraction, while high intensity resistance training preferentially increases net protein synthesis in the myofibrillar subfraction (9, 23, 50). Moreover, with training experience these changes become increasingly more specific over time (50). When combined, however, research indicates that the up regulation of translation initiation via the PI3K-AKT-mTOR signalling pathway is impaired when resistance training is performed following glycogen depleting endurance exercise (12, 23). Moreover, while resistance training increases myofibrillar protein synthesis for up to 72 hours following an intense training bout (12), moderate intensity endurance exercise immediately acts to inhibit important elongation factors (eef2) responsible for increasing protein synthesis and maintains this inhibition for the duration of the activity (45).

To date, very little research has been conducted to disseminate which components of endurance (e.g. modality, intensity, duration) training are most detrimental to resistance training outcomes, and still further which outcomes (e.g. strength, hypertrophy, power) are affected to the greatest extent. A robust and quantitative approach to the problem can be provided in the form of a meta-analysis of the data. This technique minimizes subjectivity by standardizing treatment effects of relevant studies into effect sizes, pooling the data, and then analyzing it to draw conclusions (41). The primary objective of this investigation was to quantitatively identify which components of endurance exercise result in detrimental effects on resistance training outcomes.

METHODS

Experimental Approach to the Problem

To evaluate what components of endurance exercise result in detrimental effects on resistance training, a meta-analytic review was conducted. Relevant studies were combined and analyzed statistically to provide an overview of the body of research on this topic. Conclusions were based on the literature with suggestions for applications and future research for strength and conditioning professionals.

Literature search

Searches were performed for published studies with a number of criteria.

First, the primary focus of the study must have compared the effects of strength training alone to concurrent training on strength, power, and hypertrophy. However, if a study's primary objective was to compare two different concurrent training methods to each other then it was also included in our analysis. Finally to be considered for our analysis, studies' subject populations had to have similar baseline characteristics in strength and aerobic capacity (e.g. both untrained or trained) so that valid outcome measures could be made. Moreover the outcome measures had to include at least one measure or a combination of measures of strength, power, or hypertrophy. Strength variables included maximal exertion against an external resistance (both dynamic and static). Hypertrophy was accepted as whole muscle volume or thickness as indicated by MRI or ultrasound respectively, or changes in muscle fiber cross sectional area (type I and II). Finally power was fractionated into immediate (e.g. vertical jump, and peak power on a Wingate) and mean power output as recorded in a Wingate 30 second test. Electronic databases searched included Science Citation Index, National Library of Medicine, Sport Discus, Google Scholar, and MEDLINE were searched in February 2011 back to the earliest available time (1980) when Hickson et al. published a foundational study on concurrent training (25). Exclusion of studies with irrelevant content and doublets was carried out in three steps. First, the titles of the articles were read. Second, the abstracts were read. Third, the entire article was read. The reference lists of relevant articles were, in turn, scanned for additional articles (published or unpublished) that met the inclusion criteria. Attempts were made to contact authors requesting any unpublished work. Conference abstracts and proceedings were excluded. Relevant studies were selected and searched for data necessary to compute effect size and descriptive information regarding the training protocol.

Coding of studies.

Each study was read and coded by the primary investigator for descriptive information including gender, age and training experience. For both endurance and resistance training we coded for frequency, mean training intensity, volume (duration of endurance and sets of strength training), and type of training split utilized. For resistance training, frequency was coded by the number of days per week that participants trained their lower or upper bodies. Endurance training was coded as days per week aerobic exercise was performed. Intensity for resistance and endurance training was coded respectively as average percent of one repetition maximum (1 RM) used and average percent of heart rate reserve or VO2max used. Volume for resistance and endurance training respectively was coded as number of sets performed for upper and lower body, and average duration of the endurance training session. Training split was coded as strength only, endurance only, strength and endurance performed on the same day, and strength and endurance performed every other day. Training status was defined as untrained, trained, and athlete. Participants must have been training for at least 1 yr with weight lifting before the study in order to be considered as trained. In order to be considered for the athlete category, participants must have been competitive athletes at the collegiate or professional level.

Calculation and analysis of Effect Size

Pre- and post effect sizes (ES) were calculated with the following formula: [(Post test mean – pretest mean)/pretest standard deviation]. ES were then adjusted for sample size bias (41, 42). This adjustment consists of applying a correction factor to adjust for a positive bias in smaller sample sizes. Descriptive statistics were calculated and univariate analysis of variance by groups was used to identify differences between training status, gender, and age with level of significance set at $P < 0.05$. All calculations were made with SPSS statistical software package v.19.0 (SPSS Inc., Chicago, IL). The scale proposed by Rhea (41, 42) was used for interpretation of effect size magnitude. Coder drift was assessed by randomly selecting 10 studies for recoding. Per case agreement was determined by dividing the variables coded the same by the total number of variables (41, 42). A mean agreement of 0.90 was required for acceptance.

RESULTS

Overall ES and moderating variables are presented in Table 1, Table 2, Table 3, Table 4, and Table 5. The 72 ES for lower-body muscle hypertrophy, 24 ES for upper-body muscle hypertrophy, 75 ES for lower-body strength development, 24 ES for upper-body strength development, 46 ES for lower-body power development, 46 ES for VO_2 max, and 43 ES for body fat were obtained from a total of 21 primary studies(3, 4, 7, 10, 11, 13, 18, 20, 24-26, 29, 30, 32, 38-40, 46-49).

Muscle hypertrophy

The mean overall ES for muscle hypertrophy for strength training was 1.23 [95% CI: 0.92, 1.53; n: 23], for endurance training was 0.27 [95% CI: -0.53, 0.60; n: 20], and for concurrent training 0.85 [95% CI: 0.57, 1.2; n: 29] (Figure 1 and Table 1). Significant differences were found between strength and endurance ($P < 0.05$), as well as between endurance and concurrent ($P < 0.05$).

Insert Table 1 and Figure 1 here.

Moderating Variables. An analysis of the differences in hypertrophy gains achieved for endurance training in male and combined gender groups from all included studies were performed to determine whether gender influenced strength gains. The combined group gained more hypertrophy than the male group 0.72 [95% CI: 0.44, 0.99; n: 9] vs. 0.12 [95% CI: -0.11, 0.36; n:11] ($P < 0.05$), respectively (Table 1). Significant difference was found between concurrent training with running endurance modality and strength training alone (without any endurance workout) 0.68 [95% CI: 0.31, 1.06; n: 16] vs. 1.54 [95% CI: 1.10, 1.97; n: 12] ($P < 0.05$), respectively (Figure 2). However, no significant differences were found between training groups for upper body; the mean overall ES for muscle hypertrophy strength training was 0.16 [95% CI: -0.03, 0.36; n: 8], for endurance training was 0.02 [95% CI: -1.71, 0.22; n: 8], and for concurrent training was 0.14 [95% CI: -0.06, 0.33; n: 8], ($P > 0.05$). Training split performing endurance and strength training on the same day resulted in an effect size for hypertrophy of 0.8, while performing them on separate days resulted in an ES of 1.06. However, these were not significantly different.

Insert Figure 2 here

Correlational analysis identified significant relationships ($P< 0.05$) between ES for lower body hypertrophy and frequency of endurance training (r: -0.26) (Figure 3) and average duration of endurance workout (r: -0.75) (Figure 4). Insufficient data were obtained for an analysis of other variables (minimum 5 ES).

Strength development

The mean overall ES for strength development for strength training was 1.76 [95% CI: 1.34, 2.18; n: 24], for endurance training was 0.78 [95% CI: 0.36, 1.19; n: 25], and for concurrent training 1.44 [95% CI: 1.03, 1.84; n: 26] (Figure 1 and Table 2). Significant differences were found between strength and endurance ($P < 0.05$), as well as between endurance and concurrent ($P < 0.05$), for lower body (Figure 1 and Table 2). However, no significant differences were found between training groups for upper body; the mean overall ES for strength development for strength training was 3.17 [95% CI: 0.88, 5.45; n: 8], for endurance training was 0.39 [95% CI: -1.89, 2.68; n: 8], and for concurrent training was 1.97 [95% CI: -0.32, 4.25; n: 8], ($P > 0.05$).

Insert Table 2 here

Moderating Variables. No significant difference was found between variables including training split (Table 2). However, a significant difference was found between ES of concurrent training with running endurance modality and strength training alone (without any endurance workout) 1.23 [95% CI: 0.81, 1.65; n: 9] vs. 2.22 [95% CI: 1.70, 2.74; n: 14] ($P < 0.05$), respectively (Figure 2). Correlational analysis identified significant relationships ($P < 0.05$) between ES for lower body strength and frequency of endurance training (*r*: -0.31) (Figure 3) and average duration of endurance workout (r: -0.34) (Figure 4). Insufficient data were obtained for an analysis of other variables.

Insert Figures 3 and 4 here

Power development

There were not enough data to compare the effects of concurrent training on immediate and mean power. Therefore we pooled this data. The mean overall ES for power development of the lower body (Figure 1 and Table 3) for strength training only was 0.91 [95% CI: 0.65, 1.30; n: 15], for endurance training was 0.11 [95% CI: -0.15, 0.38; n: 14], and for concurrent training 0.55 [95% CI: 0.31, 0.79; n: 17]. Significant differences for lower body (Figure 1 and Table 3) were found between strength, endurance, and concurrent training ($P < 0.05$). Insufficient data were obtained for an analysis of upper body.

Insert Table 3 here

Moderating Variables. No significant difference was found between moderating variables (Table 3). Correlational analysis identified significant relationships ($P < 0.05$) between effect sizes for power development and frequency of endurance training (*r*: -0.35) (Figure 3) and average duration of endurance workout (*r*: -0.29) (Figure 4). Insufficient data were obtained for an analysis of other variables.

Maximal oxygen uptake (VO_2 max)

The mean overall ES for VO_2 max for strength training was -0.11 [95% CI: -0.62, 0.41; n: 15], for endurance training was 1.37 [95% CI: 0.85, 1.88; n: 15], and for concurrent training 1.41 [95% CI: 0.91, 1.91; n: 16] (Figure 1 and Table 4). Significant differences were found between strength and endurance ($P < 0.05$), as well as between strength and concurrent ($P < 0.05$).

Insert Table 4 here

Moderating Variables. No significant differences were found for any moderating variables analyzed (Table 4).

Body Fat

The mean overall ES for changes in body fat mass for strength training was -0.62 [95% CI: -0.99, -0.25; n: 14], for endurance training was -0.75 [95% CI: -1.12, -0.37; n: 14], and for concurrent training -0.95 [95% CI: -1.30, -0.58; n: 15] (Figure 1 and Table 5). No significant differences were found between strength, endurance, and concurrent training ($P > 0.05$) (Figure 1 and Table 5).

Insert Table 5 here

Moderating Variables. No significant difference was found between variables (Table 5). Correlational analysis identified significant relationships ($P < 0.05$) between ES for decrease body fat and percent of maximal heart rate (r: 0.60) (Figure 5). Insufficient data were obtained for an analysis of other variables.

Insert Figure 5 here

DISCUSSION

Skeletal muscle demonstrates remarkable plasticity to various loading patterns and it is becoming increasingly evident that muscle tissue can distinguish between specific signals imposed by variations in the duration, modality, and type of exercise. Endurance athletes demonstrate an increase in mitochondrial density (35), and no change or a small selective hypertrophy of type I fibers, with maintenance or a decrease in type II fiber size (15). Elite weight lifters and power lifters train at relatively high percentages of their 1-repetition maximums, express preferential hypertrophy of type II fibers (17), and have a decrease in mitochondrial density relative to the general population (34).

The unique and relatively distinct adaptations of endurance training, coupled together with an increase in total training volume, and therefore probability to overreach, result in a classic interference effect between endurance and strength training adaptations. If indeed overtraining/overreaching and/or competing adaptations explain interference effects of endurance training, then it may be that specific components of endurance training are primarily responsible for the interference effects seen. The primary findings of this meta-analysis are that endurance training modality is a determinant influencing interference. Moreover interference effects are primarily body part specific as decrements were found in lower, but not upper body exercise, following what is primarily lower body dominated endurance exercise activity. We also found that training volume accounted for a small portion of the interference effects seen when concurrent training. Finally, a common benefit of concurrent training is the loss of body fat. This analysis indicated that when concurrently training, body fat declines to the greatest extent with high intensity endurance exercise.

Overall Outcome Variables Assessed

The primary outcome variables assessed in our analysis were hypertrophy, maximal strength, power, and VO_2max. Overall, the effect sizes for hypertrophy and maximal strength were not significantly different between strength and concurrent training groups. In contrast, power was significantly lower in the concurrent training group (.55) than the strength only group (.91). These findings suggest that overall power may be more susceptible to decrements than strength or hypertrophy. While past research on strength outcomes is conflicting, it appears that force at high velocities is affected more than force at low velocities (14). Thus, it could be speculated that decrements in power result from either impairments in velocity or rate of force development (21). Another important finding of our study was that concurrent training relative to endurance only training resulted in no decrements in VO2max, indicating that aerobic capacity is not inhibited when concurrent training relative to endurance training alone. While our subjects were primarily recreationally and strength trained, Aagard and Anderson (1) recently provided strong evidence in elite endurance athletes that strength training can lead to enhanced long-term (>30 min) and short-term (<15 min) endurance capacity. These researchers concluded that strength training may augment endurance performance by increases in the proportion of type IIA muscle fibers, as well as gains in maximal muscle strength and rate of force development, while likely involving enhancements in neuromuscular function.

Endurance Modality

When separating our analysis into concurrent running vs. cycling we found that strength training concurrently with running, but not cycling, resulted in significant decrements in both hypertrophy and strength. There are at least two possible reasons why runners are more susceptible to decrements than those who cycle. The first is that cycling is more biomechanically similar to the majority of measures of strength taken in the studies reviewed (compound free weights) (16, 19, 36). A second possibility concerns skeletal muscle damage. While we cannot suggest this from our analysis, it could be speculated that different types of contractions influence the differences seen between running and cycling. Running has a high eccentric component, while cycling consists of primarily concentric activity. These differences in contraction types (eccentric vs. concentric) may create greater damage in running than cycling. For example long distance running causes large increases in muscle damage while ultra-distance cycling (230 km) does not (28). However, future studies need to address contraction types before we can definitively attribute differences to this potential moderating variable. While not significantly different, it is intriguing to recognize that running, however, resulted in a larger decline in fat mass (-.8 more fat loss) than cycling. Moreover, we found that no decrements were found in upper body strength, power, or hypertrophy. These data indicate that the interference effects of endurance training with strength training outcomes are body part specific and not systemic, as primarily lower body modalities did not interfere with upper body strength training outcomes. This could be a function of the lower body endurance modality employed and it could be speculated that performing upper body endurance exercise would interfere with upper body strength training outcomes. To date, only a handful of studies have compared concurrent training, which utilized the upper body to an appreciable amount during the endurance bout. In two studies (5, 6), Bell found that rowers who added resistance training to their normal schedule increased upper body strength to the same extent as a group of non-rowers who only performed resistance training. Moreover, Abernethy (2) found that arm ergometer exercise did not interfere with arm extension strength. However, all three of these studies did not meet the criteria of our current analysis as each compared strength and concurrent groups which differed in their baseline aerobic training background (5, 6) or measured aerobic capacity (2).

Volume of Exercise

Volume is typically defined as the total amount of work done during a given exercise session. For endurance exercise this is at least partly dependent on the duration and frequency of training. We found primarily low (r= -.26 to -.35) to moderate (r= -.75) significant negative correlations for frequency and duration of endurance exercise for hypertrophy, strength, and power outcomes. As indicated by the theoretical Venn diagram in Figure 6, commonality between long duration endurance and resistance exercise may be low. However, commonality between short duration high intensity sprinting with resistance exercise may be high. As an explanation, the neuromuscular system is required to exert their lowest forces over long sustained periods of time, which likely results in adaptations with the lowest possible commonality to strength training. These results coincide with past research from Balabinis et al. (4) who found that shorter duration, high intensity sprinting exercise did not result in decrements in strength or power, and significantly increased VO2max in college level basketball players. More recently, Rhea et al. (43) found that short duration sprinting in NCAA baseball players resulted in greater increases in power than low intensity long duration exercise. It is also possible that greater total volumes of endurance training lead to a greater susceptibility for overreaching and/or under recovery. One limitation of our study is that we did not specifically analyze total frequency of muscle groups trained (endurance + strength).

Changes in Fat Mass

Perhaps the most intriguing finding of this study was that body fatness decreased with increasing endurance training intensities (Figure 5). In fact, the most dramatic loss in fat mass occurred from moderately high to very high intensities. These results seem paradoxical; research on the acute response of endurance exercise has found that maximal total fat calories are metabolized at moderate intensity endurance exercise (44). However, maximizing intensities, which are ideal for fat metabolism during an exercise, may not be ideal for maximizing fat metabolism in the long term. Research indicates that increases in metabolic rate following exercise increases exponentially with increasing intensity (8). Moreover, while traditional endurance exercise may decrease muscle mass relative to strength training alone, very high intensity exercise does not appear to have this effect (4). Finally, research comparing very high intensity to low intensity exercise demonstrates that the former results in greater increases in the activity of muscle 3-hydroxyacycl coenzyme A dehydrogenase, an enzyme critical to the rate of beta oxidation (51).

PRACTICAL APPLICATIONS

Our research suggests that overall power is the major variable, which is affected by concurrent training. Therefore athletes whose sport requires maximal power or rate of force development should limit concurrently training for strength and endurance. However, if an athlete's sport is primarily dependent on maximal strength and hypertrophy, then concurrent training may not lead to significant decrements, given the proper modality of endurance training is selected. Specifically, our research suggests that athletes seeking to concurrently train in order to obtain simultaneous increases in muscle hypertrophy, strength, and endurance, should select a modality of endurance exercise that closely mimics their sport to avoid the occurrence of competing adaptations. For example, a hockey player wanting to increase leg strength during dry ice training may want to avoid running and instead select a cycling exercise, which more closely approximates the demands of skating (37). In addition athletes should avoid long duration endurance exercise (>20-30 min) that is performed with a high frequency (> 3 days per week). Instead, athletes whose sport requires strength and power should select endurance activity that is performed at very high intensities, as this will result in lower decrements in hypertrophy, strength, and power. For individuals who are seeking to gain only small to moderate amounts of muscle and strength, while losing large amounts of body fat, it may be advantageous to select running as their modality of exercise as this resulted in the largest effect size declines in fat mass, with smaller increases in hypertrophy and strength. However, these individuals should still include higher intensity exercise during their program, as this appears to result in the greatest declines in fat mass when combined chronically with resistance exercise. Finally, our data suggests that coaches can incorporate strength training for individuals attempting to primarily increase endurance performance without a fear of interfering with their aerobic capacity.

REFERENCES

1. Aagaard P and Andersen JL. Effects of strength training on endurance capacity in top-level endurance athletes. *Scand J Med Sci Sports* 20 Suppl 2: 39-47, 2010.
2. Abernethy P and Quigley B. Concurrent strength and endurance training of the elbow extensors. *J Strength Cond Res* 7: 234-240, 1993.

3. Ahtiainen JP, Hulmi JJ, Kraemer WJ, Lehti M, Pakarinen A, Mero AA, Karavirta L, Sillanpaa E, Selanne H, Alen M, Komulainen J, Kovanen V, Nyman K, and Hakkinen K. Strength, endurance or combined training elicit diverse skeletal muscle myosin heavy chain isoform proportion but unaltered androgen receptor concentration in men. *Int J Sports Med* 30: 879-887, 2009.
4. Balabinis CP, Psarakis CH, Moukas M, Vassiliou MP, and Behrakis PK. Early phase changes by concurrent endurance and strength training. *J Strength Cond Res* 17: 393-401, 2003.
5. Bell G, Syrotuik D, Socha T, and Effect of strength training and concurrent strength and endurance training on strength, testosterone, and cortisol. *J Strength Cond Res* 11: 57-64, 1997.
6. Bell GJ, Petersen SR, Wessel J, Bagnall K, and Quinney HA. Physiological adaptations to concurrent endurance training and low velocity resistance training. *Int J Sports Med* 12: 384-390, 1991.
7. Bell GJ, Syrotuik D, Martin TP, Burnham R, and Quinney HA. Effect of concurrent strength and endurance training on skeletal muscle properties and hormone concentrations in humans. *Eur J Appl Physiol* 81: 418-427, 2000.
8. Borsheim E and Bahr R. Effect of exercise intensity, duration and mode on post-exercise oxygen consumption. *Sports Med* 33: 1037-1060, 2003.
9. Burd NA, Tang JE, Moore DR, and Phillips SM. Exercise Training and Protein Metabolism: Influences of Contraction, Protein Intake, and Sex-based differences. *J Appl Physiol* 106: 1692-1701, 2009.
10. Chtara M, Chaouachi A, Levin GT, Chaouachi M, Chamari K, Amri M, and Laursen PB. Effect of concurrent endurance and circuit resistance training sequence on muscular strength and power development. *J Strength Cond Res* 22: 1037-1045, 2008.
11. Craig B, Lucas J, and Pohlman R. Effects of running, weightlifting and a combination of both on growth hormone release. . *J Appl Sport Sci Res* 5: 198-203, 1991.
12. Creer A, Gallagher P, Slivka D, Jemiolo B, Fink W, and Trappe S. Influence of muscle glycogen availability on ERK1/2 and Akt signaling after resistance exercise in human skeletal muscle. *J Appl Physiol* 99: 950-956, 2005.
13. Dolezal BA and Potteiger JA. Concurrent resistance and endurance training influence basal metabolic rate in nondieting individuals. *J Appl Physiol* 85: 695-700, 1998.
14. Dudley GA and Djamil R. Incompatibility of endurance- and strength-training modes of exercise. *J Appl Physiol* 59: 1446-1451, 1985.
15. Edstrom L and Ekblom B. Differences in sizes of red and white muscle fibres in vastus lateralis of musculus quadriceps femoris of normal individuals and athletes. Relation to physical performance. *Scand J Clin Lab Invest* 30: 175-181, 1972.
16. Escamilla RF. Knee biomechanics of the dynamic squat exercise. *Med Sci Sports Exerc* 33: 127-141, 2001.
17. Fry AC. The role of resistance exercise intensity on muscle fibre adaptations. *Sports Med* 34: 663-679, 2004.
18. Glowacki SP, Martin SE, Maurer A, Baek W, Green JS, and Crouse SF. Effects of resistance, endurance, and concurrent exercise on training outcomes in men. *Med Sci Sports Exerc* 36: 2119-2127, 2004.
19. Gregor RJ, Broker JP, and Ryan MM. The biomechanics of cycling. *Exerc Sport Sci Rev* 19: 127-169, 1991.
20. Hakkinen A, Hannonen P, Nyman K, Lyyski T, and Hakkinen K. Effects of concurrent strength and endurance training in women with early or longstanding rheumatoid arthritis: comparison with healthy subjects. *Arthritis Rheum* 49: 789-797, 2003.
21. Hakkinen K, Alen M, Kraemer WJ, Gorostiaga E, Izquierdo M, Rusko H, Mikkola J, Hakkinen A, Valkeinen H, Kaarakainen E, Romu S, Erola V, Ahtiainen J, and Paavolainen L. Neuromuscular

adaptations during concurrent strength and endurance training versus strength training. *Eur J Appl Physiol* 89: 42-52, 2003.
22. Halson SL and Jeukendrup AE. Does overtraining exist? An analysis of overreaching and overtraining research. *Sports Med* 34: 967-981, 2004.
23. Hawley JA. Molecular responses to strength and endurance training: are they incompatible? *Appl Physiol Nutr Metab* 34: 355-361, 2009.
24. Hennessy L and Watson A. The interference effects of training for strength and endurance simultaneously. *J Strength Cond Res* 12: 9-12, 1994.
25. Hickson RC. Interference of strength development by simultaneously training for strength and endurance. *Eur J Appl Physiol Occup Physiol* 45: 255-263, 1980.
26. Hunter G, Demment R, and Miller D. Development of strength and maximum oxygen uptake during simultaneous training for strength and endurance. *J Sports Med Phys Fitness* 27: 269-275, 1987.
27. Karavirta L, Hakkinen K, Kauhanen A, Arija-Blazquez A, Sillanpaa E, Rinkinen N, and Hakkinen A. Individual responses to combined endurance and strength training in older adults. *Med Sci Sports Exerc* 43: 484-490, 2011.
28. Koller A, Mair J, Schobersberger W, Wohlfarter T, Haid C, Mayr M, Villiger B, Frey W, and Puschendorf B. Effects of prolonged strenuous endurance exercise on plasma myosin heavy chain fragments and other muscular proteins. Cycling vs running. *J Sports Med Phys Fitness* 38: 10-17, 1998.
29. Kraemer W, Patton J, Gordon S, Harman E, Deschenes M, Reynolds K, Newton R, Triplett N, and Dziados J. Compatibility of high-intensity strength and endurance training on hormonal and skeletal muscle adaptations. *J Appl Physiol* 78: 976-989, 1995.
30. Kraemer WJ, Vescovi JD, Volek JS, Nindl BC, Newton RU, Patton JF, Dziados JE, French DN, and Hakkinen K. Effects of concurrent resistance and aerobic training on load-bearing performance and the Army physical fitness test. *Mil Med* 169: 994-999, 2004.
31. Leveritt M and Abernethy P. Acute effects of high-intensity endurance exercise on subsequent resistance activity. *J Strength Cond Res* 13: 47-51, 1999.
32. Leveritt M, Abernethy PJ, Barry B, and Logan PA. Concurrent strength and endurance training: the influence of dependent variable selection. *J Strength Cond Res* 17: 503-508, 2003.
33. Leveritt M, Abernethy PJ, Barry BK, and Logan PA. Concurrent strength and endurance training. A review. *Sports Med* 28: 413-427, 1999.
34. MacDougall JD, Sale DG, Moroz JR, Elder GC, Sutton JR, and Howald H. Mitochondrial volume density in human skeletal muscle following heavy resistance training. *Med Sci Sports Exerc* 11: 164-166, 1979.
35. MacLean DA, Graham TE, and Saltin B. Branched-chain amino acids augment ammonia metabolism while attenuating protein breakdown during exercise. *Am J Physiol* 267: E1010-1022, 1994.
36. Mann RA and Hagy J. Biomechanics of walking, running, and sprinting. *Am J Sports Med* 8: 345-350, 1980.
37. Martinez ML, Ibanez Santos J, Grijalba A, Santesteban MD, and Gorostiaga EM. Physiological comparison of roller skating, treadmill running and ergometer cycling. *Int J Sports Med* 14: 72-77, 1993.
38. McCarthy JP, Agre JC, Graf BK, Pozniak MA, and Vailas AC. Compatibility of adaptive responses with combining strength and endurance training. *Med Sci Sports Exerc* 27: 429-436, 1995.
39. McCarthy JP, Pozniak MA, and Agre JC. Neuromuscular adaptations to concurrent strength and endurance training. *Med Sci Sports Exerc* 34: 511-519, 2002.

40. Nelson AG, Arnall DA, Loy SF, Silvester LJ, and Conlee RK. Consequences of combining strength and endurance training regimens. *Phys Ther* 70: 287-294, 1990.
41. Rhea MR. Determining the magnitude of treatment effects in strength training research through the use of the effect size. *J Strength Cond Res* 18: 918-920, 2004.
42. Rhea MR, Alvar BA, Burkett LN, and Ball SD. A Meta-analysis to determine the dose response for strength development. *Med Sci Sports Exerc* 35: 456-464, 2003.
43. Rhea MR, Oliverson JR, Marshall G, Peterson MD, Kenn JG, and Ayllon FN. Noncompatibility of power and endurance training among college baseball players. *J Strength Cond Res* 22: 230-234, 2008.
44. Romijn JA, Coyle EF, Sidossis LS, Gastaldelli A, Horowitz JF, Endert E, and Wolfe RR. Regulation of endogenous fat and carbohydrate metabolism in relation to exercise intensity and duration. *Am J Physiol* 265: E380-391, 1993.
45. Rose AJ, Broholm C, Kiillerich K, Finn SG, Proud CG, Rider MH, Richter EA, and Kiens B. Exercise rapidly increases eukaryotic elongation factor 2 phosphorylation in skeletal muscle of men. *J Physiol* 569: 223-228, 2005.
46. Sale DG, Jacobs I, MacDougall JD, and Garner S. Comparison of two regimens of concurrent strength and endurance training. *Med Sci Sports Exerc* 22: 348-356, 1990.
47. Sale DG, MacDougall JD, Jacobs I, and Garner S. Interaction between concurrent strength and endurance training. *J Appl Physiol* 68: 260-270, 1990.
48. Sillanpaa E, Hakkinen A, Nyman K, Mattila M, Cheng S, Karavirta L, Laaksonen DE, Huuhka N, Kraemer WJ, and Hakkinen K. Body composition and fitness during strength and/or endurance training in older men. *Med Sci Sports Exerc* 40: 950-958, 2008.
49. Sillanpaa E, Laaksonen DE, Hakkinen A, Karavirta L, Jensen B, Kraemer WJ, Nyman K, and Hakkinen K. Body composition, fitness, and metabolic health during strength and endurance training and their combination in middle-aged and older women. *Eur J Appl Physiol* 106: 285-296, 2009.
50. Tang JE, Perco JG, Moore DR, Wilkinson SB, and Phillips SM. Resistance training alters the response of fed state mixed muscle protein synthesis in young men. *Am J Physiol Regul Integr Comp Physiol* 294: R172-178, 2008.
51. Tremblay A, Simoneau JA, and Bouchard C. Impact of exercise intensity on body fatness and skeletal muscle metabolism. *Metabolism* 43: 814-818, 1994.

ACKNOWLEDGEMENTS:

This research received no funding from any organization or grants.

FIGURE LEGENDS

Figure 1. Overall effect sizes for strength, endurance, and concurrent training:

The mean overall ES (mean ± SE) for lower body strength, lower body hypertrophy, power, $V0_2$ max, and body fat.

*: Significant difference at $P < 0.05$ from strength training.

&: Significant difference at $P < 0.05$ from endurance training.

Figure 2. Overall effect sizes for running concurrent, cycling concurrent, and strength only training:

Mean ± SE for lower body strength, lower body hypertrophy, power, $V0_2$ max, and body fat of concurrent training and strength training alone (without any endurance workout).

* Significant difference at $P < 0.05$ from running concurrent group.

Figure 3. Dose-response effect size for frequency of endurance training

Figure 4. Dose-response effect size for average duration of endurance workout

Figure 5. Dose-response effect size of decrease in body fat for percent of maximal heart rate reserve for concurrent training

Figure 6. Competing long term adaptations:

Commonality of adaptations between strength training, long duration endurance exercise, and high volume sprint training

TABLE LEGENDS:

Table 1. Effect size for muscle hypertrophy:

Strength + Endurance same day: Strength training /endurance training performed on the same day

Strength + Endurance every other day: Strength training and endurance training were performed every other day.

Table 2. Effect size for strength development:

Strength + Endurance same day: Strength training /endurance training performed on the same day

Strength + Endurance every other day: Strength training and endurance training were performed every other day.

Table 3. Effect size for muscle power development:

Strength + Endurance same day: Strength training /endurance training performed on the same day

Strength + Endurance every other day: Strength training and endurance training were performed every other day.

Table 4. Effect size for VO_2 max:

Strength + Endurance same day: Strength training /endurance training performed on the same day

Strength + Endurance every other day: Strength training and endurance training were performed every other day.

Table 5. Effect size for body fat

Strength + Endurance same day: Strength training /endurance training performed on the same day

Strength + Endurance every other day: Strength training and endurance training were performed every other day.

Table 1. Effect size for muscle hypertrophy

	Strength Mean (95% CI)	N		Endurance Mean (95% CI)	N		Concurrent Mean (95% CI)	N	
Overall	1.23 (0.92, 1.53)	23		0.27 (-0.53, 0.60)	20		0.85 (0.57, 1.2)	29	
Moderators:									
Gender									
Male	1.12 (0.49, 1.75)	14	*P* >0.05	0.12 (-0.11, 0.36)	11	*P* < 0.05	0.81 (0.42, 1.20)	15	*P* >0.05
Female	I.D.			I.D.			I.D.		
Both	1.42 (0.67, 2.17)	9		0.72 (0.44, 0.99)	9		1.08 (0.52, 1,63)	14	
Age									
< 25 years	1.14 (0.48, 1.80)	13	*P* >0.05	0.28 (0.04, 0.52)	13		0.87 (0.41, 1.31)	18	*P* >0.05
25-50 years	1.70 (0.99, 2.41)	7		I.D.			1.11 (0.63, 1.59)	8	
>50 years	I.D.			I.D.			I.D.		
Training status									
Untrained	1.19 (0.59, 1.78	18		0.31 (0.08, 0.53)	15		0.94 (0.56, 1.38)	24	
Trained	I.D.			I.D.			I.D.		
Athletes	I.D.			I.D.			I.D.		
Split									
Only strength training	1.22 (0.73, 1,17)	23							
Only endurance training				0.32 (0.14, 0,50)	20				
Strength+Endurance (I)							0.80 (0,38, 1,22)	20	*P* >0.05
Strength+Endurance (II)							1.06 (0.59, 1,53	8	
Strength+Endurance (III)							I.D.		

I.D.: insufficient data (< 5 ESs)

Strength+Endurance (I)=3:Strength/endurance same day

Strength+Endurance (II)= 4 strength
/endEOD
Strength+Endurance (III)= 5strength endurance on same day half time, and half strength alone

Table 2. Effect size for strength development

	Strength Mean (95% CI)	N		Endurance Mean (95% CI)	N		Concurrent Mean (95% CI)	N	
Overall	1.76 (1.34, 2.18)	24		0.78 (0.36, 1.19)	25		1.44 (1.03, 1.84)	26	
Moderators:									
Gender									
Male	1.53 (0.96, 2.10)	18	*P* >0.05	0.79 (0.18, 1.33)	18	*P* >0.05	1.38 (0.72, 2.04)	18	*P*
Female	I.D.			I.D.			I.D.		
Both	2.15 (1.30, 3.00)	6		1.01 (0.14, 1.88)	7		1.82 (0.76, 2,88)	8	
Age									
< 25 years	1.68 (1.10, 2.26)	17	*P* >0.05	0.82 (0.29, 1.35)	20		1.63 (0.99, 2.28)	22	
25-50 years	2.58 (1.79, 3.46)	7		I.D.			I.D.		
>50 years	I.D.			I.D.			I.D.		
Training status									
Untrained	1.63 (1.11, 2.15	17	*P* >0.05	0.61 (-0.19, 1.26)	15	*P* >0.05	1.30 (0.64, 1.96)	17	*P*
Trained	2.12 (1.27, 2.97)	6		1.27 (0.39, 2.14)	7		2.13 (1.07, 3.19)	8	
Athletes	I.D.			I.D.			I.D.		
Split									
Only strength training	1.71 (1.23, 2,18)	24							
Only endurance training				0.83 (0.35, 1.31)	25				
Strength+Endurance (I)							1.28 (0,51, 2,06)	16	*P*
Strength+Endurance (II)							1.36 (0.45, 2,27)	8	
Strength+Endurance (III)							I.D.		

I.D.: insufficient data (< 5 ESs)

Strength+Endurance (I)=3:Strength/endurance same day

Strength+Endurance (II)= 4 strength /endEOD
Strength+Endurance (III)= 5strength endurance on same day half time, and half strength alone

Table 3. Effect size for muscle power development

	Strength		Endurance		Concurrent		
	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)	N	
Overall	0.91 (0.65, 0.13)	15	0.11 (-0.15, 0.38)	14	0.55 (0.31, 0.79)	17	
Moderators:							
Gender							
Male	0.87 (0.41, 1.33)	12	0.22 (0.10, 0.33)	11	0.43 (-0.81, 0.94)	18	
Female	I.D.		I.D.		I.D.		
Both	I.D.		I.D.		I.D.		
Age							
< 25 years	0.88 (0.39, 1.36)	17	I.D.		0.44 (-0.04, 0.93)	15	
25-50 years	I.D.		0.56 (0.23, 0.88)	13	I.D.		
>50 years	I.D.		I.D.		I.D.		
Training status							
Untrained	I.D.		I.D.		I.D.		
Trained	0.85 (0.29, 1.41)	7	0.05 (-0.09, 0.18)	7	0.56 (-0.19, 1.10)	5	
Athletes	I.D.		I.D.		I.D.		
Split							
Only strength training	0.96 (0.56, 1,36)	15					
Only endurance training			0.21 (0.11, 0.31)	14			
Strength+Endurance (I)					0.36 (-0,27, 0.98)	9	*P* >0.05
Strength+Endurance (II)					0.47 (-0.22, 1.16)	7	
Strength+Endurance (III)					I.D.		

I.D.: insufficient data (< 5 ESs)

Strength+Endurance (I)=3:Strength/endurance same day

Strength+Endurance (II)= 4 strength /endEOD
Strength+Endurance (III)= 5strength endurance on same day half time, and half strength alone

Table 4. Effect size for $V0_2max$

	Strength Mean (95% CI)	Strength N	Endurance Mean (95% CI)	Endurance N	Concurrent Mean (95% CI)	Concurrent N	
Overall	- 0.11 (- 0.62, 0.41)	15	1.37 (0.85, 1.88)	15	1.41 (0.91, 1.91)	16	
Moderators:							
Gender							
Male	-0.29 (-0.85, 0,26)	10	1.45 (0.57, 2,33)	10	1.94 (0.93, 2.95)	10	
Female	I.D.		I.D.		I.D.		*P* >0
Both	I.D.		I.D.		0.97 (-0.36, 2.31)	6	
Age							
< 25 years	-0.03 (-0.49, 0.48)	12	1.39 (0.69, 2,08	13	1.61 (0.73, 2.48)	14	
25-50 years	I.D.		I.D.		I.D.		
>50 years	I.D.		I.D.		I.D.		
Training status							
Untrained	0.00 (-0.62, 0.63)	8	1.36 (0.35, 2.36)	8	1.56 (0.49, 2.63)	9	
Trained	I.D.		I.D.		I.D.		
Athletes	I.D.		I.D.		I.D.		
Split							
Only strength training	-0.21 (-0.66, 0,24)	15					
Only endurance training			1.30 (0.60, 2.01)	15			
Strength+Endurance (I)					1.15 (0.16, 2.15)	11	
Strength+Endurance (II)					I.D.		
Strength+Endurance (III)					I.D.		

I.D.: insufficient data (< 5 ESs)

Strength+Endurance (I)=3:Strength/endurance same day
Strength+Endurance (II)= 4 strength /endEOD
Strength+Endurance (III)= 5strength endurance on same day half time, and half strength alone

Table 5. Effect size for body fat

	Strength		Endurance		Concurrent
	Mean (95% CI)	N	Mean (95% CI)	N	Mean (95% CI)
Overall	- 0.62 (-0.99, -0.25)	14	-0.75 (-1.12, -0.37)	14	-0.95 (-1.30, -0.58)
Moderators:					
Gender					
Male	-0.76 (-1.08, -0.46)	12	-0.68 (-0.99, -0.37)	12	-0.99 (-1.22, -0.77)
Female	I.D.		I.D.		I.D.
Both	I.D.		I.D.		I.D.
Age					
< 25 years	-0.50 (-0.84, -0.17)	9	-0.86 (-1.18, -0.55)	10	-1.18 (-1.42, -0.94)
25-50 years	I.D.		I.D.		I.D.
>50 years	I.D.		I.D.		I.D.
Training status					
Untrained	-0.38 (-0.71, -0.05)	9	-0.64 (-0.99, -0.28)	9	-0.65 (-0.91, -0.39)
Trained	I.D.		I.D.		I.D.
Athletes	I.D.		I.D.		I.D.
Split					
Only strength training	-0.74 (-1.02, -0,46)	14			
Only endurance training			-0.75 (-1.03, -0.47)	14	
Strength+Endurance (I)					-0.88 (-1,16, -0,61)
Strength+Endurance (II)					I.D.
Strength+Endurance (III)					I.D.

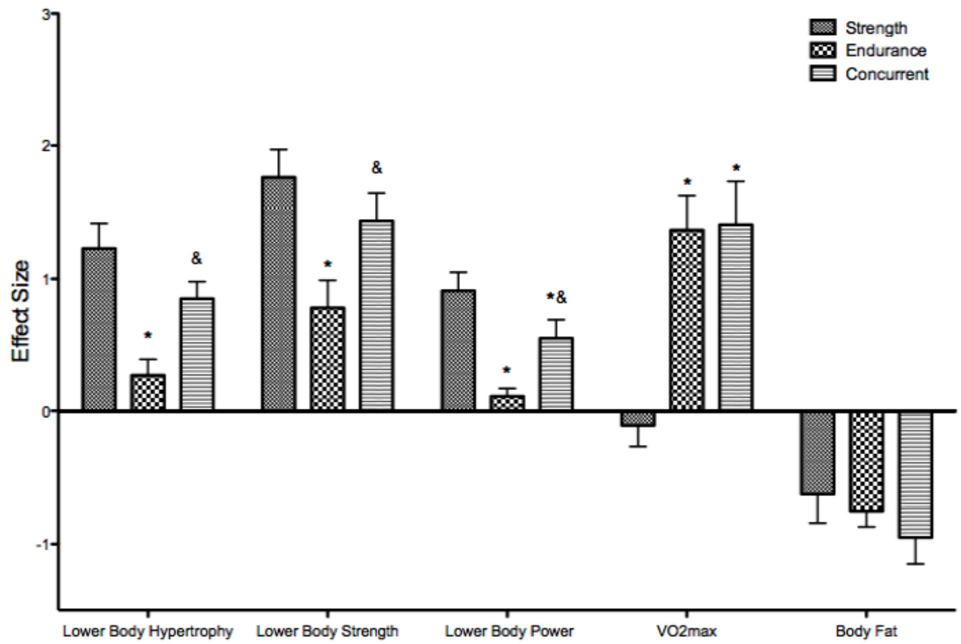
I.D.: insufficient data (< 5 ESs)

Strength+Endurance (I)=3:Strength/endurance same day
Strength+Endurance (II)= 4 strength /endEOD
Strength+Endurance (III)= 5strength endurance on same day half time, and half strength alone

FIGURES

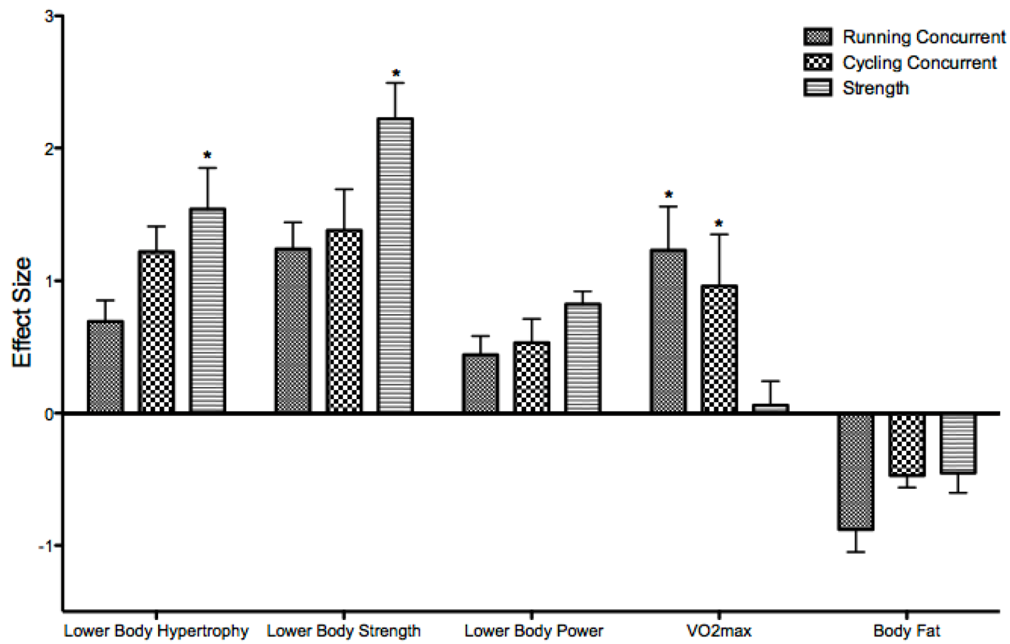
Concurrent Training: A Meta Analysis Examining Interference of Aerobic and Resistance Exercise

Figure 1



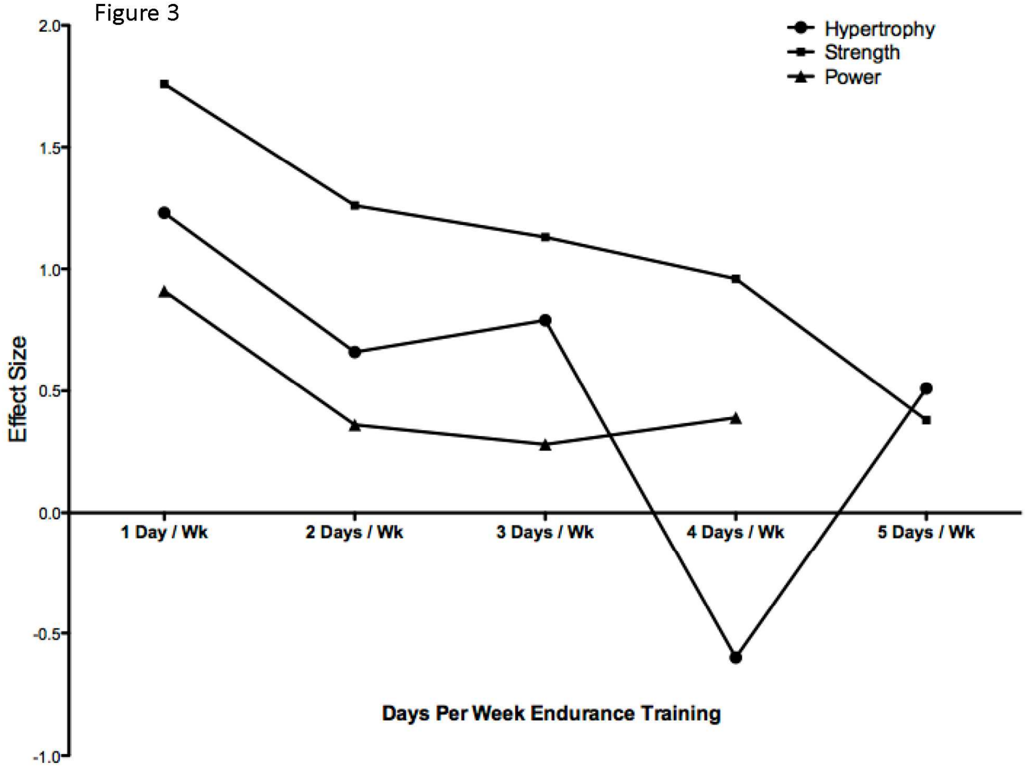
Strength
Endurance
Concurrent
Effect Size
3
2
1
0
-1
&
*
&
*
&
*
*&
*
*
Lower Body Hypertrophy
Lower Body Strength
Lower Body Power
VO2max
Body Fat

Figure 2



Running Concurrent
Cycling Concurrent
Strength
Effect Size
3
2
1
0
-1
*
*
*
*
Lower Body Hypertrophy
Lower Body Strength
Lower Body Power
VO2max
Body Fat

Figure 3



Hypertrophy
Strength
Power
Effect Size
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
1 Day / Wk
2 Days / Wk
3 Days / Wk
4 Days / Wk
5 Days / Wk
Days Per Week Endurance Training

Figure 4

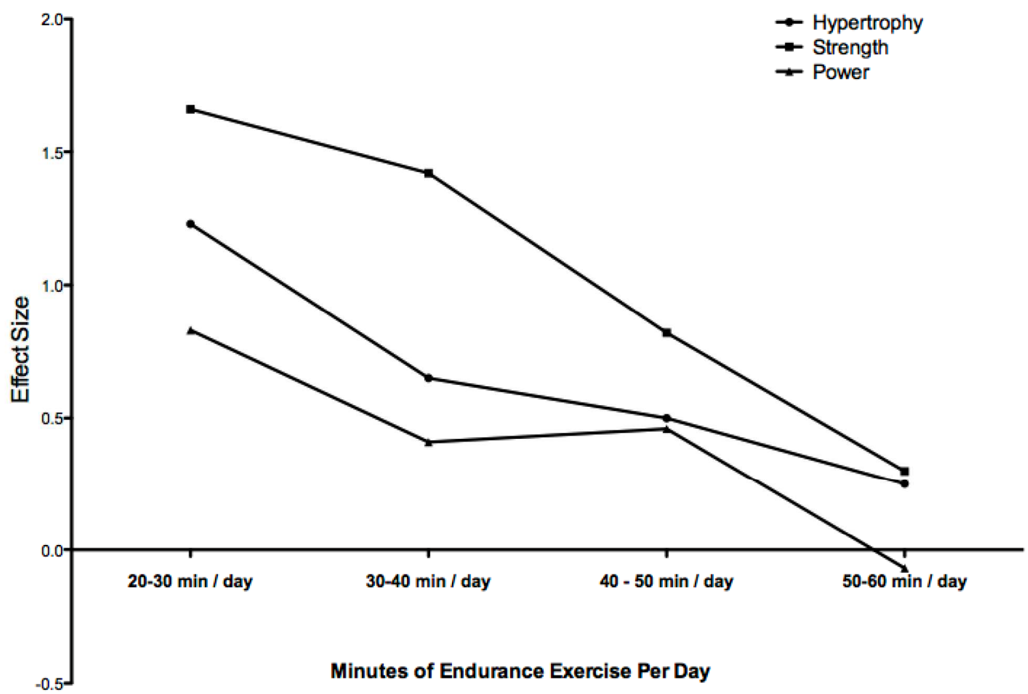
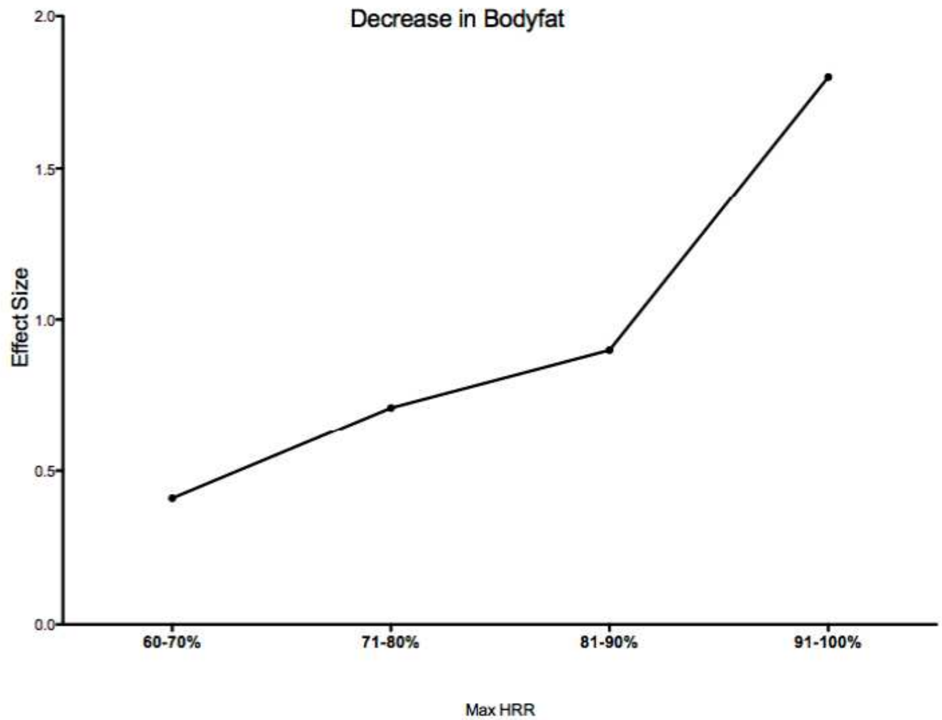

Hypertrophy
Strength
Power
2.0
1.5
1.0
0.5
0.0
-0.5
Effect Size
20-30 min / day
30-40 min / day
40 - 50 min / day
50-60 min / day
Minutes of Endurance Exercise Per Day

Figure 5



Decrease in Bodyfat
2.0
1.5
1.0
0.5
0.0
Effect Size
60-70%
71-80%
81-90%
91-100%
Max HRR

Competing Long Term Adaptations