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Research article

Maximum Strength Development and Volume-Load during Concurrent High Intensity Intermittent Training Plus Strength or Strength-Only Training

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Abstract
The purpose of this study was to compare maximal strength gains during strength training (ST) and concurrent training (CT) consisting of high-intensity intermittent training plus strength training over the course of a 12-week intervention. A secondary purpose was to examine the relationship between strength training volume and strength gain in both groups. Nineteen recreationally active males were divided into CT (n = 11) and ST (n = 8) groups. The CT group performed repeated 1 min efforts at 100% of maximal aerobic speed interspersed by 1 min of passive recovery until accumulating a total running distance of 5km followed by a strength session (consisting of three sets of seven exercises with loads of 8-12 repetition maximum) twice weekly for a period of 12 weeks. The ST group performed only strength training sessions during the same 12-week period. Strength training total volume-load (Σ repetitions × load) for the upper- and lower-body was computed, while maximal strength (1RM) was evaluated at baseline, week 8, and week 12. Lower-body volume-load over 12 weeks was not different between groups. Absolute 1RM increased in both groups at week 8 and week 12, while 1RM relative to body mass increased in both groups at week 8, but only ST increased relative maximum strength between week 8 and week 12. There was a statistically significant correlation between strength training lower-body volume-load and maximum strength change between baseline and week 8 for the CT group (r = 0.656), while no significant correlations were found for the ST group. In summary, executing high-intensity intermittent exercise twice a week before strength training did not impair maximal strength after 8 weeks, however, only ST demonstrated an increase in relative strength after 12 weeks.

Key words: Total volume performed, maximum number of repetitions, strength gain.

Introduction

Among the desired outcomes of regular exercise training, strength and endurance are the most prominent physical abilities considered (Reilly et al., 2009). Strength training improves skeletal muscle contractile capacity (Costill et al., 1979), whereas aerobic training improves oxygen delivery to muscle and oxygen extraction from the blood (Holloszy and Coyle, 1984). Thus, both strength and aerobic training programs are commonly employed to improve cardiovascular fitness and force production (Garber et al., 2011).

The combination of aerobic exercise and strength training, known as concurrent training (CT), has received particular focus in the scientific literature due to the potential for antagonistic adaptations (Bell et al., 2000; Hakkinen et al., 2003; Kraemer et al., 1995). Some investigations have demonstrated that maximum strength was reduced after a period of concurrent training when compared with isolated strength training (Bell et al., 2000; Hickson, 1980; Kraemer et al., 1995; Fyfe et al., 2016), while others have failed to replicate this type of interference effect (Eklund et al., 2015; McCarthy et al., 2002; Gentil et al., 2017). Thus, this topic remains the aim of recent investigations (Fyfe et al., 2016; Gentil et al., 2017).

The causes of impairments in long-term strength gains (interference effect) are not well-established; however, acute training adaptations may be partially responsible (Leveritt et al., 1999; Craig et al., 1991). The acute hypothesis suggests that acute decrements in force production during resistance training when preceded by aerobic activity are potentially due to insufficient recovery between training sessions and residual multifactorial fatigue (i.e., pH reduction and decrease of Ca^+ sensitivity) (Fitts, 2016). The acute force reductions and subsequent impairments in total work observed during CT (Sale et al., 1990) may partially explain the long-term impairment of strength development which may be dependent on the volume of work performed (Rhea et al., 2003).

In fact, many studies have shown performance decrements in strength tasks (maximum number of repetitions) when aerobic exercise is performed prior to strength exercise (Inoue et al., 2016; Panissa et al., 2015; 2016). The intensity of exercise is an important variable to consider in relation to the interference effect (Docherty and Sporer, 2000) with larger decrements in strength-endurance when aerobic exercise is performed at higher intensities (de Souza et al., 2007). This topic has increased relevance due to the recent popularity of interval training as an efficient strategy to increase aerobic fitness (Milanovic et al., 2015) and decrease fat mass (Panissa et al., 2016).

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A recent meta-analysis (Murlasits et al., 2018) supports acute volume maintenance as a strategy to minimize interference effects since strength training followed by aerobic exercise results in superior gains in maximum strength (3.96 kg) compared to the reverse order. This finding comes with the assumption that volume is decreased when aerobic exercise precedes strength exercise. However, few studies have tested if the CT-related decrements in acute strength training volume interfere with long-term adaptations while controlling for volume-load (Craig et al., 1991; Sale et al., 1990).

Studies from Eklund et al. (2015) and Schumann et al. (2014) comparing opposite orders of execution showed no difference in maximum strength or hypertrophy after 12 and 24 months of training; however, these studies utilized moderate intensity aerobic training, which favors the maintenance of training volume (de Souza et al., 2007). More recently, Fyfe et al. (2016) showed an attenuation of maximal strength, independent of aerobic intensity, after 8-weeks of training sessions consisting of aerobic exercise (high or moderate intensities) following by strength exercise and reported no effect of acute impairment (although the strength training volume was not reported). Furthermore, a classic study from Hickson (1980) utilized a high-intensity exercise protocol for 10 weeks and a CT-related interference (reduction in strength gains) occurred only after the eighth week of training, indicating that long-term interventions must be considered.

Thus, the aim of present study was compare the effect of high-intensity intermittent exercise performed before strength training (CT group) with strength training alone (ST group) on maximum strength after 8 and 12 weeks. A secondary aim was to evaluate the relationship between acute strength training volume-load and long-term strength gains. We hypothesized that CT would present inferior strength gains compared to ST after 8 and 12 weeks, which would be related to lower strength volume-load in the CT group.

Methods

Ethics statement

This study was carried out at São Paulo State University (UNESP), Presidente Prudente, SP, Brazil and performed according to the guidelines of the Declaration of Helsinki. The project was approved by the Ethics Research Group of the São Paulo State University (Protocol number: 22793414.7.0000.5402).

Experimental design

This was an experimental longitudinal study that compared the strength gains and maximal aerobic speed to typical training sessions in subjects assigned to either a concurrent training (CT) group or a strength training only (ST) group. Anthropometric testing, maximal aerobic speed, maximal strength, and isolated acute volume evaluations were performed at baseline and at week 8 and week 12 (Figure 1). An additional aerobic evaluation was conducted following four weeks of training in the CT group to allow for intensity adjustments in the high-intensity intermittent training (HIIT) protocol.

Subjects

Inclusion criteria for participation in the study were: 1) participating in systematic strength training during the previous 6 months (Whaley et al., 2006); 2) age between 18 to 35 years; and 3) considered physically active through aerobic conditioning (minimum twice a week). Exclusion criteria were: 1) contraindications involving the cardiovascular system, muscles, joints, bones of the lower limbs or any musculoskeletal disorders that would limit the participation in strength training; and 2) use of nutritional supplements within the past 6 months (e.g., protein, amino acids, and creatine), prior anabolic steroid use, or use of any other illegal agents known to increase performance for the previous year. All subjects were asked to maintain their usual nutritional habits and to only engage in exercise as proposed by the study protocol.

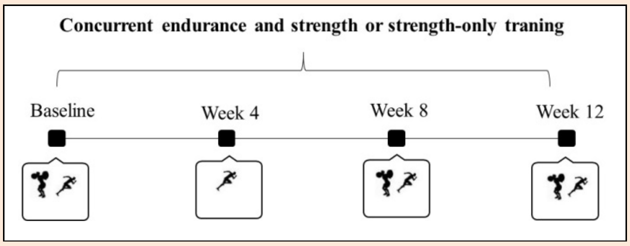

Figure 1. Study design. anthropometry, maximal strength and isolated acute volume test evaluations; maximal aerobic speed test.

Out of a total of 104 men who participated in the first screening, only 22 met all the inclusion/exclusion criteria and agreed to participate in the study protocol. Participants were randomized into two study groups: CT (n = 12) and ST (n = 10), using simple randomization techniques for allocation, which ensured that trial participants had an equal chance of being allocated to a given treatment group (Egbewale, 2014). During the 12 weeks of training, three men dropped out of the study (a dropout rate of 13.6%) and were excluded from the final analyses. The reasons for dropouts were: incompatible schedules (n = 1 from ST group) and declined participation with unspecified reasons (n = 2 from CT group).

Procedures

Anthropometric assessment

Height was measured using a fixed stadiometer (Sanny brand, São Paulo, Brazil). The participants were barefoot and wore light clothing while standing at the base of the stadiometer, touching their shoulder blades, buttocks and heels to the equipment´s vertical support. Body mass was measured using an electronic scale (Filizola PL 50, Filizola Ltda., Brazil), with a precision of 0.1 kg.

Maximal aerobic speed test

For determination of maximal aerobic speed, the subjects performed a maximal incremental test on a treadmill (Inbramed-ATL) until voluntary exhaustion. Each stage was composed of 2-min, with the first being performed at a speed of 8 $km \cdot h^{-1}$ followed by 1 $km \cdot h^{-1}$ increases at the end of each stage. In addition, heart rate was registered using a heart rate monitor (Polar Electro, model S810i or RS800, Finland). The maximal speed reached in the test was defined as maximal aerobic speed (MAS). When the subject was not able to finish the 2-min stage, the speed was expressed according to the accumulated time in the final stage, determined as follows: MAS = speed of penultimate stage + [(time, in seconds, remained in the final stage multiplied by 1 km·h^{-1})/120s]. This test was conducted in an isolated session at baseline, week 8, and week 12 for both groups, and following four weeks in the CT group only, to adjust the speed of the HIIT sessions. All participants arrived at the laboratory early in the morning and the time of day and environmental conditions (temperature: 22 ± 2ºC) were consistent between testing sessions.

Strength test procedures

One week prior to testing, the participants attended three familiarization sessions (Monday, Wednesday and Friday) in which they performed four sets of 12-15 repetitions of each exercise, to become accustomed to the equipment and testing protocols performed throughout the study (Ritti-Dias et al., 2011). During the subsequent week, approximately 72 hours after the aerobic test, the subjects performed a maximum dynamic strength test consisting of a one repetition maximum (1RM) half-squat using a Smith machine (Ipiranga®, São Paulo/Brazil). The participants performed a five-minute general warm-up on a treadmill at 50% MAS followed by a specific warm-up consisting of 1 set of eight repetitions at 50% 1RM, and 1 set of three repetitions at 80% of 1RM on a Smith machine with 2 min rest between sets. After 3 min rest, subjects had up to five attempts to achieve the 1RM load with rest intervals between three to five minutes (Brown and Weir, 2001).

For better control of the 1RM test procedures, the body position and feet placement of each participant in the half-squat exercise were recorded and reproduced throughout the study. In addition, a wooden seat with adjustable heights was placed behind the participant in order to keep the bar displacement and knee angle (~90º) constant during each half-squat repetition. This test was conducted in an isolated session at baseline, week 8, and week 12 for both groups. All participants arrived at the laboratory early in the morning (between 7 and 9 a.m.) and environmental conditions (temperature: 22 ± 2ºC) were consistent between testing sessions.

Isolated acute volume test

In addition to calculation of intersession volume-load performed throughout the intervention period in both groups, an acute strength training session was conducted in isolation at baseline, 8, and 12 weeks. This measurement was performed because it could be conducted in a much more controlled manner than the training sessions, including the ability to standardize time and dietary intake. This session started upon the arrival of the participant at approximately 8 a.m., with the participant having fasted for at least 10 hours previously. Participants received a standardized breakfast fixed at 25% of the estimated daily energy needs for each participant (Mifflin et al., 1990). This meal was composed of cheese, toast and strawberry yogurt. Exercise started 90 minutes after breakfast. For this session, the ST group performed only strength exercise composed by maximum number of repetitions, four half-squat sets at 80% of 1RM), while the CT performed both aerobic and strength exercise with 10 minutes of interval between exercises. The volume-load of each experimental session was calculated by summing the maximal number of repetitions in all four sets, and multiplying by load (Σ repetitions x load).

Strength and concurrent training protocol

Initially, both groups performed a warm-up on a treadmill at 50% MAS for five minutes with a 1% inclination. The ST group trained two times per week (Monday and Thursday or Tuesday and Friday). The strength training program consisted of three sets with a load lifted at which 8-12 repetitions could be completed and 90 s of rest were provided between sets and exercises. The exercises used in the program were: bench press, half-squat, triceps extension, leg extension, seated row, leg curl and arm curl, and were always performed in this same order. The participants were encouraged to execute at least 8 and no more than 12 repetitions. If more than 12 repetitions were achieved during a session, the load was adjusted to remain in the planned intensity zone.

The CT group also trained two times per week with each session consisting of a HIIT protocol followed by the same strength protocol completed by the ST group. During the HIIT protocol, subjects ran on a treadmill for one minute at 100% MAS interspersed by one minute of passive recovery (without exercise) until they completed 5 km. The number of efforts completed during the HIIT sessions were recorded. A 10-minute recovery period was given between the HIIT and strength protocol. The aerobic test results completed at week 4 and week 8 were used to adjust the intensity.

To ensure that the load and technical aspects of the training protocols were correct, the groups were supervised by professionals who monitored the exercise programs on a daily basis. Participants were instructed to maintain hydration levels and wear appropriate shoes and clothes during training. The strength training total volume-load was calculated by summing the number of repetitions and multiplying by load (Σ repetitions × load). Volume-load for the lower- and upper-body exercises were evaluated following eight and 12 weeks of training to verify the relationship with maximal strength gains. The entire concurrent exercise session lasted approximately 100 minutes, and the strength training session lasted approximately 50 minutes.

Statistical analysis

All analyses were performed using the Statsoft Statistica Software Package (version 12.0, Tulsa, Oklahoma, United States). Data were reported as means and standard deviation (SD). A Mauchly's test of sphericity was used to test this assumption, and a Greenhouse-Geisser correction was applied when necessary. A two-way mixed factorial analysis of variance [ANOVA; group (ST vs CT) × time point (baseline, 8 weeks, 12 weeks)] was conducted to compare maximal strength (absolute and relative to body mass), isolated acute volume (volume-load and maximum number of repetitions), and MAS, and to compare changes [group (ST vs CT) × time point (8-week Δ, 12-week Δ)] in maximal strength and MAS (post minus pre divided by pre multiplied by 100). A two-way mixed factorial ANOVA [group (ST vs CT) × time point (8-week total, 12-week total)] was conducted to compare upper-body volume-load and lower-body volume-load, while a one-way ANOVA was conducted to compare the number of efforts completed during HIIT for the CT group at weeks 1-4, 5-8 and 9-12.

When a significant main effect or interaction was observed, a Bonferroni post hoc test was applied. Statistical significance was set at $p < 0.05$. Effect sizes for post hoc tests were calculated using Cohen'*d* as proposed by Rhea (2004) using the following scale (in recreationally trained individuals) for interpretation: <0.35 [trivial]; 0.35 to < 0.80 [small]; 0.80 to < 1.50 [moderate]; > 1.5 [large]. The post hoc effect sizes were presented in the event of statistical significance or when the effect size was large. The correlation between strength training volume-load and strength gains was verified through Pearson correlation coefficients.

Results

Table 1 presents the pre-training subject characteristics. For these variables, we analysed the body mass between groups throughout the training period and no main effect for time point or interactions were found (CT at 8^{th} week: 75.6 ± 8.1 kg and 12^{th} week: 75.2 ± 7.9 kg; ST at 8^{th} week: 77.9 ± 12.5 kg and 12^{th} week: 76.1 ± 11.6 kg).

Table 1. General characteristics of the sample from baseline.

	Concurrent training Group (n = 11)	Strength Training Group (n = 8)
Age (years)	24.5 ± 3.7	28.7 ± 3.4
Body mass (kg)	74.6 ± 6.8	77.5 ± 12.9
Height (m)	1.79 ± 0.07	1.77 ± 0.08

Maximal aerobic speed

For maximal aerobic speed (Table 2), there was a main effect for time point ($F_{2,34}$ = 14.72; $p < 0.001$) with greater values at week 8 ($p < 0.001$; *d* = 0.46 [small]) and week 12 compared with baseline ($p < 0.001$; *d* = 0.60 [moderate]). For the change of maximal aerobic speed, there was no interaction or main effects.

HIIT efforts (CT group only)

For the number of efforts completed during HIIT, there was main effect for time point ($F_{2,20}$ = 22.59; $p < 0.001$) with a greater number of efforts completed in weeks 1-4 (21 ± 2) compared to weeks 5-8 (20 ± 2; p = 0.004; d = 0.500 [moderate]), and weeks 9-12 (20 ± 1; p = 0.001; *d* = 1.26 [moderate]).

Maximal strength

For absolute maximal strength (Figure 2), there was a main effect for time point ($F_{1.3,34}$ = 66.91; $p < 0.001$) with greater values at week 8 and week 12 compared to baseline ($p < 0.001$ for both comparisons; *d* = 0.98 [moderate]; *d* = 1.37 [moderate], respectively) and values at week 12 being greater than values at week 8 (p = 0.008; *d* = 0.41 [small]). A large effect size (*d* = 1.51) was shown for the ST group when comparing absolute strength values at baseline and week 12.

For the absolute maximal strength change values (Figure 2), there was a main effect for time point ($F_{1,17}$ = 6.87; p = 0.018;) with the 12-week Δ being greater than the 8-week Δ (p = 0.018; *d* = 0.58 [small]).

For maximal strength relative to body mass (Figure 3), there was a main effect for time point ($F_{1.5,34}$ = 76.25; $p < 0.001$) with greater values at week 8 and week 12 compared to baseline ($p < 0.001$ for both; *d* = 0.81 [moderate]; *d* = 1.24 [moderate]) and values at week 12 being greater than values at week 8 ($p < 0.001$; *d* = 0.42 [small]).

For relative maximal strength change (Figure 3), there was a main effect of time point ($F_{1,17}$ = 36.97 $p < 0.001$) with the 12-week Δ being higher than the 8-week Δ ($p < 0.001$; *d* = 1.13 [moderate]). There was also an interaction effect ($F_{1,17}$ = 11.62; p = 0.003) with the 12-week Δ being higher than the 8-week Δ only for the ST group ($p < 0.001$; *d* = 0.877 [moderate]) while no differences were found for the CT group.

Accumulated strength training volume-load

For upper-body volume-load (Figure 4), there was a main effect of time point ($F_{1,17}$ = 715.2 $p < 0.001$) with lower volume-load calculated between baseline and week 8 compared to between baseline and week 12 ($p < 0.001$; *d* = 2.46 [large]. No differences were found between groups.

For lower-body volume-load (Figure 4) there was a main effect of time point ($F_{1,17}$ = 715.2 $p < 0.001$) with greater volume-load calculated between baseline and week 12 compared to between baseline and week 8 ($p < 0.001$; *d* = 2.14 [large]). No differences were found between groups.

Isolated acute volume test

For half-squat volume-load in the isolated acute volume test (Table 3) there was a main effect of time point ($F_{2,34}$ = 10.87; $p < 0.001$) with greater volume-load in week 8 (p = 0.003; d = 0.712 [small]) and week 12 (p = 0.003;

Table 2. Maximal aerobic speed during strength training only (ST) or high-intensity intermittent training plus strength training (CT).

	Maximal aerobic speed ($km.h^{-1}$)		Change from Baseline (%)	
	ST	CT	ST	CT
Baseline	13.2 ± 1.7 *	14.1 ± 1.3 *	-	-
Week 8	13.5 ± 1.4	14.9 ± 1.1	2.3 ± 3.1	6.0 ± 4.0
Week 12	13.6 ± 1.3	15.1 ± 1.0	3.5 ± 7.3	7.3 ± 5.4

Data are mean ± standard deviation.* different from weeks 8 and 12 ($p < 0.05$).

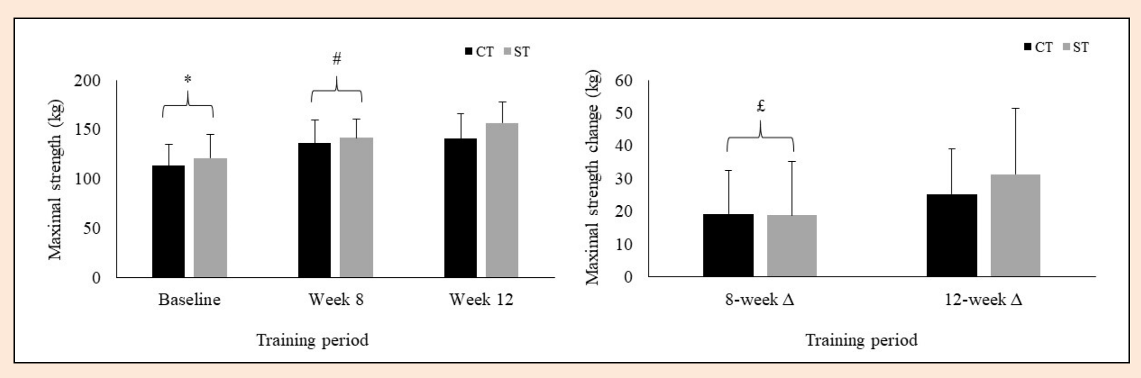

Figure 2. Lower-body absolute maximal strength during strength training only (ST) or high-intensity intermittent training plus strength training (CT). Data are mean ± standard deviation; * different from weeks 8 and 12 (p < 0.05); # different from week 12 (p < 0.05); £ different from week 12 change (p < 0.05).

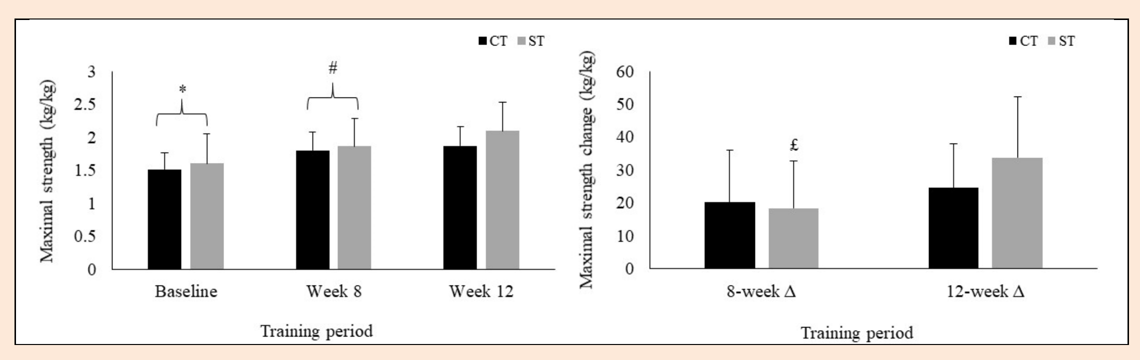

Figure 3. Lower-body relative maximal strength during strength training only (ST) or high-intensity intermittent training plus strength training (CT). Data are mean ± standard deviation; * different from weeks 8 and 12 (p < 0.05); # different from week 12 (p < 0.05); £ different from week 12 change in ST group (p < 0.05).

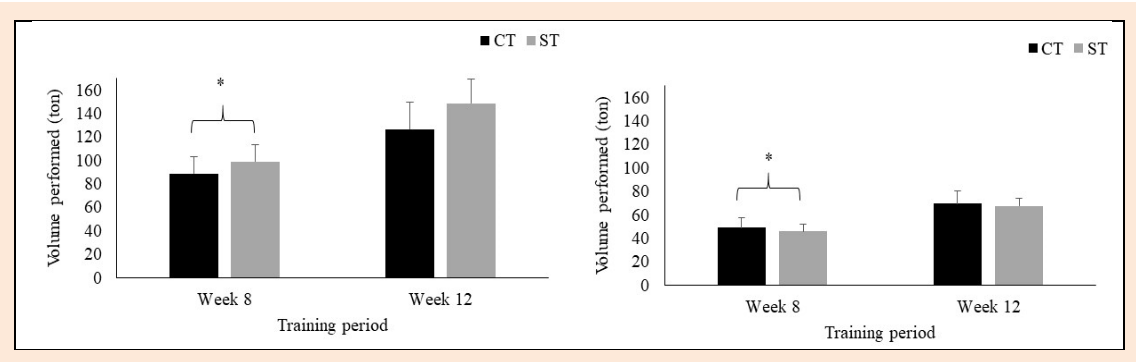

Figure 4. Accumulated strength-training volume-load during strength training only (ST) or high-intensity intermittent training plus strength training (CT). Data are mean ± standard deviation. * different from week 12 (p = 0.053).

Table 3. Volume-load and maximum number of repetitions in four sets (at 80% of maximal strength) during an isolated acute volume test throughout 12 weeks of strength training only (strength group) or high-intensity intermittent training plus strength training (concurrent training group).

	Volume-load (kg)	MNR
Strength training group		
Baseline	3542 ± 952*	38 ± 12
Week 8	4822 ± 858	42 ± 4
Week 12	5391 ± 1115	44 ± 12
Concurrent training group		
Baseline	3444 ± 1109	38 ± 11
Week 8	3990 ± 1572	37 ± 12
Week 12	3893 ± 1439	34 ± 12

Data are mean ± standard deviation; MNR: maximum number of repetitions; * different from weeks 8 and week 12 in ST group (p < 0.05).

d = 0.814 [moderate]) than baseline. There was also an interaction effect ($F_{2,34}$ = 3.62; p = 0.037), with greater values in the ST group at week 8 (p = 0.040; d = 0.786 [small]) and week 12 (p < 0.001; d = 1.94 [large]) compared to baseline with no differences between time points for the CT group. There was no effect for maximum number of repetitions.

Correlations

There was a large statistically significant correlation (Figure 5) between strength training lower-body volume-load and maximum strength change between baseline and week 8 for CT group (r = 0.656; p = 0.028); however, there were no statistical or practical correlations between for the ST group or the overall group. There were no correlations between baseline and week 12.

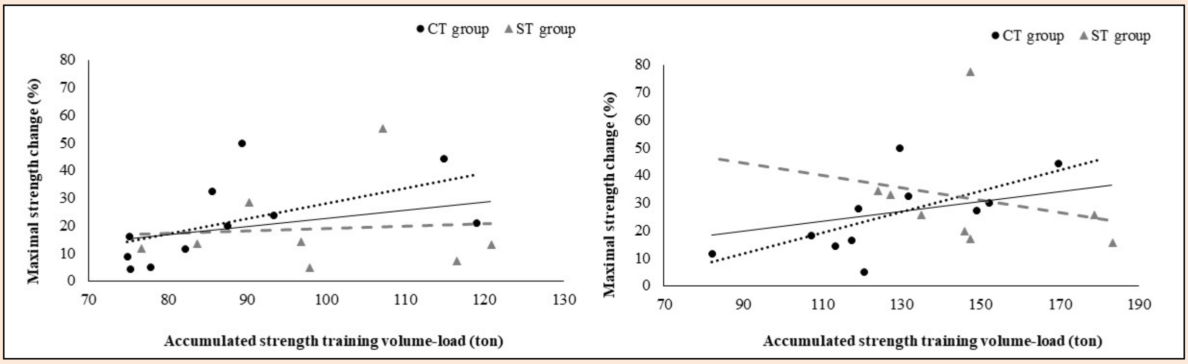

Figure 5. Relationships between changes in maximal strength and accumulated volume-load at week 8 and week 12 for the ST and CT groups. Solid trend line: overall group; grey streak trend line: ST group; black dashed trend line: CT group. There was a statistically significant positive correlation between accumulated volume-load performed and maximum strength gains in 8 weeks for CT group isolated ($p = 0.028$; $r = 0.645$).

Discussion

To our knowledge, this is the first study to compare the extended effect (8-12 weeks) of high-intensity intermittent exercise performed before strength training with isolated strength training on maximal strength, and its relationship with strength training total volume-load during training. We hypothesized that high-intensity intermittent exercise performed before strength training would decrease strength training volume-load while impairing strength gains following eight and 12 weeks of training. Results from the present study partially refute this hypothesis with similar absolute strength gains between groups following eight weeks and 12 weeks and a small impairment in maximal strength relative to body mass in the CT group following 12 weeks. This finding was supported by the ST group demonstrating an increase over 12 weeks compared to over 8 weeks, while no changes were observed in CT group. Lower-body volume-load was not different between the CT and ST groups over 12 weeks of training.

While impairments in maximal strength relative to body mass, but not absolute strength, were shown during the final 4 weeks of the training intervention in the CT group, a large effect size was observed for absolute strength gains after 12 weeks in the ST group despite the absence of statistical significance between groups. While it was expected that the CT group would perform lesser volume throughout the study, we did not find a difference between groups. However, previous research supports acute decrements in training volume during an isolated session (Bentley et al., 2000; de Souza et al., 2007; Panissa et al., 2015; Panissa et al., 2016).

Using acute protocols similar to the present study, de Souza et al. (2007) reported a decrease of 27% in leg press, while Panissa et al. (2016) reported a decrease of 30% in half squat with an interval of 30 minutes between exercises. However, in our study, we found differences between groups of 3, 17 and 27% at baseline, 8 and 12 weeks, respectively, in the isolated acute volume test with only the ST group showing improvements over time. However, no statistically significant difference between groups in accumulated volume-load was observed over the 12 weeks of training. Nevertheless, the previously mentioned acute studies were designed to compare intra-subject interference while the present study aimed to evaluate between-subjects (between-group) differences. In addition, we believe that the 10-minute recovery period between the aerobic and strength sessions, starting the strength session with an upper-body exercise, and alternating lower and upper body exercises during strength training in the current study may have contributed to the lack of differences between groups. This may have occurred by allowing additional recovery between exercises and minimizing the detrimental effects of concurrent training.

The acute negative effects of high-intensity aerobic training prior to strength exercise seem to be caused by contractile and metabolic mechanisms (Bentley et al., 2000; Inoue et al., 2016). Bentley et al. (2000) observed that the effects of high-intensity endurance exercise performed before strength exercise can induce excitation-contraction disruptions, synaptic transmission and altered nerve conduction for at least 6 h after exhausting cycling. Further, Inoue et al. (2016) investigated the influence of the order of concurrent strength and high-intensity aerobic exercise on strength performance, metabolic, and inflammatory responses using the same protocol as the present study. The authors concluded that when aerobic exercise was followed by strength training, decrements in performance and lower glucose, lactate and higher IL-6 concentrations were observed. Thus, we believe that the limited improvements during the isolated acute volume test over time for the CT group can be considered evidence of residual fatigue despite similar accumulated strength training volume-load between groups throughout the training intervention.

In the isolated acute volume test, no between-group differences were unexpectedly observed in volume-load at baseline. We can speculate that the lack of between-group differences may have been related to individual responses to ST and CT. However, the ST group increased volume-load performed compared with baseline at week 8 and week 12, and the CT group remained unchanged, while both groups maintained the same maximum number of repetitions in all time points. Thus, the increase demonstrated by the ST group in volume-load was likely a function of increased load (as demonstrated by the increase in maximum strength at week 8 and 12).

Controversial results regarding the presence or absence of CT-related interference in strength gains can be found in the literature (Kraemer et al., 1995; McCarthy et al., 2002). However, a recent study Fyfe et al. (2016) with a similar experimental design, participant characteristics, and objectives (high-intensity intermittent exercise performed before strength training, in physically active men) demonstrated that ST increased maximal strength (38%) more than CT (performed at both high and moderate intensities - 29 and 28% respectively) after 8 weeks of training, indicating an interference effect independent of aerobic exercise intensity. While it is well documented in the literature that moderate intensity exercise appears to preserve strength training volume (de Souza et al., 2007), Fyfe et al. (2016) reported trivial differences in strength gains between CT with the aerobic component performed at moderate and high-intensities while hypertrophy gains were more apparent with ST. Furthermore, Gentil et al. (2017) demonstrated no interference in strength gains when high-intensity intermittent exercise was performed prior to strength training in premenopausal women after 8 weeks of training, corroborating results from the present study.

Aerobic training volume has been considered an important variable influencing the magnitude of interference effects during CT because both frequency and duration (minutes per day) are negatively correlated with strength gains (Wilson et al., 2012). The major difference between the present and the above-cited studies involving HIIT (Fyfe et al., 2016; Gentil et al., 2017) is the dose/volume of aerobic training. Gentil et al. (2017) utilized lower duration high-intensity protocols (6-8 efforts of 60s with 90s of passive rest) performed three times a week, while Fyfe et al. (2016) utilized a protocol with slightly greater volume (5-10 efforts of 120s with 60s passive rest) performed three times a week which was similar to the protocol used in the present study (~20 efforts totaling 5km; but training only twice a week). Nonetheless, the volume of aerobic training used in our study was still lower than that used in the seminal study of Hickson (1980) which featured alternating high-intensity intermittent and continuous training completed 6 times per week over a period of 10 weeks. Thus, the lack of interference until 8 weeks as found by Gentil et al. (2017) and a slight interference between 8 and 12 weeks in the current study likely occurred due to the relatively low volume HIIT programs that were utilized.

Regarding the importance of strength training volume for long-term strength gains, Krieger (2010) observed that multiple sets of strength exercises were associated with 46% greater strength gains when compared to one set in both trained and untrained subjects. This finding supports the importance of acute training volume on long-term strength improvements. Meta-analyses have also shown the importance of training volume with respect to the type of sets (cluster or traditional sets) (Tufano et al., 2017), training to failure (Davies et al., 2016) , and the dose-response relationship (Rhea et al., 2003). On the other hand, Mattocks et al. (2017) demonstrated that simply practicing the test repeatedly could increase strength similar to high volume training. Therefore, no consensus has been made regarding the association of between training volume and strength development, particularly in resistance-trained individuals who have already experienced muscular adaptations (Ralston et al., 2017). Despite no differences in volume-load between groups in the present study, there was a significant relationship between volume-load and maximum strength in CT group. Therefore, it can be suggested that for a condition in which there is residual fatigue (i.e. concurrent training group), the volume-load performed seems to be an important aspect related to maximal strength gains.

Maximal aerobic speed improved throughout the training program with no difference between groups (7.3% for CT and 3.5% for ST after 12 weeks). Although improvement in the ST group was not expected, a recent study also showed an enhancement of the maximal aerobic speed after both strength-only and concurrent training in recreationally active females (Laird et al., 2016). This finding could be explained by enhanced efficiency of the neuromuscular system via improved coordination and motor unit recruitment, as well as morphological and musculotendinous stiffness alterations (Beattie et al., 2014). Improvements in maximal strength may also permit running at a lower relative force resulting in delayed fatigue, and, ultimately, the achievement of higher maximal aerobic speed (Tanaka and Swensen, 1998).

There are several factors that could influence individual responses to training, such as intensity, volume, frequency, repetition speed, recovery interval, and training status, as well as, lifestyle and psychological factors (Mann et al., 2014). The high variability of the currently examined data may have attenuated some of the interference effect. Despite the importance of our data, some limitations need to be considered: including small sample size, lack of dietary intake control, limited mechanistic evaluation since we did not investigate potential mechanisms related to interference, no measurement of hypertrophy and lack of familiarization with 1RM since participants were only familiarized with 12-15RM exercises. Finally, we did not examine the reverse order (strength followed by HIIT) for the CT group or separate training days in order to isolate the impairment on strength training volume-load.

In the present study, physically active men submitted to twice weekly concurrent training (high-intensity intermittent exercise followed by strength exercises) or strength training alone had similar maximal strength gains until the eighth week of training, however, the CT group experienced a lesser gain of strength between week 8 and week 12 compared with the ST group. Therefore, we suggest future research be conducted to analyze the interference effect over 12 weeks of concurrent training and to further investigate chronic adaptations by manipulating other training variables, such as aerobic training volume or inducing greater impairments in the strength training volume-load given that the interference effect on maximum strength appears to occur in specifically in the context of high volume training (Hickson, 1980; Wilson et al., 2012).

Conclusion

The combination of high-intensity intermittent exercise with strength exercises in the same session (aerobic followed by strength), may be employed during training in order to improve both capacities (aerobic and strength). The use of both types of training (high-intensity intermittent aerobic and strength) in a single session provides an alternative to separate sessions, without concern for incomplete recovery and decrements in performance, while allowing for the improvement of relevant health-related capacities.

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Key points

- The combination of HIIT with strength exercises in the same session (aerobic followed by strength), may be employed during training in order to improve both capacities (aerobic and strength).
- Maximal strength gains were not different between groups after 8 weeks, however only ST increased relative maximal strength between 8 and 12 weeks.
- There was correlation between strength training lower-body volume-load and maximum strength change between baseline and week 8 for the CT group.

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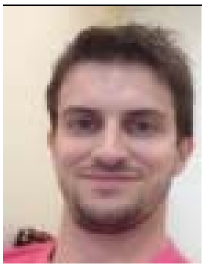

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