Maximal strength, power, and aerobic endurance adaptations to concurrent strength and sprint interval training

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Received: 28 August 2013 / Accepted: 20 December 2013 © Springer-Verlag Berlin Heidelberg 2013

Abstract
Purpose This study was designed to examine whether concurrent sprint interval and strength training (ct) would result in compromised strength development when compared to strength training (St) alone. In addition, maximal oxygen consumption (VO₂ max) and time to exhaustion (TTE) were measured to determine if sprint interval training (SIt) would augment aerobic performance.

Methods Fourteen recreationally active men completed the study. ST (n = 7) was performed 2 days/week and CT (n = 7) was performed 4 days/week for 12 weeks. CT was separated by 24 h to reduce the influence of acute fatigue. Body composition was analyzed pre- and post-intervention. Anaerobic power, one-repetition maximum (1RM) lower- and upper-body strength, VO₂ max and TTE were analyzed pre-, mid-, and post-training. Training intensity for ST was set at 85 % 1RM and SIT trained using a modified Wingate protocol, adjusted to 20 s.

Results Upper- and lower-body strength improved significantly after training (p < 0.001) with no difference between the groups (p > 0.05). VO₂ max increased 40.9 ± 8.4 to 42.3 ± 7.1 ml/kg/min (p < 0.05) for CT, whereas ST remained unchanged. A significant difference in VO₂ max (p < 0.05) was observed between groups post-intervention (CT: 42.3 ± 7.1 vs. ST: 36.0 ± 3.0 ml/kg/min). A main effect for time and group was observed in TTE (p < 0.05). A significant main effect for time was observed in average power (p < 0.05).

Conclusion Preliminary findings suggest that performing concurrent sprint interval and strength training does not attenuate the strength response when compared to ST alone, while also improves aerobic performance measures, such as VO₂ max at the same time.

Keywords Wingate training · High-intensity endurance training · Back squat · Bench press · Interference effect

Abbreviations
1RM One-repetition maximum
ANOVA Analysis of variance
BP Bench press
BPM Beats per minute
BS Back squat
CT Concurrent training
DEXA Dual energy X-ray absorptiometry
ES Effect size
GXT Graded exercise test
ml/kg/min Milliliters per kilogram per minute
RPM Revolutions per minute
SIT Sprint interval training
ST Strength training
TTE Time to exhaustion
VO₂ max Maximal oxygen consumption
W Watts

Introduction
Coaches and practitioners often implement simultaneous strength and endurance training protocols in an attempt to...
optimize peak performance or recovery in a timely manner. However, exercise results in distinct adaptive responses, which are influenced by the nature of exercise performed, the specific energy systems, and the signaling pathways associated with these energy systems. Specifically, strength training has been shown to improve performance markers such as force production (Ahtiainen et al. 2003), muscular power (Iñigo et al. 2011), and lean muscle mass (Ahtiainen et al. 2003) with concomitant reductions in the density of mitochondria (MacDougall et al. 1979) and capillaries (Sale et al. 1990). Such reductions in mitochondrial and capillary density are detrimental in optimizing endurance performance. In contrast to strength training, endurance exercise results in an increase in mitochondrial protein content (Holloszy 1967), an increase in respiratory enzyme activity (Burgomaster et al. 2008; Holloszy 1967; MacDougall et al. 1998), and an increase in maximum rate of oxygen consumption (VO2max) (Hickson et al. 1977). Furthermore, endurance training has been shown to increase the percentage of type I fibers (i.e., slow twitch) and decrease the area of type IIa muscle fibers (i.e., fast twitch oxidative) (Staron et al. 1984) when compared to strength training alone. When considering specific adaptations of endurance or strength training alone, it appears the integration of both modalities would result in potential combative adaptations.

The concomitant utilization of aerobic and anaerobic energy systems within the same defined training period is commonly referred to as concurrent training, and has become a popular training strategy in both athletic and general fitness populations. Concurrent training has been shown to improve performance variables such as one-repetition maximum strength (Hennessy and Watson 1994) and VO2max (Hickson 1980). Yet, when compared to strength training alone, the majority of concurrent training research has demonstrated compromised maximal strength (Hickson 1980), power (Izquierdo et al. 2005), peak torque (Glowacki et al. 2004), and rate of force development (Hakkinen et al. 2003; Mikkola et al. 2012) with little or no impairments in cardiovascular performance, such as VO2max (Hickson 1980). However, others have provided contradicting outcomes on strength performance, making it difficult to specify the mechanisms associated with attenuated strength development (Davis et al. 2008; Hakkinen et al. 2003; Nelson et al. 1990). In addition, many concurrent training studies (Glowacki et al. 2004; Hakkinen et al. 2003; Hickson 1980; Mikkola et al. 2012) have implemented protocols of strength and endurance components with the same time commitment, resulting in approximately double the training time of either modality alone. This substantial increase in training volume in concurrent training groups has been postulated to promote a state of overtraining (Nader 2006). Overtraining is characterized as a state in which high levels of training volume and/or intensity is coupled with inadequate recovery resulting in sub-optimal adaptations (Kreider et al. 1998). This imbalance in training volume and/or intensity to rest is considered one mechanism of interference associated with concurrent training.

Concurrent training is a popular and growing trend in the exercising community, and a necessity in many sports. Therefore, by developing a better understanding of the interference associated with strength development, concurrent training programs can be designed in a more effective manner to control for the mechanisms that may otherwise present interference. To date, the majority of literature investigating concurrent training has implemented continuous or continuous and interval endurance training protocols alongside strength training. This is of interest considering that ample evidence demonstrates that high-intensity endurance exercise, specifically sprint interval training (SIT), results in similar adaptations as low-intensity, high-volume endurance training (Burgomaster et al. 2008; Gibala et al. 2006; Hazell et al. 2010; MacDougall et al. 1998; Rodas et al. 2000). One study in particular demonstrated significant improvements in peak oxygen uptake, at a substantially less training volume (Burgomaster et al. 2008). In fact, the weekly training volume for SIT was ~90 % lower than the traditional ET group (i.e., 225 vs. 2,250 kJ) (Burgomaster et al. 2008). Therefore, along with offering similar physiological adaptations, SIT may potentially decrease the risk of overtraining, providing an optimal complement to strength training in a concurrent training program.

To our knowledge, no data exist which examine chronic physiological adaptations to concurrent sprint interval and strength training in recreationally active individuals. For that reason, the purpose of this study was to examine whether performing concurrent sprint interval (i.e., modified Wingate training) and strength training results in improved strength performance while also maintaining aerobic capacity. Therefore, it was hypothesized that adding SIT to a strength training protocol would not interfere with strength development.

Methods

Subjects

Sixteen healthy, non-smoking, recreationally active, college-aged (25.6 ± 6.1 years) men from the university and surrounding area were recruited for participation in this study (descriptive characteristics are presented in Table 1). A power analysis using methods described by Glowacki et al. (2004) was utilized to estimate sample size. With the alpha level set at 0.05 in anticipation of an effect size (ES) of 1.15 and a power of 0.80, it was determined that 13 subjects...
Table 1 Pre- and post-training descriptive characteristics

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>Pre-test</th>
<th>Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>ST</td>
<td>24.7 ± 5.9</td>
<td>24.7 ± 5.9</td>
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<td></td>
<td>CT</td>
<td>26.6 ± 6.6</td>
<td>26.6 ± 6.6</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>ST</td>
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<td>175 ± 9.1</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>176 ± 6.5</td>
<td>176 ± 6.5</td>
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<tr>
<td>Weight (kg)</td>
<td>ST</td>
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<tr>
<td></td>
<td>CT</td>
<td>80.9 ± 11.2</td>
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<tr>
<td>UB ALM (kg)</td>
<td>ST</td>
<td>8.3 ± 1.1</td>
<td>8.2 ± 0.9</td>
</tr>
<tr>
<td></td>
<td>CT</td>
<td>8.1 ± 1.6</td>
<td>8.3 ± 1.7</td>
</tr>
<tr>
<td>LB ALM (kg)*</td>
<td>ST</td>
<td>20.1 ± 1.8</td>
<td>20.5 ± 1.3</td>
</tr>
<tr>
<td></td>
<td>CT</td>
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<td>Total ALM (kg)</td>
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<td>TLM (kg)</td>
<td>ST</td>
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<tr>
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<td>59.1 ± 8.0</td>
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<tr>
<td>TBF (kg)</td>
<td>ST</td>
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<td>CT</td>
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<tr>
<td>BF %</td>
<td>ST</td>
<td>17.3 ± 3.4</td>
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<tr>
<td></td>
<td>CT</td>
<td>17.4 ± 5.0</td>
<td>17.8 ± 4.5</td>
</tr>
</tbody>
</table>

Values presented as mean ± SD

CT concurrent training, ST strength training, UB ALM upper-body appendicular lean mass, LB ALM lower-body appendicular lean mass, TLM total lean mass, TBF total body fat, BF % body fat percentage

* Significant main effect for time *p* < 0.05

would be needed in each group. However, due to the specific performance requirements, the level of commitment, and the length of the intervention, we were able to successfully enroll 16 subjects. All subjects completed a health history questionnaire to document that they were free of cardiovascular disease, physiological disorders, or any other illness that may have increased the risk of participation or introduced unwanted variability in the results. Inclusion criteria required subjects to have been involved in resistance training for a minimum of two days per week for at least six months prior to enrollment in the study, and must have been capable of lifting 1.0 and 1.25 times their body weight for bench press and back squat, respectively. Subjects were encouraged to ask questions prior to and throughout the duration of the study. All subjects were familiarized with all equipment used for testing and training and provided written informed consent prior to participation in the study. The study was approved by the university’s Institutional Review Board for the protection of human subjects in accordance with the Declaration of Helsinki.

Experimental design

Overall, subjects reported for three test visits during each testing phase (i.e., pre-, mid-, and post-test), with 24–48 h rest between each test visit, plus one familiarization visit, for a total of ten testing visits. The total duration of the present study was 14 weeks, including test weeks and the 12-week training period. Mid-test measurements were conducted during the experimental training period at week seven. Further, in an attempt to avoid diurnal variation in test measures, subjects were scheduled at approximately the same time for each testing and training sessions. To limit experimental variability, the same qualified investigator conducted all testing sessions. Upon completion of the first and second six-week training periods, subjects reported for mid- and post-testing, respectively, which were identical to pre-testing. Mid- and post-testing began 24 h after the most recent training session. Successive testing visits (i.e., two and three) were separated by 48 h. Testing was performed so that no longer than one week elapsed in-between training sessions.

Testing procedures

On day one of testing, height and weight were measured using a stadiometer and a digital scale, respectively, prior to analyzing body composition (DEXA, Hologic, Inc., Bedford MA). Then, subjects’ completed a 30-s Wingate anaerobic test. On the second visit, subjects performed a one-repetition maximum (1RM) bench press and back squat test as an indicator of maximal upper- and lower-body strength (Bachele and Earle 2008). On the final pre-test visit, subjects completed a graded exercise test (GXT) with finger stick lactate measurement (Lactate Plus, Nova Biomedical, Waltham, MA) to determine maximal aerobic capacity. Upon completion of all baseline test measurements, subjects were randomly assigned to 12 weeks of (1) strength training (ST) or (2) concurrent training (CT; strength + sprint interval training). ST trained two days per week with 24 h recovery between sessions, while CT trained four days per week with 24 h rest separating training modes. All testing and training were supervised by a National Strength and Conditioning Association, Certified Strength and Conditioning Specialist (NSCA–CSCS).

Dual energy X-ray absorptiometry

Body composition (total fat mass and fat free mass), upper and lower body, and total appendicular lean mass were analyzed using dual energy X-ray absorptiometry (DEXA; Hologic Discovery W, Bedford, MA). The subjects lay motionless in a supine position (i.e., on their backs) on a table for ~eight min, while an X-ray fan array passed above the table. All DEXA scans were performed by the same certified densitometry technician. Subjects reported in a total of fasting state for both (i.e., pre- and post-) scans, and were asked to wear appropriate (i.e., gym attire) clothing, which would allow proper scanning of the entire body.
Wingate anaerobic test

Anaerobic power assessment (i.e., peak and mean power) and fatigue index were recorded during pre-, mid-, and post-testing. Fatigue index is the % drop from peak power to the lowest power output recorded during the test. All selected variables were obtained by successfully completing a 30-s Wingate anaerobic test performed on a computer-interfaced friction-resisted cycle ergometer (Monark Ergometric 894e Peak Bike™, Sweden). Initially, subjects’ saddle heights were adjusted and recorded (for retest purposes) to ensure that at the lowest position of the pedal there were ~10° of knee flexion. Subjects then performed a five-min warm-up against minimal resistance (unloaded basket) incorporating two brief (3–5 s) pre-starts on the ergometer. Pre-starts were used to ensure subjects understood the level of intensity, or effort to be put-forth, as well as to provide feedback on further instructions that may be needed for the subjects (i.e., not to stand). Upon initiation of the test, subjects were instructed to begin a maximal sprint against no resistance until maximum revolutions per minute (RPM) were reached (determined by the investigator), after which a designated load (0.075 kg per kg mass) was applied.

Maximal muscular strength

1RM back squat and bench press were recorded as the maximum amount of weight a subject was capable of successfully lifting one time while displaying proper technique throughout the complete range of motion, adapted from Bachele and Earle (2008). A general warm-up consisting of cycling for five min preceded the strength tests. All subjects began by performing 5–10 repetitions with a self-perceived “light” load. The external load was then progressively increased during subsequent trials until no more than one repetition could be performed successfully. If the load was lifted successfully, testing continued, incorporating three-minute rest intervals between attempts, until the maximal load was met.

Graded exercise test

A maximal graded exercise test (GXT) was performed on an electrically braked cycle ergometer (Lode Excalibur Sport™, the Netherlands) to measure VO2max and to determine time to exhaustion (TTE). Prior to testing, subjects were provided a three-min warm-up against light resistance (50 W). Immediately following the warm-up, subjects began the test at 100 W with an increase of 25 W every minute thereafter. Pedaling rate was maintained between 50 and 75 RPM throughout the test. Expired gases were collected and analyzed (ParvoMedics® TrueOne 2400 Metabolic Measurement System, Sandy, Utah) to quantify VO2max (ml/kg/min). To ensure accuracy of our measurements, the metabolic system was calibrated before each test. This metabolic measurement system has been shown to be a reliable device in estimating VO2max (Bassett et al. 2001). The test was terminated once the subject was no longer able to maintain a pedaling rate of 50 RPM due to fatigue. Heart rate was continuously monitored before, during and immediately following completion of the test via a chest strap heart rate monitor (Polar Electro, Lake Success, NY). Additionally, subjects rated their perceived exertion (RPE) via the Borg scale of exertion (6–20), with a 6 representing very, very light exertion and 20 denoting maximal exertion. A test stage was successfully completed only if a total of 30 s was completed. VO2max was determined using a 30-s average. Time to exhaustion was determined by the exact duration of time from the start of the test until the subject reached the predetermined test termination (exhaustion) criterion (i.e., RPM fell below 50). Following test termination, subjects were provided an active cool-down session, pedaling against very light resistance (30 W) until their heart rate dropped below 100 beats per minute (bpm). For the test to be considered a maximal effort, four criteria for a VO2max test had to be met. These criteria were: VO2 plateau, blood lactate greater than 8 mmol/l, a respiratory exchange ratio of greater than 1.14, and heart rate had to reach at least 90 % of their age-predicted maximum heart rate (Howley et al. 1995).

Experimental training protocols

Strength training

Prior to each ST session, subjects (n = 8) completed a general five-min warm-up on a cycle ergometer. Training incorporated both upper and lower body, performed in the following order: back squat, bench press, leg extension, leg curl, pull-down, and shoulder press. Prior to performing the back squat and bench press, an additional warm-up set of 8–10 repetitions was performed at 50 % of the individual’s calculated maximum. Training progression was applied as subjects were capable of successfully lifting their current load during all three sets for four consecutive sessions. This progression allowed subjects to remain training in the four to six repetition range (i.e., 85 % 1RM) throughout the duration of the study. Two-minute rest intervals were provided between all sets. Each training session lasted ~45 min and was performed twice per week.

Concurrent training

We have previously established in our laboratory that performing four to six sets of modified 20 s Wingate protocol
over 12 weeks improves aerobic performance as measured by \( \text{VO}_2\text{max} \) and TTE (unpublished data). Briefly, during the first four weeks, SIT sessions consisted of four repeats, with one additional set added every four weeks so that by the end of the study six repeats were performed. This particular design resulted in significant improvements in \( \text{VO}_2\text{max} \) and TTE.

Subjects assigned to concurrent training (CT; \( n = 8 \)) performed identical protocols as ST and modified Wingate training but on separate days. A minimum of 24 h was provided between sessions to provide recovery from any fatigue that resulted from the previous training session. CT took place on Monday, Tuesday, Thursday, and Friday with half of the group strength training on Monday and Thursday, while the others performed strength training on Tuesday and Friday. SIT was performed the other two days.

Statistical analysis

A two-way ANOVA (groups \( \times \) time) with repeated measures was performed to assess training-related differences in the ST and CT groups for each dependent variable. Bonferroni post hoc adjustments to independent and dependent \( t \) tests were used to determine where pairwise differences existed. Cohen’s \( d \) effect sizes were reported for all observations with \( \leq 0.20 \) representing a small effect, \( 0.20 \) representing a medium effect, and \( \geq 0.80 \) representing a large effect (Cohen 1988). If a violation of Mauchly’s test of Sphericity was observed, Greenhouse Geisser’s corrected model was used. All statistical analyses were conducted SPSS (IBM SPSS, Version 20; SPSS Inc., Armonk, NY), with statistical significance set at \( p \leq 0.05 \). Reliability of measures was determined using a two-way average measure of the intraclass correlation coefficient.

Results

Of the 16 subjects enrolled in the study, 14 successfully finished and were included in the analyses. One subject in each training group was excluded for non-compliance, resulting in seven men in each training group. Training session compliance during the study was 93% (ST = 94%, CT = 92%).

Body composition

Pre- and post-test body composition values are presented in Table 1. No pre-training differences were observed between ST and CT in total body fat (\( p = 0.838 \), upper- (\( p = 0.819 \)) and lower-body lean mass (\( p = 0.907 \)), and total appendicular lean mass (\( p = 0.994 \)). No significant differences were observed between the two groups in total body fat (\( p = 0.486 \); ES = 0.42), upper-body appendicular lean mass (\( p = 0.969 \); ES = 0.02), and total appendicular lean mass (\( p = 0.782 \); ES = 0.41) after training. A significant main effect for time was observed in appendicular lower-body lean mass (20.2 ± 2.4 to 20.8 ± 2.6 kg; \( p = 0.026 \); ES = 2.36).

Maximal strength

Pre-, mid-, and post-test 1RM scores for upper and lower body are presented in Table 2. No pre-training differences were observed between ST and CT for upper- and lower-body maximal strength. No significant interaction effects were observed after training (\( p > 0.05 \)). No significant group main effect was observed for maximal upper- and lower-body strength after training (\( p > 0.05 \)). A significant time effect was observed in maximal lower-body (\( p < 0.001 \); ES = 1.65) and upper-body strength (\( p < 0.001 \); ES = 0.74). Upper- and lower-body strength increased from pre- to mid- to post-intervention (\( p < 0.001 \)).

Aerobic performance

All subjects achieved >90% of their estimated max heart rate, respiratory exchange ratio value of >1.14, blood lactate values of >8 mmol/l, measured via finger stick, and expressed an RPE value ≥18. No significant differences were observed between ST and CT in pre-training TTE and \( \text{VO}_2\text{max} \) values. No significant interaction (group \( \times \) time) was observed (\( p = 0.069 \)). A significant time main effect was observed in TTE (\( p = 0.021 \)). TTE increased from pre- to post-test (10.46 ± 1.3 to 11.25 ± 1.2 min; \( p = 0.026 \); ES = 0.66) and mid- to post-test (10.86 ± 1.05 to 11.25 ± 1.24 min; \( p = 0.046 \); ES = 0.35). A significant group main effect was observed in TTE (ST: 10.22 ± 0.69 vs. CT: 11.50 ± 1.16; \( p = 0.016 \); ES = 2.13). TTE values for both ST and CT are presented in Table 3.

A significant interaction (time \( \times \) training) effect was observed in \( \text{VO}_2\text{max} \) (\( p = 0.043 \)). \( \text{VO}_2\text{max} \) increased significantly from pre- to post-testing for CT (40.9 ± 8.4 to

<table>
<thead>
<tr>
<th>Table 2 Pre-, mid-, and post-testing 1RM values for upper and lower body</th>
</tr>
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<tbody>
<tr>
<td>Group</td>
</tr>
<tr>
<td>-------</td>
</tr>
<tr>
<td>Bench press (kg)*</td>
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<tr>
<td></td>
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<tr>
<td>Back squat (kg)*</td>
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</tbody>
</table>

Values presented mean ± SD

CT concurrent training, ST strength training

* Significant main effect for time \( p < 0.05 \)
42.3 ± 7.1 ml/kg/min; \( p = 0.026; \) ES = 5.71), while ST remained unchanged \( (p = 0.151; \) ES = 0.39). No significant differences were observed between ST and CT at mid-test \( (p = 0.086; \) ES = 1.09); however, the VO\(_2\)\(_{\text{max}}\) differences between groups were significant at post-test \( \text{ST}: 36.0 \pm 3.0 \) versus CT: 42.3 ± 7.1 ml/kg/min; \( p < 0.05; \) ES = 1.25) (Fig. 1).

**Anaerobic power**

No significant differences were observed across all pre-training anaerobic power variables \( (p > 0.05) \). No significant interaction effects were observed for all anaerobic power variables \( (p > 0.05) \). No significant group main effects were observed for all anaerobic power variables

#### Table 3  Time to exhaustion values during graded exercise test

<table>
<thead>
<tr>
<th>Group</th>
<th>Pre-test</th>
<th>Mid-test</th>
<th>Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>ST</td>
<td>10.2 ± 0.7</td>
<td>10.1 ± 0.5</td>
<td>10.4 ± 0.9</td>
</tr>
<tr>
<td>CT</td>
<td>10.7 ± 1.7</td>
<td>11.6 ± 0.9</td>
<td>12.1 ± 0.9</td>
</tr>
</tbody>
</table>

Values presented as mean ± SD (min)

**CT** concurrent training, **ST** strength training

#### Table 4  Pre-, mid-, and post-training Wingate test values

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th>Pre-test</th>
<th>Mid-test</th>
<th>Post-test</th>
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</thead>
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<tr>
<td><strong>Peak power (W)</strong></td>
<td>ST</td>
<td>727.7 ± 63.3</td>
<td>767.6 ± 100.8</td>
<td>741.6 ± 128.1</td>
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<tr>
<td></td>
<td>CT</td>
<td>756.6 ± 113.2</td>
<td>829.4 ± 222.1</td>
<td>820.9 ± 211.5</td>
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<td><strong>Average power (W)</strong></td>
<td>ST</td>
<td>541.0 ± 45.2</td>
<td>559.8 ± 52.1</td>
<td>544.5 ± 74.4</td>
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<tr>
<td></td>
<td>CT</td>
<td>571.1 ± 95.6</td>
<td>630.6 ± 149.6</td>
<td>634.5 ± 156.7</td>
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<td><strong>Fatigue index (%)</strong></td>
<td>ST</td>
<td>59.6 ± 16.0</td>
<td>63.0 ± 12.5</td>
<td>57.8 ± 11.3</td>
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<tr>
<td></td>
<td>CT</td>
<td>53.7 ± 10.2</td>
<td>52.0 ± 10.1</td>
<td>51.5 ± 8.5</td>
</tr>
</tbody>
</table>

Values presented as mean ± SD

**CT** concurrent training, **ST** strength training

* Significant main effect for time \( p < 0.05 \)

**Discussion**

The primary findings of the present study suggest that performing sprint interval training (SIT) concurrently with heavy strength training (ST) does not result in compromised strength development, and improves aerobic performance measures of VO\(_2\)\(_{\text{max}}\). To our knowledge, this was the first study to examine the effects of concurrent heavy strength training and SIT on strength, anaerobic power, and aerobic performance variables. Others (Kraemer et al. 1995; Leveritt and Abernethy 1999) have prescribed heavy strength training alongside high-intensity endurance training; however, these experimental training programs consisted of a heterogeneous mix of low-, moderate-, and high-intensity training sessions. Moreover, while the endurance component was more consistent with the present study, Leveritt and Abernethy (1999) examined only the acute effects of high-intensity concurrent training.

Previous concurrent training studies have demonstrated interference in strength development (Hickson 1980; Glowacki et al. 2004; Izquierdo et al. 2005); however, our initial findings suggest that concurrent sprint interval and heavy strength training does not compromise upper- or lower-body strength development. Moreover, the relative magnitude of change was greater in the lower body when compared to upper body, suggesting SIT does not interfere with maximal strength development, but appears to provide an added stimulus for strength development. We also observed a significant increase in appendicular lean mass for lower body in those of the concurrent group, further supporting the improvements seen in maximal lower-body strength. With that said, the improvements observed in upper body strength for both groups can be considered...
the result of neural adaptations. Moritani and DeVries (1979) initially demonstrated strength adaptations during the first 8 weeks of training to be a consequence of neural adaptations. Further, Aagaard et al. (2002) demonstrated significant improvements in maximal strength following 14 weeks of heavy strength training to be the result of neural gains. Specifically, both studies reported increases in electromyographic activity in the absence of increased lean mass. Based on the observations of both studies, and the suggested time frame for neural adaptations, the strength improvements in our study appear to be the result of neural adaptations, thereby explaining the improvements in strength in the absence of increases in lean body mass.

McCarthy et al. (1995) and Balabinis et al. (2003) have shown that adding endurance training of various intensities to a strength training protocol does not result in local or systemic interference. Focused on developing maximal strength, power, and muscular endurance, training intensities in the work of Balabinis et al. (2003) ranged from 40 to 95 % 1RM, while McCarthy et al. (1995) implemented strength training intensities more similar to our study. In our study, the strength training intensity was set at 85 % 1RM with a maximal goal of six repetitions to focus on developing optimal gains in maximal strength (Bachele and Earle 2008). Moreover, some researchers (de Souza et al. 2007; Leveritt and Abernethy 1999; Reed et al. 2013) have suggested that the aerobic component of concurrent training programs induces an acute state of local fatigue; however, this is not always the case (Balabinis et al. 2003; McCarthy et al. 1995; Nelson et al. 1990). Balabinis et al. (2003) described a significant superiority for the concurrent training group in 1RM half-squat following just seven weeks of same day concurrent training. Nonetheless, in an attempt to attenuate the potential for acute fatigue, concurrent training in our study was performed on separate days.

Others (Hakkinen et al. 2003; Izquierdo et al. 2004; Mikkola et al. 2012) that performed concurrent training on separate days have observed results comparable to those in the present study. For instance, Mikkola et al. implemented strength training two days per week and concurrent training four days per week and observed a significant increase in knee extensor force in untrained men with no difference between groups. Likewise, maximal bilateral leg extension increased significantly over 21 weeks when strength training was performed two days per week and concurrent training was performed four days per week in recreationally active men (Hakkinen et al. 2003). Interestingly, strength development is insignificant in concurrently trained individuals when strength and endurance training are performed on separate days but just once per week (Izquierdo et al. 2004, 2005) indicating the requisite of adequate stimulation for muscle adaptation. Therefore, based on previous literature, as well as the preliminary results in the present study, there appears to be an advantage to implementing strength and endurance training on alternate days and at least twice a week for each modality.

Unlike previous studies that have reported significant changes in body fat percentage (Glowacki et al. 2004; Hakkinen et al. 2003; Mikkola et al. 2012) or total body mass (Glowacki et al. 2004), total body fat and body fat percentage remained unchanged in the present study. With that said, we observed increases in lower-body appendicular lean mass after training. Moreover, despite a large effect size (e.g., 1.58) for total appendicular lean mass, our small sample size most likely resulted in a lack of significant improvement in total appendicular lean mass. However, our training program was not designed to elicit hypertrophic gains, but to achieve maximal strength and increase aerobic capacity with minimal training volume in recreationally active men. Conversely, Glowacki et al. (2004) incorporated strength training intensities ranging from ten repetitions at 75 % to six repetitions at 85 % 1RM and an endurance component more efficacious for reductions in body fat percentage especially in untrained individuals. Similarly, Mikkola et al. (2012) reported reductions in body fat percentage in untrained middle-aged men. Therefore, considering the activity level and physical age of the individuals recruited, these changes seem ideal.

In addition to improving upper- and lower-body strength, the integration of SIT into a strength training program appears to improve VO$_2$max and TTE. The SIT in the present study was performed in 20 s bouts and ranged from 28 to 34 min total training time per week (including rest intervals). Previous work has shown that SIT for six weeks with four to six 30 s bouts or six SIT sessions
performed over two weeks resulted in similar adaptations as traditional endurance training ranging from 45 to 60 min (Burgomaster et al. 2008) or 90 to 120 min in duration (Gibala et al. 2006) of cycling, respectively. In particular, peak oxygen consumption appears to respond similarly to both distinct intensities of endurance training (Burgomaster et al. 2008). Moreover, SIT has been shown to increase maximal activity of aerobic enzymes (Gibala et al. 2006). However, only VO₂max and TTE were collected in the present study, therefore, the mechanisms of change remain undetermined. With that said, significant improvements in VO₂max were observed in the concurrent group, whereas VO₂max remained unchanged in the strength training group [consistent with the work of (Balabinis et al. 2003)]. Similarly, improvements in aerobic performance were further suggested as TTE increased for the CT group, yet remained unchanged in the ST group. While VO₂max was not examined in the early work of (Tesch 1988), the observations on strength training’s combative influence on oxidative enzymatic activity may have played a role in VO₂max attenuation for the ST group.

The anaerobic power results in the present study are not consistent with previous concurrent training studies (Balabinis et al. 2003), nor do they align with the observed improvements in lower-body strength or appendicular lower-body lean mass. No significant differences in peak power were observed at each time point for either group, despite observing an increase in lower-body strength. The lack of adaptation in peak power may be a consequence of the expeditious turnover from exercise training to testing. In particular, subjects reported for Wingate testing 24 h following their most recent training session, while 48 h separated the other test sessions. Therefore, if an additional day of rest had been provided, these values may have improved. One other plausible explanation for the unchanged peak power is intra-training session fatigue. More specifically, as our subjects continued to train despite being fatigued, this acute fatigue may have translated into compromised power output observed during testing. Although maximal cycling speed was not monitored during training, this protocol was designed with short rest periods to improve aerobic performance, so by the end of each training session we observed clear decrements in the potential for maximal cycling speed and power. The combination of inadequate recovery prior to Wingate testing in addition to intra-session fatigue may explain the lack of development in anaerobic power measures.

Conversely, this was not the case with average power from pre- to mid-test, as both groups significantly increased power output over 30 s. However, despite that initial increase, average power remained unchanged at post-test. Specificity of training may have been the cause of this observation. Specifically, our SIT training consisted of 20 s bouts, while testing was conducted for 30 s, thus according to the specificity principle the transfer of training effect was likely low. Nevertheless, when comparing average power with the increase in maximal lower-body strength, it can be speculated that seven weeks of strength training translates into improved average power output over 30 s, and then begins to plateau. Further, when visually inspecting average power values at mid- and post-test, there appears to be a difference, however, this was not determined statistically. That lack of significance was most likely a consequence of large standard deviations associated with the CT values, which could be reduced with additional subjects. Therefore, the small sample size in our study is a limitation that requires addressing. That being said, average power in the CT sample approached significance from pre-test to post-test with a considerably large effect size (2.00). Nonetheless, future research is warranted to better understand the influence of concurrent SIT and strength training on anaerobic power measurements.

One limitation of the present study is our small sample size. As a consequence, the chance for committing a type II error in evaluating our measurements was increased. Therefore, our ability to determine statistical significance was reduced when significance, in fact, could have been reported. For example, despite a large effect size (e.g., 1.58), total appendicular lean mass did not reach significance. Having said that, even in the absence of significance, the moderate to large effect sizes associated with our data are very telling and should be considered physiologically meaningful.

While not as defining, a second limitation of this study is the duration of the training. For example, the initial gains seen in average power in both groups were attenuated post-intervention. Furthermore, it is unlikely that recreationally active individuals would train for 12 weeks at an intensity similar to the present study (i.e., all-out modified Wingate protocol). Therefore, our ability to generalize our findings to a larger population is reduced. That being said, this training design may be more applicable to elite athletes, who need to increase aerobic capacity while maintaining/improving maximal strength. Therefore, the preliminary findings of the present study, although attractive, warrant the need for future research.

In summary, the findings of the present study suggest that SIT performed concurrently with heavy strength training on separate days does not appear to interfere with the development of maximal strength. Also, aerobic performance measures (i.e., VO₂max) appear to respond positively to low volume, high-intensity SIT. While these findings may be of interest to athletes and individuals seeking to optimize maximal strength and aerobic performance in a time-efficient manner, this was a preliminary design that warrants the need for future research to establish greater certainty.
Acknowledgments This study was funded by a Graduate Student Research grant to Gregory Cantrell from the National Strength and Conditioning Association.

Conflict of interest The authors declare that they have no conflict of interest.

References


