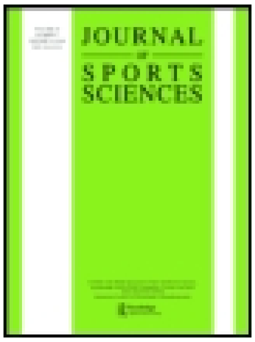

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The compatibility of concurrent high intensity interval training and resistance training for muscular strength and hypertrophy: a systematic review and meta-analysis

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ABSTRACT

The purpose of this systematic review and meta-analysis is to assess the effect of concurrent high intensity interval training (HIIT) and resistance training (RT) on strength and hypertrophy. Five electronic databases were searched using terms related to HIIT, RT, and concurrent training. Effect size (ES), calculated as standardised differences in the means, were used to examine the effect of concurrent HIIT and RT compared to RT alone on muscle strength and hypertrophy. Sub-analyses were performed to assess region-specific strength and hypertrophy, HIIT modality (cycling versus running), and inter-modal rest responses. Compared to RT alone, concurrent HIIT and RT led to similar changes in muscle hypertrophy and upper body strength. Concurrent HIIT and RT resulted in a lower increase in lower body strength compared to RT alone ($ES = -0.248$, $p = 0.049$). Sub analyses showed a trend for lower body strength to be negatively affected by cycling HIIT ($ES = -0.377$, $p = 0.074$) and not running ($ES = -0.176$, $p = 0.261$). Data suggests concurrent HIIT and RT does not negatively impact hypertrophy or upper body strength, and that any possible negative effect on lower body strength may be ameliorated by incorporating running based HIIT and longer inter-modal rest periods.

ARTICLE HISTORY
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KEYWORDS
Interval training; resistance training; concurrent training; strength; hypertrophy

Introduction

Many sports require athletes to perform repeated high-intensity exertions with minimal break between efforts (Bangsbo, 2014; Duthie, Pyne, & Hooper, 2003) and consequently, coaches often implement high-intensity interval training (HIIT) to emulate match situations and improve "on-field" performance (Dellal et al., 2008; McMillan, Helgerud, Macdonald, & Hoff, 2005; Wong, Chaouachi, Chamari, Dellal, & Wisloff, 2010). Due to muscular strength being highly correlated with frequently used movements such as jumping and sprinting times (Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004) and reducing the risk of injury (Prior, Guerin, & Grimmer, 2009) coaches often prescribe HIIT and resistance training (RT) concurrently, particularly in the pre-season (Manolopoulos, Papadopoulos, Salonikidis, Katartzi, & Poluha, 2004; Wong et al., 2010). Whilst combining multiple training modalities may appear to be time efficient, there have been reports of compromised adaptive responses when compared to single modal training, a phenomenon which has been termed 'the interference effect' (Wilson et al., 2012).

The simultaneous combination of resistance training (RT) and endurance training is known as concurrent training. Studies have shown that concurrent training can compromise muscle hypertrophy (Hickson, 1980; Kraemer et al., 1995), strength (Bell, Syrotuik, Martin, Burnham, & Quinney, 2000; Dolezal & Potteiger, 1998; Kraemer et al., 1995) and power (Hunter, Demment, & Miller, 1987; Kraemer et al., 1995; Leveritt, Abernethy, Barry, & Logan, 1999), when compared to RT alone. This supposedly results from a combination of chronic overreaching, and long-term competing adaptations at the cellular level (Leveritt et al., 1999). Interestingly, the interference effect appears to be exclusive to RT outcomes as RT appears to have little to no effect on endurance training outcomes such as VO2max (Hickson, 1980; Leveritt et al., 1999). Whilst endurance training traditionally involves continuous bouts of ≥20 minutes of aerobic exercise (e.g. running, cycling, rowing), HIIT involves short (duration) high effort (intensity) repetitions of aerobic exercises with recovery periods in-between efforts. Due to endurance training frequency and duration (i.e. volume) appearing to contribute to the interference effect observed with concurrent training (Wilson et al., 2012), it seems plausible that simultaneous HIIT and RT may not negatively affect RT adaptations. Multiple studies have assessed whether HIIT and RT can be trained concurrently without compromising the training outcomes (Balabinis, Psarakis, Moukas, Vassiliou, & Behrakis, 2003; de Souza et al., 2013; Fyfe, Bartlett, Hanson, Stepto, & Bishop, 2016; Gentil et al., 2017; Kikuchi, Yoshida, Okuyama, & Nakazato, 2016; Leveritt & Abernethy, 1999; Robineau, Babault, Piscione, Lacome, & Bigard, 2016; Robineau, Lacome, Piscione, Bigard, & Babault, 2017; Ross et al., 2009; Wilson et al., 2012). However, the results vary with some studies showing that HIIT does not impede strength development and hypertrophy (Cantrell, Schilling, Paquette, & Murlasits, 2014; de Souza et al., 2013;

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Laird et al., 2016), whilst others studies have reported contrary findings (Fyfe et al., 2016; Gentil et al., 2017; Kikuchi et al., 2016).

A previous systematic review and meta-analysis compared the effect of concurrent aerobic training and RT (Wilson et al., 2012). The authors reported that for measures of strength, power and hypertrophy, RT alone was superior to concurrent aerobic training and RT. Interestingly the total volume of training and training modality of endurance exercise appeared to play a significant role in the observed interference of training adaptations, with running, but not cycling, resulting in significant decrements in both hypertrophy and strength. To date no systematic review and meta-analysis has been conducted investigating whether concurrent HIIT and RT compromises muscle strength and hypertrophy. Although less volume of work is undertaken, HIIT can recruit higher threshold motor units which are also recruited during resistance exercise (Gollnick, Piehl, Karlsson, & Saltin, 1975). Thus, the purpose of this study is to assess whether the previously reported "interference effect" is exacerbated or ameliorated by comparing concurrent HIIT and RT to RT alone on measures of strength and hypertrophy via a systematic review and meta-analysis. Where possible, subgroup analyses were conducted to determine whether HIIT affected lean muscle mass change in the lower limbs, and whether the modality (running versus cycling) and sequencing of HIIT and RT (< versus >24 hours rest) affected training adaptations. Information gathered from this meta-analysis will provide clarity on this topic which may be useful to coaches, athletes, and recreational resistance trainers when devising concurrent HIIT and RT programs.

Methods

Search strategy

This systematic review and meta-analysis was conducted in accordance with the recommendations outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher, Liberati, Tetzlaff, Altman, & Group, 2009). A search from the earliest record up to and including September 2017 was carried out using the following electronic databases: Medline, PubMed, Scopus, SPORTDiscus and Web of Science. The search strategy employed combined the terms "strength training" OR "weight training" OR "weight lifting" OR "resistance training" OR "resistance exercise" AND "high intensity interval training" OR "HIIT" OR "interval training" OR "interval exercise" OR "high intensity intermittent training" OR "high intensity intermittent exercise" OR "sprint interval training" OR "SIT" OR "concurrent training" OR "concurrent exercise". Titles and abstracts of retrieved articles were individually evaluated by two reviewers (T.E. and A.N.) to assess their eligibility for review and meta-analysis. Any disagreements were solved by consensus by a third reviewer (D. H.). The reviewers were not blinded to the studies' authors, institutions or journals of publication. Study abstracts that did not provide sufficient information according to the inclusion criteria were retrieved for full-text evaluation. Corresponding authors of articles that were potentially eligible were contacted for any missing data or clarification of data presented.

Eligibility criteria

Articles eligible for inclusion were randomised and non-randomised comparative studies published in English that included healthy adult participants (≥18 years of age). Interventions needed to be ≥4 weeks in duration and compare a group performing HIIT combined with RT to a group performing the same RT program alone. HIIT was defined as involving repeated bouts of ≤5 minutes of exercise where intensities were either >80% maximal heart rate or >100% lactate threshold or >90% maximal oxygen uptake (VO2max), or expressed as "sprinting or HIIT". Studies needed to report changes in muscular strength via dynamic repetition maximum measurements or changes in lean muscle mass via biopsy, ultrasonography, computed tomography, dual x-ray absorptiometry, magnetic resonance imaging and/or densitometry.

Data extraction

Using a standardised, predefined form, two reviewers (A.S. and A.N.) separately and independently evaluated full-text articles. Any discrepancies were discussed until a consensus was reached with any disagreements being resolved by consultation with a third reviewer (D.H.). Data extraction was performed by one reviewer (A.S.). Relevant data regarding participant characteristics (age, sex, training status, height and body weight), and study characteristics (measurement techniques for strength or hypertrophy, training frequency, description of HIIT, resistance exercises prescribed, sets, repetitions, intensity, and intervention length) were extracted.

Quality analysis

The methodological quality of studies meeting the inclusionary criteria were assessed using a modified Downs and Black quality assessment tool (Downs & Black, 1998). A description of the scale can be found in a previous review (Davies, Kuang, Orr, Halaki, & Hackett, 2017). Briefly, scores ranged from 0 to 29 points, with higher scores reflecting higher-quality research. Scores above 20 were considered good; scores of 11–20 were considered moderate and scores below 11 were considered poor methodological quality (Laframboise & Degraauw, 2011). Studies were independently rated by 2 researchers (S.M. and A.N.) and checked for internal consistency across items before scores were merged into a spreadsheet for discussion. Disagreements between ratings were resolved by discussion or sought from a third reviewer (D.H.) if no consensus was reached by discussion.

Statistical analysis

Data is presented as mean ± standard deviation (SD) or confidence interval (CI). All analyses were conducted using Comprehensive Meta-Analysis version 2 software (Biostat Inc., Englewood, NJ, USA). The level of significance was set at $p < 0.05$ and trends were declared at $p = 0.05–0.10$). Effect size (ES) values were calculated as standardised differences in the means and expressed as Hedges' g which corrects for parameter bias due to small sample sizes (Ugille, Moeyaert, Beretvas, Ferron, & Van Den Noortgate, 2014). An ES of 0.2 was considered a small effect, 0.5 a moderate effect and 0.8 a large effect (Cohen, 1977). Within-group change in muscular strength and lean body mass were determined by calculation of the difference between pre- and post-intervention. The mean relative percentage change (post- minus pre-training of muscular strength or lean body mass, divided by pre-training muscular strength or lean body mass, multiplied by 100) was calculated for the concurrent HIIT and RT as well as RT alone groups. When studies had multiple outcomes (e.g. lean body mass results from multiple sites), the software was used to average ESs across outcomes. Where possible, a Z test was used to compare the means of two sub-groups within an analysis.

Between-study variability was examined for heterogeneity, using the I^2 statistic for quantifying inconsistency (Higgins, Thompson, Deeks, & Altman, 2003). The heterogeneity thresholds were set at I^2 = 25% (low), I^2 = 50% (moderate) and I^2 = 75% (high) (Higgins et al., 2003). A conservative random-effects model of meta-analysis was applied to the pooled data. A funnel plot and rank correlations between effect estimates and their standard errors (SE), using Kendall's τ statistic (Begg & Mazumdar, 1994), were used to determine publication bias when a significant result ($p < 0.05$) was found. The primary analysis compared the effect of concurrent HIIT and RT versus RT alone on outcomes of muscle strength and hypertrophy. Sub-analyses were performed on the modality and sequencing of HIIT to allow further exploration into whether these factors influenced the training adaptations. A sub-analysis was also performed on lower body hypertrophy.

Results

Description of studies

The database search yielded 6036 potential studies (Figure 1). Fourteen studies (Balabinis et al., 2003; Cantrell et al., 2014; de Souza et al., 2013; Fyfe et al., 2016; Gentil et al., 2017; Kikuchi et al., 2016; Laird et al., 2016; Leveritt, Abernethy, Barry, & Logan, 2003; Robineau et al., 2016, 2017; Ross et al., 2009; Sale, Jacobs, MacDougall, & Garner, 1990; Silva et al., 2012; Tsitkanou et al., 2016) met the eligibility criteria and were included in the systematic review and meta-analysis. Only 1 study (Gentil et al., 2017) was excluded from the meta-analysis for displaying a p score of <0.05 using Kendall's τ statistic. There were a total of 263 participants (182 males and 81 females) aged 18–34 years. Of the 14 studies, 4 studies (de Souza et al., 2013; Gentil et al., 2017; Kikuchi et al., 2016; Sale et al., 1990) involved "untrained" or "inactive" populations whilst the remaining studies involved "trained" or "active populations" (Table 1), however only 4 studies (Balabinis et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009) utilised semi-professional or college level subjects.

Intervention characteristics

A summary of the intervention characteristics including the HIIT and RT frequency, volume, and intensity are displayed in Table 2. Seven of 14 studies performed cycling HIIT (Cantrell et al., 2014; Fyfe et al., 2016; Gentil et al., 2017; Kikuchi et al., 2016; Leveritt et al., 2003; Sale et al., 1990; Tsitkanou et al., 2016), whilst the remaining 7 studies performed running HIIT (Balabinis et al., 2003; de Souza et al., 2013; Laird et al., 2016; Robineau et al., 2016, 2017; Ross et al., 2009; Silva et al., 2012). Eight of the 14 studies (Balabinis et al., 2003; Cantrell et al., 2014; Gentil et al., 2017; Kikuchi et al., 2016; Laird et al., 2016; Robineau et al., 2016, 2017; Ross et al., 2009) performed sprint-interval or a variation of supramaximal training whilst the remaining 6 studies (de Souza et al., 2013; Fyfe et al., 2016; Leveritt et al., 2003; Sale et al., 1990; Silva et al., 2012; Tsitkanou et al., 2016) performed a variation of HIIT with peak workload intervals reaching but not exceeding 100% VO2max.

Ten studies (Balabinis et al., 2003; Cantrell et al., 2014; Fyfe et al., 2016; Gentil et al., 2017; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009; Silva et al., 2012) prescribed upper and lower body resistance training exercises, whilst 3 studies (de Souza et al., 2013; Sale et al., 1990; Tsitkanou et al., 2016) prescribed only lower body exercises and 1 study (Kikuchi et al., 2016) prescribed only upper body exercises. The number of sets per session ranged from 1–6. All but 3 studies (Balabinis et al., 2003; Sale et al., 1990; Silva et al., 2012) prescribed resistance exercise repetitions ranging from 3–12.

Muscular strength of the lower body was measured in twelve studies (Balabinis et al., 2003; Cantrell et al., 2014; de Souza et al., 2013; Fyfe et al., 2016; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009; Sale et al., 1990; Silva et al., 2012; Tsitkanou et al., 2016) (Table 3). Six of the 12 studies (Cantrell et al., 2014; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009) assessed lower body strength via back squat 1RM, another 4 studies (de Souza et al., 2013; Fyfe et al., 2016; Sale et al., 1990; Silva et al., 2012) assessed lower body strength via leg press 1RM, whilst 2 studies (Balabinis et al., 2003; Tsitkanou et al., 2016) assessed lower body strength via leg press and back squat 1RM. Muscular strength of the upper body was measured in eight studies (Balabinis et al., 2003; Cantrell et al., 2014; Fyfe et al., 2016; Gentil et al., 2017; Kikuchi et al., 2016; Robineau et al., 2016, 2017; Silva et al., 2012). Six of 8 studies (Balabinis et al., 2003; Cantrell et al., 2014; Fyfe et al., 2016; Robineau et al., 2016, 2017; Silva et al., 2012) assessed upper body strength via 1RM bench press, whilst the remaining 2 studies (Gentil et al., 2017; Kikuchi et al., 2016) assessed upper body strength via 1RM elbow flexion.

Lean muscle mass changes were reported in seven studies (Cantrell et al., 2014; de Souza et al., 2013; Fyfe et al., 2016; Kikuchi et al., 2016; Laird et al., 2016; Sale et al., 1990; Tsitkanou et al., 2016) (Table 4). Three studies (Cantrell et al., 2014; Fyfe et al., 2016; Laird et al., 2016) assessed muscular hypertrophy via change in total lean body mass, using dual x-ray absorptiometry (DXA) and another 3 studies assessed changes in lean muscle mass of the lower body (i.e. thigh) using computed-tomography (CT) (Sale et al., 1990), ultrasonography (Tsitkanou et al., 2016), or magnetic resonance imaging (MRI) (de Souza et al., 2013). Only one study (Kikuchi et al., 2016) assessed lean muscle mass change of the upper limbs via change in bicep brachii and brachialis muscles using MRI.

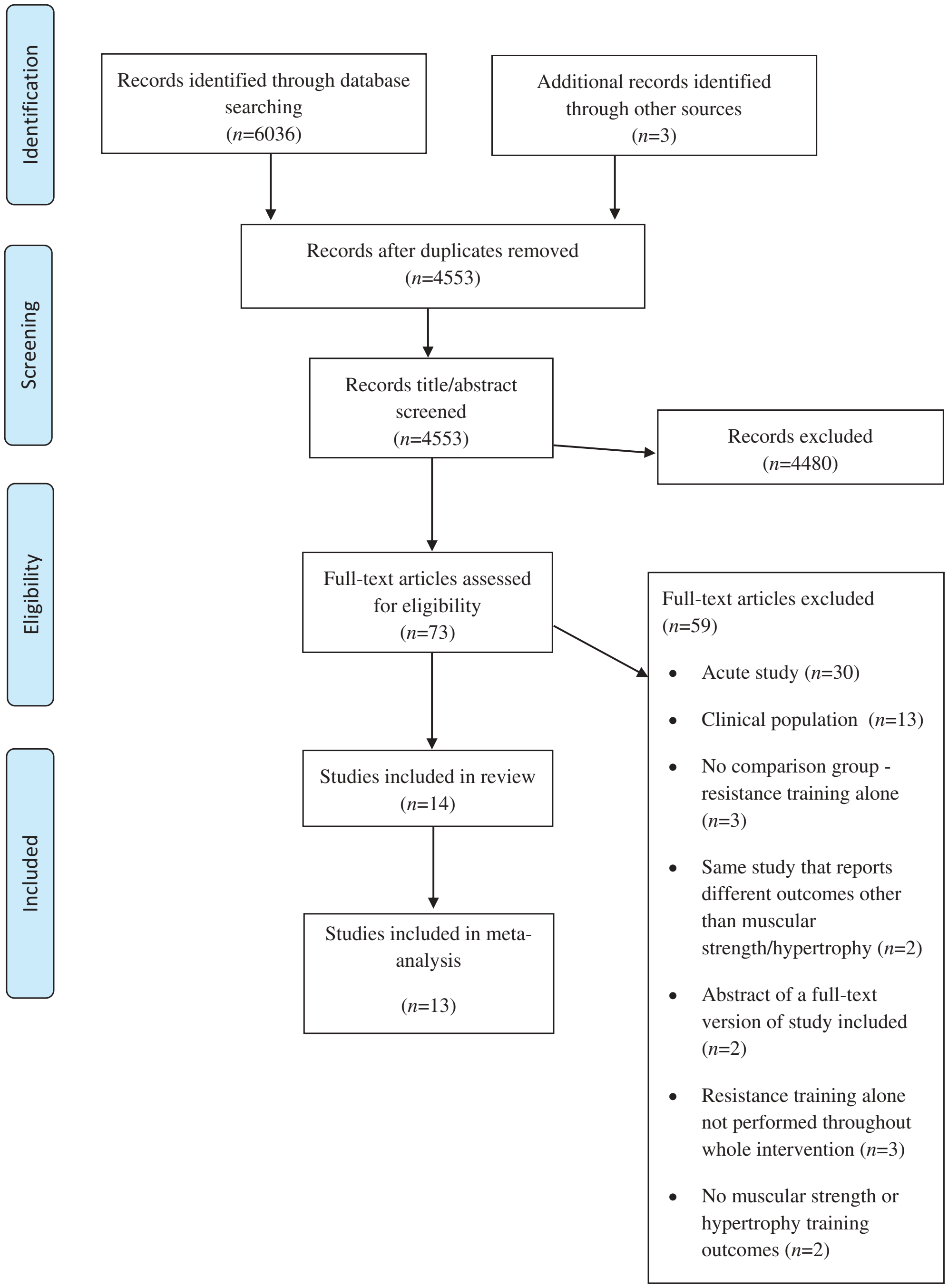

Figure 1. PRISMA flow diagram of literature screening process.

Primary analyses: muscle strength and hypertrophy

The effect of current HIIT and RT on upper and lower body strength is shown in Figure 2. There was a significant small negative effect size favouring RT alone when compared to concurrent HIIT and RT on lower body strength (ES = –0.248, 95%CI: –0.495 to –0.001; p = 0.049). Low (non-significant) heterogeneity amongst studies was observed (I^2 = 0, p = 0.925). For upper body strength, there were no significant effects for concurrent HIIT and RT compared to RT alone (ES = 0.016, 95% CI: –0.319 to 0.351; p = 0.927). Low (non-significant) heterogeneity amongst studies was observed (I^2 = 0, p = 0.889). Also, there was no significant effect of concurrent HIIT and RT compared to RT alone on changes in lean muscle mass (ES = 0.106, 95% CI: –0.224 to 0.435; p = 0.529) (Figure 2). Low (non-significant) heterogeneity was observed amongst studies (I^2 = 0, p = 0.996).

Sub-analyses: lower body muscle strength and hypertrophy

A sub-analysis was performed assessing the effect of the modality of HIIT when performed with RT versus RT alone on lower body strength. Twelve studies (Balabinis et al., 2003; Cantrell et al., 2014; de Souza et al., 2013; Fyfe et al., 2016; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009; Sale et al., 1990; Silva et al., 2012;

Table 1. Participant characteristics of included studies.

Study	Group	Number of participants	Sex: M [%]	Age [years][a]	Height [cm] [a]	Weight [kg][a]	Training status
Balabinis et al., 2003	HITT + RT	7	100	22.6 ± 0.8	188 ± 0.5	86.1 ± 0.7	Trained
	RT	7	100	22.2 ± 0.4	188 ± 0.9	85.4 ± 0.5	Trained
Cantrell et al., 2014	HIIT + RT	7	100	26.6 ± 6.6	176 ± 6.5	80.9 ± 11.2	Active
	RT	7	100	24.7 ± 5.9	175 ± 9.1	78.1 ± 9.7	Active
de Souza et al., 2013	HIIT + RT	11	100	22.5 ± 3.9	176 ± 8.1	72.9 ± 9.8	Untrained
	RT	11	100	25.9 ± 6.4	172 ± 4.3	73.5 ± 16.1	Untrained
Fyfe et al., 2016	HIIT +RT	8	100	29.5 ± 2.1	181.3 ± 5.8	82.6 ± 10.9	Active
	RT	8	100	28.6 ± 6.4	182.7 ± 7.6	86.6 ± 14	Active
Gentil et al., 2017	HIIT + RT	8	0	32.6 ± 3.9	1.65 ± 0.10	68.8 ± 13.8	Inactive
	RT	8	0	34.1 ± 4.3	1.66 ± 0.05	70.1 ± 9.3	Inactive
Kikuchi et al., 2016	HIIT + RT	6	100	20 ± 1.8	171.2 ± 4.9	64.5 ± 4.7	Untrained
	RT	6	100	20 ± 1.8	171.2 ± 4.9	64.5 ± 4.7	Untrained
Laird et al., 2016	HIIT + RT	12	0	20.2 ± 1.5	170.8 ± 5	63.3 ± 9.9	Active
	RT	14	0	20.4 ± 1.9	168.7 ± 2.2	62.6 ± 8.2	Active
Leveritt et al., 2003	HIIT + RT (males)	3	100	19.3 ± 1.5	183.3 ± 3.1	84.4 ± 10.7	Active
	RT (males)	5	100	19.2 ± 1.3	178.6 ± 3.4	71.7 ± 9.4	Active
	HIIT+ RT (females)	6	0	18.3 ± 0.8	165.3 ± 3.2	64.5 ± 15.3	Active
	RT (females)	3	0	18.3 ± 0.6	162.3 ± 1.5	55.8 ± 1.6	Active
Robineau et al., 2016	HIIT + RT	15	100	24.3 ± 3.8	172.4 ± 41.7	85.7 ± 11.5	Active
	RT	10	100	25.2 ± 4.4	180.7 ± 7.4	90.8 ± 14.5	Active
Robineau et al., 2017	HIIT + RT	10	100	26.4 ± 3.0	179.7 ± 8.0	89.3 ± 10.3	Trained
	RT	11	100	27.5 ± 2.5	177.3 ± 5.6	89.4 ± 14.2	Trained
Ross et al., 2009	HIIT + RT	10	100	19.8 ± 1.2	182.5 ± 5	93.3 ± 11.6	Trained
	RT	9	100	19.9 ± 1.4	181.7 ± 6.2	93.5 ± 12.6	Trained
Sale et al., 1990	HIIT + RT	8	50	20.9 ± 0.5	169.2 ± 4.7	65.7 ± 5.1	Untrained
	RT	8	50	20.9 ± 0.5	169.2 ± 4.7	65.7 ± 5.1	Untrained
Silva et al., 2012	HIIT + RT	11	0	24.3 ± 5.0	166.7 ± 4.0	59.0 ± 5.9	Active
	RT	12	0	23.5 ± 2.5	165.8 ± 6.5	59.2 ± 8.3	Active
Tsitkanou et al., 2016	HIIT + RT	11	100	21.8 ± 0.6	177.4 ± 1.5	74.2 ± 2.1	Active
	RT	11	100	21.8 ± 0.6	177.4 ± 1.5	74.2 ± 2.1	Active

[a] Data are reported as mean ± SD or as a range.
cm = centimetres, kg = kilograms, SD = standard deviation, HIIT = high intensity interval training, RT = resistance training.

Tsitkanou et al., 2016) provided sufficient information for the calculation of mean differences, effect size, and 95% confidence intervals (95%CI). Seven studies utilised running HIIT as part of their concurrent training program (Balabinis et al., 2003; de Souza et al., 2013; Laird et al., 2016; Robineau et al., 2016, 2017; Ross et al., 2009; Silva et al., 2012), whilst the remaining 5 studies utilised cycling HIIT (Cantrell et al., 2014; Fyfe et al., 2016; Kikuchi et al., 2016; Leveritt et al., 2003; Sale et al., 1990; Tsitkanou et al., 2016). There was a trend for a small negative effect favouring RT alone compared to concurrent HIIT-cycling and RT on lower body strength (ES = –0.377, 95%CI: –0.792 to –0.037, p = 0.074). There was no effect of concurrent HIIT-running and RT compared to RT alone on lower body strength (ES = –0.176, 95%CI: –0.484 to 0.131, p = 0.261). There was no statistical difference between the means for HIIT-cycling versus running and RT on lower body strength (p = 0.18). Low (non-significant) heterogeneity was observed amongst studies (I^2 = 0, p = 0. 93)

A sub-analysis was performed assessing the effect of concurrent HIIT and RT with rest and no rest between modes of training vs RT alone on lower body strength. Twelve studies (Balabinis et al., 2003; Cantrell et al., 2014; de Souza et al., 2013; Fyfe et al., 2016; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009; Sale et al., 1990; Silva et al., 2012; Tsitkanou et al., 2016) provided sufficient information for the calculation of mean differences, effect size, and 95% confidence intervals (95%CI). Three studies (Cantrell et al., 2014; Robineau et al., 2016, 2017) implemented rest periods of 24 hours whilst 10 studies (Balabinis et al., 2003; de Souza et al., 2013; Fyfe et al., 2016; Laird et al., 2016; Leveritt et al., 2003; Robineau et al., 2016; Ross et al., 2009; Sale et al., 1990; Silva et al., 2012; Tsitkanou et al., 2016) implemented HIIT protocols with <24 hours rest. One study (Robineau et al., 2016) had multiple concurrent HIIT and RT groups in which both the 0-hour rest group and 24-hour rest group were included in the analysis. The analysis showed a trend for <24 hours rest between HIIT and RT to favour the RT alone group (ES = –0.263, 95%CI: –0.549 to 0.023, p = 0.071), however the incorporation of an inter-modal rest period of >24 hours resulted in similar changes between the concurrent HIIT and RT group and RT alone group (ES = –0.078, 95%CI: –0.575 to –0.419, p = 0.759). A comparison of means showed no difference (p = 0.40) between the two analyses. Low (non-significant) heterogeneity was observed amongst the analyses (I^2 = 0, p = 0. 93, respectively).

A sub-analysis was performed assessing the effect of concurrent HIIT and RT vs RT alone on lower limb lean muscle mass. Four studies (de Souza et al., 2013; Fyfe et al., 2016; Sale et al., 1990; Tsitkanou et al., 2016) provided sufficient information for the calculation of mean differences, effect size, and 95% confidence intervals (95%CI). There was no significant effect of concurrent HIIT and RT compared to RT alone on lean muscle mass change in the lower limbs (ES = 0.158, 95% CI: –0.296 to 0.612; p = 0.495). Low (non-significant) heterogeneity was observed amongst studies (I^2 = 0, p = 0.993).

Methodological quality

The methodological quality of studies was considered moderate based on a mean ± SD rating score of 16.2 ± 1.9 out of a possible score of 29. All studies scored 0 (not reported or unable to

Table 2. Training characteristics of included studies.

Study	Group	Exercise prescription	Frequency [days/week]	Duration [weeks]
Balabinis et al., 2003	HIIT + RT	HIIT: 1–8 repetitions of 30–90 sec sprints @ 85%MHR – full speed. RT (7 h later) 1–5 sets of 3–40 rep @ 40–85% 1RM of HS, BP, LP, + LPD	4/7	7
	RT	RT: Same as above	4/7	7
Cantrell et al., 2014	HIIT + RT	HIIT: 4–6 x 20 sec cycling efforts (max) ergometer. RT (separate day): 3 x 4-6RM of BS, BP, KE, KF, LPD, + SP	4/7	12
	RT	RT: Same as above	4/7	12
de Souza et al., 2013	HIIT + RT	HIIT: 15–20 x 60 sec running @ 80-100VO$_{2max}$. RT (≤ 5 min later): 3–5 x 6-12RM of LP, KE, + KF	2/7	8
	RT	RT: same as above	2/7	8
Fyfe et al., 2016	HIIT + RT	HIIT: 5–11 x 2-min cycling @ 120–150% LT. RT (10 min later): 3–5 x 4–12 rep @ 65–90% 1RM of LP, BP, SR, KE, KF, DP, LPD, + LG	2–3/7	8
	RT	RT: Same as above.	2–3/7	8
Gentil et al., 2017	HIIT + RT	HIIT: 6–8 x 60 sec cycling efforts @ 7–10 RPE (CR10). RT (10 min later): 8–12 rep of supersets (intensity NR).	3/7	8
	RT	RT: Same as above	3/7	8
Kikuchi et al., 2016	HIIT + RT	HIIT: 4 × 30 sec cycling efforts (max) using resistance = 7.5% of participants' BW. RT (immediately following): 3 × 10 rep @ 80% 1RM of BC	3/7	8
	RT	RT: Same as above	3/7	8
Laird et al., 2016	HIIT + RT	HIIT: 8 × 20 sec running @ 110–120% VO$_{2max}$. RT (4 hours later): 3–5 x 3–10 rep @ 70–87.5% 1RM of BS, BOR, BP, AB, SJ, DL, SP + BE	3/7	11
	RT	RT: Same as above	3/7	11
Leveritt et al., 2003	HIIT + RT	HIIT: 5 min cycling efforts @ 40, 60, 80, 100 and 100% VO$_2$peak. RT (immediately following): 3 x 4-10RM of KE, KF, BP, LPD, BC, LR, + AB	3/7	6
	RT	RT: Same as above	3/7	6
Robineau et al., 2016	HIIT + RT	HIIT: 3 × 15 sec running @ 120% MAV. RT (immediately following) 3–4 x 3–10RM of HS, LP, BP,+ BR	2/7	9
	RT	RT: Same as above	2/7	9
Robineau et al., 2017	HIIT + RT	HIIT: 4–8 x 30 sec sprinting (max effort). RT (performed 24 h prior): 3 x 3-10 rep @ 70–90% 1RM of BP, HS, KE, + DL	4/7	8
	RT	RT: Same as above	4/7	8
Ross et al. 2009	HIIT + RT	HIIT: 8–12 rep x 40–60 m sprints using resistance = 0–25% of participants' BW. RT (following HIIT on 2 days and alone on 2 days): 3–4 x 6–10 rep of 8–9 circuit style exercises	4/7	7
	RT	RT: Same as above	4/7	7
Sale et al., 1990	HIIT + RT	HIIT: 3–5 min efforts cycling @ 90–100 VO$_{2max}$. RT (immediately following): 6 x 15-20RM of LP	3/7	22
	RT	RT: Same as above	3/7	22
Silva et al., 2012	HIIT + RT	HIIT: 25 × 60 sec running @ vVO$_{2max}$. RT (2 min following): 2 3 x 8-18RM of LP, KE, KF, BP, CF, UR, + AB	2/7	11
	RT	RT: Same as above	2/7	11
Tsitkanou et al., 2016	HIIT + RT	HIIT: 10 × 60 sec cycling @ 100% W$_{max.}$ RT (10 min later): 4 x 6RM of LP + HS	2/7	8
	RT	RT: Same as above	2/7	8

HIIT = high intensity interval training; RT = resistance training; % = percentage; MHR = maximum heart rate; rep = repetitions; 1RM = one repetition maximum; RM = repetition maximum; sec = seconds; min = minutes; h = hours; BW = body weight; RPE = rating of perceived exertion; CR = category ratio; max = maximum; MAV = maximal aerobic velocity; Wmax = workload maximum; vVO$_{2max}$ = velocity at maximal oxygen uptake; VO$_{2max}$ = maximal oxygen uptake; VO$_{2peak}$ = peak oxygen uptake; LT = lactate threshold; HS = half squat; BP = bench press; LP = leg press; LPD = lat pulldown; BS = barbell squat; KE = knee extension; KF = knee flexion; SP = shoulder press; SR = seated row; DP = dumbbell press; LG = lunge; BC = bicep curl; BOR = bent over row; AB = abdominal exercise; SJ = squat jump; DL = dead lift; BE = back extension; LR = lateral raise; UR = upright row; BR = bench row; CF = chest fly; NR = not reported.

determine) for reporting of adverse events, participants being representative of population where they were recruited, blinding of participants to the intervention, period of time participants were recruited, concealed intervention assignment and adjusting for confounding in analyses. All studies reported the aims and purpose of the study, outcome measures, characteristics of participants, main findings clearly described, point estimates of random variability, made clear any data dredging and main outcome measures used were accurate. Outcome measures of muscular strength and hypertrophy were considered valid and reliable. Three studies reported compliance to each intervention with the range being 93–98% (Cantrell et al., 2014; Fyfe et al., 2016; Laird et al., 2016). Only 2 studies (Balabinis et al., 2003; Gentil et al., 2017) did not use a randomisation protocol. Seven studies reported that exercise sessions were supervised by trained personnel (Balabinis et al., 2003; Cantrell et al., 2014; Gentil et al., 2017; Kikuchi et al., 2016; Laird et al., 2016; Leveritt et al., 2003; Silva et al., 2012). One study (Gentil et al., 2017) was excluded from the meta-analysis for demonstrating bias as per Kendall's τ statistic.

Discussion

This is the first systematic review and meta-analysis to compare the effects of concurrent HIIT and RT to RT alone on outcomes of muscle strength and hypertrophy. The results indicate that the groups had similar increases in upper body strength and muscular hypertrophy. However, there was a greater increase in lower body strength following RT alone compared to concurrent HIIT and RT, although there was no difference between groups when comparing lower body lean muscle mass change. Sub analyses revealed that this impediment on lower body strength may manifest with cycling but not running. Also, there is some evidence that 24 hours rest between HIIT and RT may alleviate the impediment in lower body muscular strength following concurrent HIIT and RT. Studies were considered to be of moderate methodological quality.

Whilst the attenuating effect of concurrent HIIT and RT on lower body strength is statistically small, it may be of importance to certain population groups. To non-athletic populations, this small effect may not influence their exercise

Table 3. High intensity interval training and resistance training compared to resistance training alone on muscular strength.

		HIIT + RT				RT alone			
Study	Exercise	n	Pre-training [kg] [a]	Post-training [kg] [a]	Change [%][b]	n	Pre-training [kg] [a]	Post-training [kg] [a]	Change [%][b]
Balabinis et al., 2003	Leg Press	7	220.0 ± 2.0	235.3 ± 4.0	6.5	7	220.5 ± 2.4	240.7 ± 4.9	8.4
	Half Squat	7	102.1 ± 2.3	125.9 ± 5.3	18.9	7	100.8 ± 2.3	120.2 ± 1.4	16.1
	Bench Press	7	85.2 ± 1.3	110.8 ± 3.9	23.1	7	84.4 ± 0.5	110.5 ± 2.1	23.6
Cantrell et al., 2014	Back Squat	7	114.4 ± 24.1	147.6 ± 32.7	29.0	7	115.2 ± 13.9	153.1 ± 19.1	32.9
	Bench Press	7	98.4 ± 22.2	111.1 ± 22.8	12.9	7	96.0 ± 11.5	107.7 ± 10.8	12.2
de Souza et al., 2013	Leg press	11	268.4 ± 47.6	315.7 ± 63.5	17.6	11	270.3 ± 45.5	320.3 ± 57.0	18.5
Fyfe et al., 2016	Leg press	8	299.0 ± 56.0	383.0 ± 60.0	28.1	8	301.0 ± 59.0	412.0 ± 53.0	36.9
	Bench Press	8	78.0 ± 15.0	90.0 ± 15.0	15.4	8	70.0 ± 21.0	83.0 ± 22.0	18.6
Gentil et al., 2017	Bicep curl	8	12.9 ± 3.2	14.0 ± 1.5	8.5	8	13.0 ± 1.8	15.9 ± 2.5	22.3
Kikuchi et al., 2016	Bicep curl	6	19.2 ± 5.6	27.5 ± 8.1	43.2	6	21.7 ± 4.1	29.6 ± 5.8	36.4
Laird et al., 2016	Back Squat	12	113.2 ± 29.0	NR	6.1 (17.0 ± 3.6[c])	14	85.7 ± 23.9	NR	32.8 (18.1 ± 4.4[c])
Leveritt et al., 2003	Back Squat	9	103.0 ± 30.0	NR	25.2 (26.0 ± 18.0[c])	8	115.0 ± 39.0	NR	28.7 (33.0 ± 17.0[c])
Robineau et al., 2016	Back Squat	15	156.0 ± 20.3	182.0 ± 28.5	16.8	10	152.5 ± 24.6	190.0 ± 38.4	23.9
	Bench press	15	87.5 ± 22.2	94.5 ± 23.3	8.4	10	85.5 ± 13.8	95.3 ± 14.7	11.6
Robineau et al., 2017	Back Squat	10	161.0 ± 18.7	184 ± 38.6	12.8	11	161.4 ± 18.2	187.3 ± 34.1	15.0
	Bench press	10	95.0 ± 19.3	102.5 ± 21.6	7.7	11	89.3 ± 12.3	99.5 ± 14.2	11.4
Ross et al., 2009	Back Squat	10	166.8 ± 28.1	175.2 ± 26.6	5.0	9	158.1 ± 34.2	164.6 ± 29	4.1
Sale et al., 1990	Leg press	8	103.8 ± 14	125.0 ± 11.0	20.4	8	101.0 ± 14.0	131.5 ± 15.0	30.2
Silva et al., 2012	Leg press	11	104.2 ± 19.6	152.3 ± 26.3	46.8	12	89.8 ± 16.8	135.3 ± 29	52.6
	Bench press	11	32.0 ± 5.5	37.5 ± 5.9	17.7	12	29.5 ± 6.5	35.4 ± 6.9	20.8
Tsikanou et al. 2016	Half squat	10	150.5 ± 6.4	187.0 ± 6.2	25.0	11	149.5 ± 8.7	191.8 ± 7.7	30.5
	Leg press	10	259.0 ± 18.5	335.5 ± 14.1	32.3	11	258.6 ± 16.2	355.9 ± 17.2	39.3
Mean					**19.4**				**23.9**

[a] Data are reported as mean ± SD or as a range.
[b] Calculated as post-training value minus pre-training value, divided by pre-training value, multiplied by 100.
[c] Value expressed in kilograms
HIIT = high intensity interval training; RT = resistance training

Table 4. High intensity interval training and resistance training compared to resistance training alone on muscular hypertrophy.

		HIIT + RT				RT alone			
Study		n	Pre-training [kg][a]	Post-training [kg][a]	Change [%][b]	n	Pre-training [kg][a]	Post-training [kg][a]	Change [%][b]
Cantrell et al., 2014	TLBM	7	59.1 ± 8.0	59.9 ± 8.7	1.4	7	57.3 ± 5.3	57.3 ± 4.2	0
de Souza et al., 2013	LT-CSA	11	8340.8 ± 1000[c]	8996.8 ± 919.5[c]	7.8	11	8332.4 ± 893.3[c]	8849.5 ± 893.3[c]	6.2
	RT-CSA		8261.4 ± 1002[d]	8882.7 ± 868.4[d]	7.5		8215.4 ± 898.8[d]	8668 ± 952.4[d]	5.0
Fyfe et al., 2016	TLBM	8	60.1 ± 6	60.9 ± 5.5	1.6	8	60.9 ± 7.2	61.7 ± 6.5	1.6
	ULBM		38.6 ± 3.7	39.1 ± 3.5	1.4		39.7 ± 5.5	39.8 ± 5.1	0.4
	LLBM		21.4 ± 2.5	21.9 ± 2.5	2.2		21.2 ± 2.2	22.0 ± 1.8	4.1
Kikuchi et al., 2016	UL-CSA	6	13.6 ± 1.4[d]	16.3 ± 3.5[d]	19.9	6	14.2 ± 2.0[d]	16.6 ± 1.1[d]	16.9
Laird et al., 2016	TLBM	12	38.7 ± 1.3	40.6 ± 2.2	4.9	14	38.3 ± 2.5	39.8 ± 2.6	3.9
Sale et al., 1990	LE-CSA	8	68.6 ± 7.0	76.5 ± 8.9	11.5	8	67.0 ± 7.8	75.5 ± 8.6	12.7
Tsitkanou et al., 2016	LE-CSA	10	78.0 ± 2.1	96.0 ± 2.9	23.0	11	75.8 ± 3.5	95.2 ± 5.0	25.6
Mean					**8.1**				**7.6**

[a] Pre- and post-training values are presented as mean ± SD (standard deviation).
[b] Calculated as post-training value minus pre-training value, divided by pre-training value, multiplied by 100.
[c] Data represented in mm^2 (millimetres).
[d] Data represented in cm^2 (centimetres).
HIIT = high intensity interval training; RT = resistance training; % = percentage; TLBM = total lean body mass, LT-CSA = left thigh cross sectional area; RT-CSA right thigh cross sectional area; ULBM = upper limb lean body mass; LLBM = lower limb lean body mass; UL-CSA = upper limb cross sectional area; LE-CSA = leg extensor cross sectional area.

behaviour or programming, however in an elite sporting context; small differences in lower body strength may have a meaningful impact on performance (e.g. sprinting and jumping ability). In light of this, and given the studies in this review varied in training methodology, it seems that the manner in which concurrent HIIT and RT is executed could either exacerbate or ameliorate the reported "interference effect". Based on the results of the sub-analyses, coaches and athletes need to carefully consider the modality and sequencing when programming concurrent training.

The analysis showed that modality may play a role in preventing the attenuation of muscular strength following concurrent training. Previously, Wilson et al. (2012) found that only running based endurance exercise and not cycling led to significant decrements in both hypertrophy and strength, a finding they presumed was linked to the greater eccentric component of running and consequential muscle damage not seen in more concentric-heavy exercises such as cycling. However, inferring exercise induced muscle damage as a causal mechanism for decreased strength and hypertrophy is

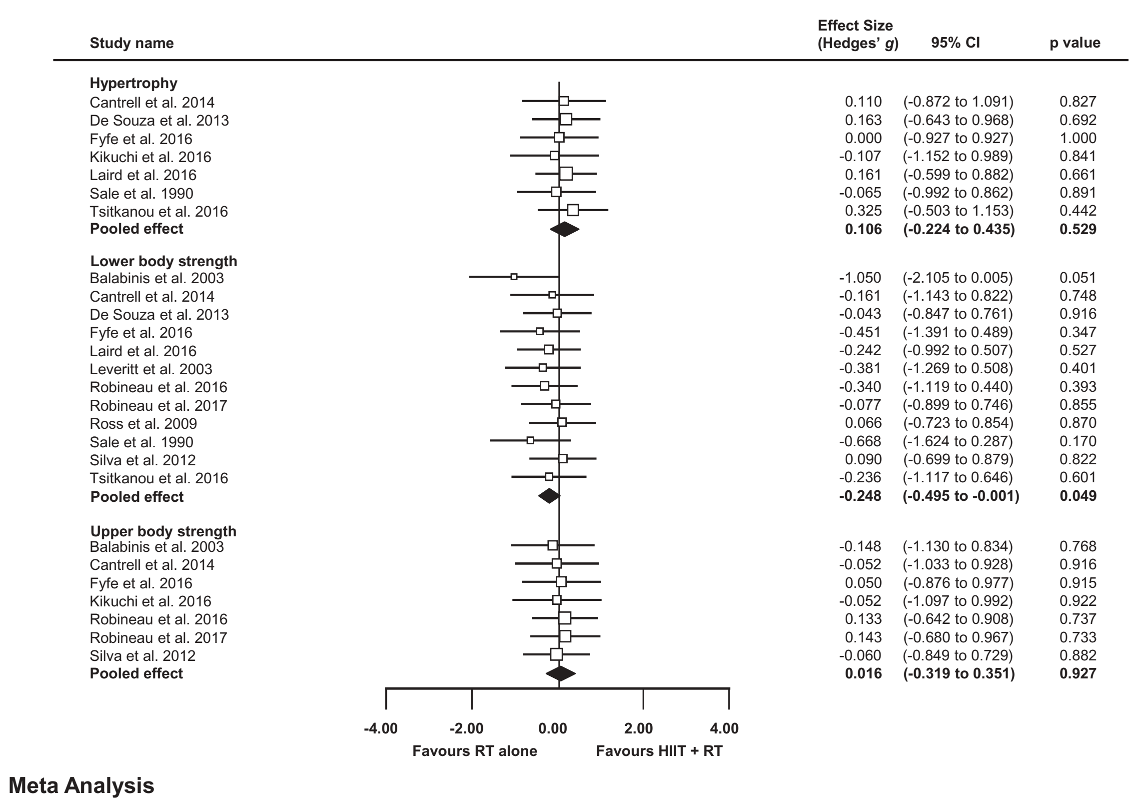

Figure 2. Effect of concurrent high intensity interval training and resistance training versus resistance training alone on muscle strength and hypertrophy.
The *open squares* and *error bars* signify the standardised difference (*Std diff*) values in the means (effect size) and 95% confidence interval (*CI*) values, respectively. The *open diamond* represents the pooled effect sizes.
HIIT: High intensity interval training; RT = resistance training.

debatable as exercise induced muscle damage is known to decrease after the first exercise session, a phenomena known as "the repeated bout effect" (McHugh, 2003). The current review aimed to determine whether concurrent RT and high intensity bouts of short duration and distance would lead to similar findings as the Wilson et al. (2012) review on concurrent RT and aerobic training. Because HIIT recruits from higher threshold motor units, frequently recruited in high intensity RT, it would be reasonable to hypothesise that fatigue-related decreases in muscle strength would occur in both the running and cycling groups. Interestingly, when we compared the ESs of HIIT-running to HIIT-cycling, only the latter showed a trending for a negative ES favouring RT alone for lower body strength development indicating that HIIT-cycling and not HIIT-running may attenuate muscular strength development in the lower limbs. However, when the means of the two groups were compared using a z test, there was no significant difference. Therefore, further field studies are required to assess whether HIIT-running can ameliorate the interference effect commonly associated with concurrent training.

Previously, aerobic training has been shown to negatively impair force production and power during ensuing RT, a finding previously attributed to the residual fatigue associated with aerobic exercise (Leveritt et al., 1999). This impaired force production capacity of muscles following aerobic exercise has been shown to last for at least 6 hours (Leveritt & Abernethy, 1999). Bentley, Zhou, and Davie (1998) showed that 24 hours of recovery following both continuous aerobic training, and HIIT, is sufficient for muscle force production capacity to return to baseline levels. Consequently, by strategically sequencing training sessions and incorporating adequate recovery periods between training modalities (HIIT and RT), researchers have been able to diminish the interference effect (Robineau et al., 2017) and in some cases even eliminate it (Robineau et al., 2016).

Mechanisms

The mechanisms responsible for muscular strength have historically been associated with muscle morphology and size, and neural adaptations such as motor unit recruitment (Hakkinen, Alen, & Komi, 1985). There are two possible mechanistic explanations for the inferior increase in lower body strength following concurrent HIIT and RT compared to RT alone. Firstly, previous studies have shown aerobic exercise and RT may recruit from the same motor unit (MU) pool (Nelson, Arnall, Loy, Silvester, & Conlee, 1990) particularly for aerobic exercise of >90% VO2max (Sale, 1987), thus fatiguing the MU's neurophysiological capability to generate force efficiently (de Souza et al., 2007) potentially impeding the subjects ability to perform RT at the prescribed intensities. Secondly, during HIIT, energy production is generally anaerobic in nature and thus the accumulation of metabolic by-products such as lactate, and of hydrogen ions and inorganic phosphate in the sarcoplasm have been reported to inhibit contractile force (Ament & Verkerke, 2009; Sahlin, 2014). Because upper body strength was not impeded by concurrent HIIT and RT it is likely that the interference effect occurs only in the predominant muscle groups utilised during HIIT consequently indicating peripheral fatigue may be culpable for the observed attenuation of lower body muscular strength in our analysis.

Aerobic exercise has been shown to increase adenosine monophosphate-activated protein kinase (AMPK) and eukaryotic translation initiation factor-4E-binding protein 1 (4E-BP1) and that the degree of activation is relative to intensity (Rose, Bisiani, Vistisen, Kiens, & Richter, 2009), in which case activation is observed at intensities >60% maximal aerobic capacity (Chen et al., 2003; Richter & Ruderman, 2009). In rodent models, the activation of AMPK has been shown to impede mammalian target of rapamycin complex 1 (mTORC1) signalling (Bodine et al., 2001; Bolster, Crozier, Kimball, & Jefferson, 2002), a potent kinase which stimulates muscular hypertrophy. Considering this information, Fyfe, Bishop, and Stepto (2014) speculated that HIIT may exacerbate the acute molecular interference when compared to moderate intensity training. This hypothesis was later tested in a human study (Apro et al., 2015) where despite HIIT activating AMPK, there appeared to be no inhibition of resistance training–induced mTORC1 signalling. Consequently, it has been hypothesised that factors which play a key role in the protein breakdown, muscle remodelling, and adaptation to training, had potentially ameliorated the alleged interference effect of concurrent exercise (Borgenvik, Apro, & Blomstrand, 2012; Mascher et al., 2008). In this light, and because post exercise mTORC1 signalling changes correlate with muscle hypertrophy in some but not all studies (Fyfe & Loenneke, 2018), there is insufficient evidence to attribute the attenuation of muscular hypertrophy to AMPK-dependent inhibition of mTORC1 signalling pathways as previously proposed (Bodine et al., 2001; Bolster et al., 2002; Kikuchi et al., 2016). Our data show that concurrent HIIT and RT does not impair hypertrophy, possibly because the exercise-induced stimulation of anabolic pathways appear to be greater than the catabolic response (Kazior et al., 2016).

Limitations

This study has several limitations which should be considered before interpreting these findings. Firstly, due to the small number of studies currently available, studies varying in duration, intensity, volume, and sequencing were pooled together for the analyses of lower and upper body strength and hypertrophy. Secondly, due to the limited number of studies with specific training interventions, particularly those incorporating 24-hours recovery, there was a significant discrepancy between number of participants in each of the subgroups (>24 hours break n = 29, <24 hours break n = 102). It is therefore difficult to conclude with certainty that increased recovery periods would ameliorate any interference effects. Thirdly, variations in intervention duration meant we were unable to comment on whether the impedance of lower body strength is immediate or occurs after a certain period. Hickson (1980) showed that the interference effect only manifested after the 8th week of training, which Kraemer et al. (1995) attributed to overtraining. Finally, despite encompassing all healthy adult subjects in the analysis, differences in training status have been shown to considerably alter the physiological response (Peterson, Rhea, & Alvar, 2005). A recent review suggested the interference effect primarily manifests in moderate to highly trained individuals and is also dependent on the training program length (Coffey & Hawley, 2017). Only 4 studies (Balabinis et al., 2003; Robineau et al., 2016, 2017; Ross et al., 2009) included in this review incorporated trained athletes who competed at a college or semi-professional level, whilst the remaining studies were performed on recreationally active and inactive individuals. Therefore, coaches should consider the training status of the athlete when interpreting the findings from the present review.

Conclusion

Despite the limitations of this systematic review and meta-analysis, these findings can be utilised by coaches to design training schedules which can maximise training outcomes relative to the specific needs of a sport. The findings of this review show that HIIT can be prescribed alongside RT without negatively impacting changes in lean muscle mass and that any attenuation of lower body muscular strength might be ameliorated by prescribing running based HIIT and providing adequate rest between HIIT and RT sessions. It is important to consider that concurrent HIIT and RT as well as RT alone both improved dynamic strength across all studies and that the difference in lower body strength between the two groups was only small. Also, because HIIT has been shown to improve VO2max (Sperlich et al., 2011), sprint time and maximal aerobic speed (Dupont, Akakpo, & Berthoin, 2004), the slight reduction in lower body strength may be a small price to pay for improvements in other key aspects of sporting performance particularly under time constraints.

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A.S was involved in study selection, data extraction, statistical analysis and manuscript write up. T.E. was involved in search strategy and study selection. A.N was involved in search strategy, study selection, data extraction and risk of bias scoring. S.M was involved in data extraction and risk of bias scoring. M.H was involved in statistical analysis and manuscript write up. D.H was involved in study selection, data extraction, risk of bias scoring, and manuscript write up.

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