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The physiological effects of concurrent strength and endurance training sequence: A systematic review and meta-analysis

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ABSTRACT

We conducted a systematic literature review and meta-analysis to assess the chronic effects of the sequence of concurrent strength and endurance training on selected important physiological and performance parameters, namely lower body 1 repetition maximum (1RM) and maximal aerobic capacity (VO_2max/peak). Based on predetermined eligibility criteria, chronic effect trials, comparing strength-endurance (SE) with endurance-strength (ES) training sequence in the same session were included. Data on effect sizes, sample size and SD as well other related study characteristics were extracted. The effect sizes were pooled using, Fixed or Random effect models as per level of heterogeneity between studies and a further sensitivity analyses was carried out using Inverse Variance Heterogeneity (IVHet) models to adjust for potential bias due to heterogeneity. Lower body 1RM was significantly higher when strength training preceded endurance with a pooled mean change of 3.96 kg (95%CI: 0.81 to 7.10 kg). However, the training sequence had no impact on aerobic capacity with a pooled mean difference of 0.39 ml.kg.min^{-1} (95%CI: −1.03 to 1.81 ml.kg.min^{-1}). Sequencing strength training prior to endurance in concurrent training appears to be beneficial for lower body strength adaptations, while the improvement of aerobic capacity is not affected by training order.

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KEYWORDS
Combined training; resistance training; exercise order; training interference

Introduction

Performing strength and endurance training simultaneously in the same training period, typically called concurrent training, is a popular training strategy to develop various aspects of physiological capabilities in most sports (Balabinis, Psarakis, Moukas, Vassiliou, & Behrakis, 2003; Wong & Chaouachi, 2010). Concurrent training can also impact overall health, including cardiovascular risk factors and muscular fitness to a greater extent than each modality alone (Häkkinen, Hannonen, Nyman, Lyyski, & Häkkinen, 2003; Sheikholeslami-Vatani, Siahkouhian, Hakimi, & Ali-Mohammadi, 2015; Takeshima et al., 2004). However, the compatibility of these different training methods has been questioned as it appears that performing strength and endurance training concurrently can interfere with long-term adaptations compared to when they are performed alone (Dudley & Djamil, 1985; Glowacki et al., 2004; Hennessy & Watson, 1994; Hickson, 1980). Studies in general show that while strength performance is negatively affected by the inclusion of endurance training, concurrent training seems to have no negative impact on cardiovascular adaptations (Wilson et al., 2012). This concept is very practically relevant, because maximal strength is a major determinant of athletic performance as well as daily functioning (Beattie, Carson, Lyons, Rossiter, & Kenny, 2017; Mitchell et al., 2012). Therefore, optimizing strength adaptations with endurance training remains an important goal both for clinical and performance research.

However, it has been shown that several factors, such as exercise mode and intensity, muscle groups trained (upper vs. lower body) and subject characteristics (elite athletes vs. sedentary, young vs. old), along with inter-individual variations may influence the outcome of concurrent strength and endurance training (Docherty & Sporer, 2000; Fyfe, Bishop, & Stepto, 2014; Gergley, 2009). Additionally, the impact of sequence, that is strength training performed prior to endurance training as opposed to endurance training prior to strength training is not well known. Previous studies on this area were small, under-powered and contradictory.

It is conceivable that when one type of training is performed immediately prior to the second stimulus, acute local or systemic fatigue would interfere with the later performance (Reed, Schilling, & Murlasits, 2013). Along these lines, Sporer and Wenger (2003) demonstrated that both high-intensity interval exercise and continuous submaximal exercise bouts reduced the number of repetitions performed in strength training for at least eight hours after these sessions. Similarly, back squat performance, but not bench press repetitions, were affected immediately following a 45-min submaximal cycle session at 75% of maximal heart rate (Reed et al., 2013). Therefore, long-term adaptations may be optimised when strength and endurance training are performed on alternate days, separated by at least 24 hours (Cantrell, Schilling, Paquette, & Murlasits, 2014; Karavirta et al., 2011). On the other hand, the current literature is in conflict whether the

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order of the strength and endurance protocols in a concurrent training session impacts chronic adaptations. While a number of investigations found no effect due to sequence when analysing long-term adaptations (McGawley & Andersson, 2013; Schumann et al., 2014) other studies have demonstrated the superiority of a specific exercise sequence (Cadore et al., 2012; Tarasi, Beiki, Hossini, & Malaei, 2011). For instance, 5 weeks of concurrent training improved strength and football specific performance measures equally in elite players regardless of whether strength training was performed before or after high-intensity running in the program (McGawley & Andersson, 2013). On the other hand, Tarasi and colleagues (Tarasi et al., 2011) have reported that the endurance-strength order produced greater maximal strength and agility adaptations in high school students.

Therefore, we conducted a systematic review and meta-analyses to evaluate the chronic effects of the sequence in which the concurrent strength and endurance training were carried out. Outcome measures included selected physiological and performance parameters, that were lower body 1 repetition maximum strength (1RM) and maximal aerobic capacity (VO_2max/peak).

Methods

Literature search

A systematic, disciplined literature search was conducted by three researchers independently using several data bases, including PubMed, Google Scholar, Web of Science, Scopus and SportDiscus. The search used the following comprehensive terms and their combinations: "concurrent strength and endurance training", "combined strength and endurance training", "concurrent resistance and endurance training", "combined resistance and endurance training", "sequence of concurrent training", "sequence of combined training", "order of concurrent training", "order of combined training". The search was limited to full text, English language manuscripts. All human studies and trials published since the 1st of January, 1966 until the end of the search period, 30th of May 2016, were included. Additional manual search, included screening through the reference list of the selected articles and contacting the known research groups in the field.

Inclusion criteria

Following the literature search, the PRISMA statement for meta-analyses, which includes Identification, Screening, Eligibility and Inclusion, was applied for selecting articles for meta-analysis. Based on the predetermined eligibility criteria, only controlled randomised or matched chronic effect trials with at least eight weeks of follow-up duration, comparing strength-endurance with endurance-strength training sequence in the same session (defined as one training mode following the other immediately or with a short rest period of approximately 5–10 min) were included. We decided to include only studies with at least eight weeks of duration, because longer training periods are more practical and meaningful for athletic populations as well as for those seeking life-long wellbeing. Although, strength adaptations may occur with shorter training, the manifestation of interference effect, if any, in concurrent training, especially due to training sequence may also require longer time period.

The flow chart depicts the number of studies extracted and those included in the study (Figure 1).

Data extraction and outcome measures

Data from the selected studies were extracted using a pre-prepared data sheet by two independent researchers. Any conflict was resolved by including the third member. Our primary outcome included lower body 1RM, including the same large muscle groups, while the secondary outcome measure was aerobic capacity (VO_2max/peak) (Table 1). Upper body 1RM strength was not included in the meta-analysis, either because of the trials included in the study did not report the outcome or it was measured in different muscle groups (e.g. elbow flexors, bench press), which could not be combined in the same analysis.

Quality assessment of the studies

Quality analysis of the identified articles was conducted independently by two researchers using Cochrane's Collaborations tool for bias assessment. All relevant biases, such as selection, attrition and reporting biases as well as any other form of information bias were checked and studies were graded (Table 2).

Statistical analyses

The pre and post-mean measurements of 1RM and VO_2 max/peak were extracted from each of the studies. The effects size in this meta-analysis was computed firstly by determining mean changes in before and after training in each sequence group. Then the difference in means were computed between two arms for each study, i.e. differences in means in the Strength-Endurance (SE) exercise sequence was compared to that of the reverse order training arm. Standard deviation (SD) of the difference of the means between arms were computed using the following formulation based on Lipsey and Wilson (Lipsey & Wilson, 2000).

The pooled variance was computed first as follows:

$$SD_{\mu g} = \sqrt{2s_p^2(1 - r)}$$

Then the Standard deviation (SD) of the mean difference was obtained as follows:

Where the correlation coefficient (r) was assumed to be 0.5. In case of data for standard deviation (or standard error or confidence interval or range) was missing for the post intervention measurements, the pre-intervention standard deviation value was used to impute the data. One article, Schuman et al. (Schumann, Yli-Peltola, Abbiss, & Häkkinen, 2015) reported the results separately for female and male subjects, thus we considered them as two independent strata (Table 1).

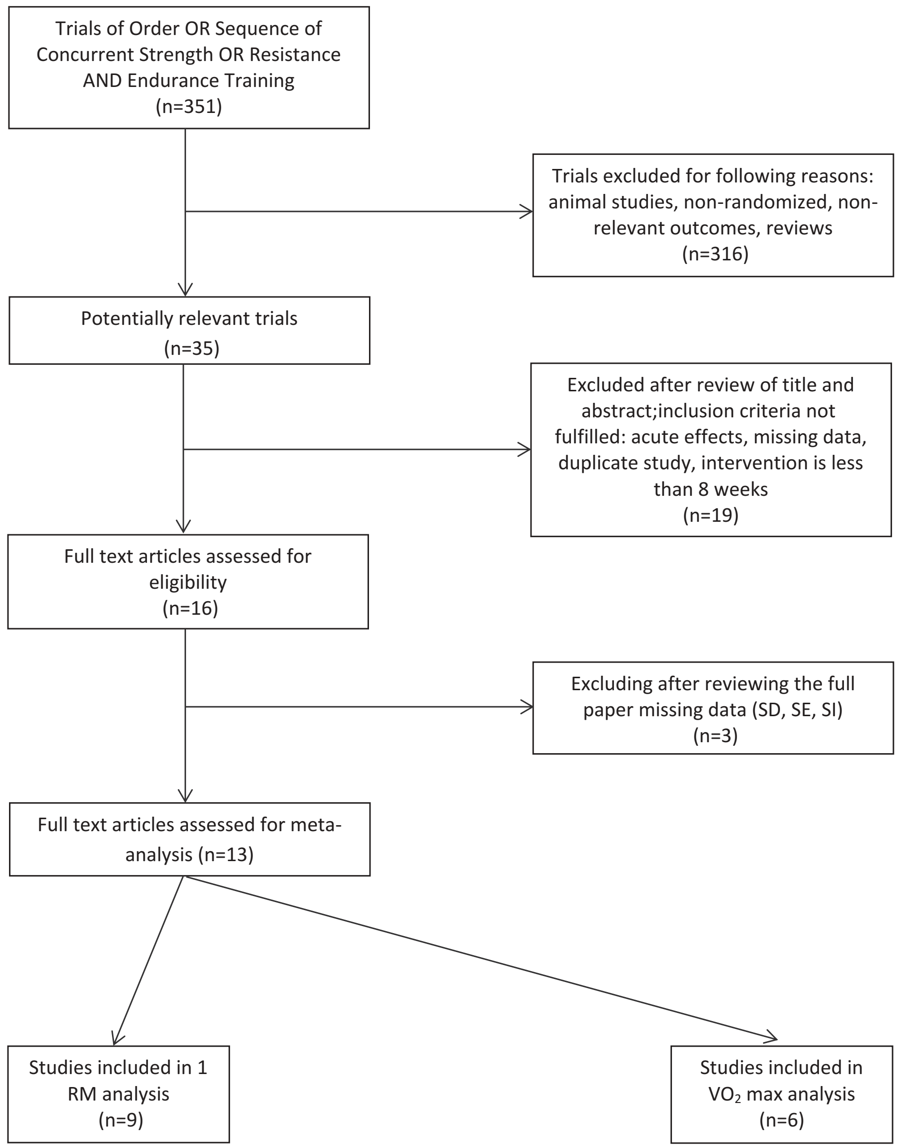

Figure 1. Study selection flow-chart for meta-analysis.

Table 1. Characteristics of the studies included in the meta-analysis.

Study	Study design	Gender	Mean age	SE N	ES N	Duration (Week)	Outcomes
Banitalebi et al. (2016)	randomised	F	60.3	10	9	8	VO_2max
Cadore et al. (2012)	randomised	M	64.7	13	13	12	VO_2peak
Cadore et al. (2013)	randomised	M	64.7	13	13	12	1RM KE
Chtara et al. (2005)	matched groups	M	21.4	10	10	12	VO_2max
Davitt, Pellegrino, Schanzer, Tjionas, and Arent (2014)	randomised	F	19.8	10	13	8	VO_2max
Eklund et al. (2015)	matched groups	M	29.4	18	17	24	1RM LP
Eklund, Schumann, et al. (2016)	matched groups	F	29	14	15	24	1RM LP
Makhlouf et al. (2016)	randomised	M	13.7	15	14	12	1RM HSQ
Pinto et al. (2014)	randomised	F	25.1	13	13	12	1RM KE
Pinto et al. (2015)	randomised	F	57.1	10	11	12	1RM KE
Schumann et al. (2014)	matched groups	M	30	18	16	24	1RM LP
Schumann et al. (2015)	matched groups	M	29.7	13	15	24	1RM LP
		M/F	29.7	31	31	24	VO_2peak
Wilhelm et al. (2014)	matched groups	M	65.8	12	10	12	1RM KE, VO_2peak

KE = Knee extension, HSQ = Half squat, LP = Leg press, F = Female, M = Male

The pooled estimates were obtained using appropriate meta analytical models. The robustness of meta-analyses was explored using a fixed effects or random effects models based on the level of heterogeneity. Heterogeneity was determined to be present when the value I^2 was > 50% or if the Q-statistic was significant at a $P < 0.10$. (Takkouche,

Table 2. Risk of bias assessment.

Author	Selection Bias	Attrition Bias	Reporting Bias	Other Bias
Banitalebi et al. (2016)	+	?	+	-
Cadore et al. (2012)	?	+	+	?
Cadore et al. (2013)	?	+	+	?
Chtara et al. (2005)	-	?	+	-
Davitt et al. (2014)	+	+	+	?
Eklund et al. (2015)	-	+	+	+
Eklund, Schumann, et al. (2016)	-	+	+	?
Makhlouf et al. (2016)	+	?	+	?
Pinto et al. (2014)	?	+	+	?
Pinto et al. (2015)	?	+	+	?
Schumann et al. (2014)	+	+	+	?
Schumann et al. (2015)	-	+	+	?
Wilhelm et al. (2014)	-	+	+	+

(+) = low risk of bias; (-) = high risk of bias;(?) = unclear risk of bias

Cadarso-Suárez, & Spiegelman, 1999). I^2 is a transformation of the Q statistic that quantifies the excess heterogeneity beyond random error across studies. If there were no significant heterogeneity present between the studies, the fixed effect meta-analysis models were used to obtain the pooled estimates, confidence intervals and the level of significance. In case of significant heterogeneity the Random effect models were used. To adjust for bias, we also carried out a further sensitivity analyses using, recently developed, inverse variance heterogeneity model (Doi, Barendregt, Khan, Thalib, & Williams, 2015). Forrest plots for 1RM and VO2 Max are presented (Figure 2). Forrest plot is a graphical display of pooled estimated results along with 95% CI as well as the estimates and the CI from each study included in the estimation process. They are presented here as two columns, the left-hand column lists the names of the studies and the right-hand column is a plot of the measure of effect, in our case mean difference. Further analysis was carried out to see the effective covariates like age, gender and training status of the participants. Tables 3 and 4 report the pooled estimates and 95%CI for each of the subgroups of age, gender and training levels for 1RM and VO2 Max respectively. Studies with mean age of less than 50 and more than 50 were considered for stratification. Gender stratified subgroup analyses as well as studies that involved all trained personals or untrained subjects were used to stratify the sporting level.

Publication bias was assessed using funnel plots. All analyses were done using MetaXL version 5.2 (Epigear International Pty Ltd, Brisbane, Australia) and double checked using CMA (Comprehensive Meta Analyse, Version 2.2,054, USA).

Results

Following the extensive database searches, 351 articles were identified (Figure 1). After the initial examination 35 potential trials were further assessed. Among these articles 16 were included in the full text eligibility review. Three trials were excluded due to missing data, that is no standard deviation or standard error or confidence interval was provided, thus it was not possible to include them in the meta-analyses. Of the 13 trials included in the meta-analysis, nine reported 1RM and six aerobic capacity outcomes with two studies including both outcomes. Maximal aerobic capacity (VO_2max/peak) was directly measured in these studies via either a treadmill or a bicycle ergometer protocol. The trials included both genders and different age groups, ranging from an average age of 13.7 to 65.8yrs (Table 1.).

Studies that reported 1RM results for the lower body, including the same large muscle groups (e.g. squat, leg press or knee extension) were included in the primary outcome

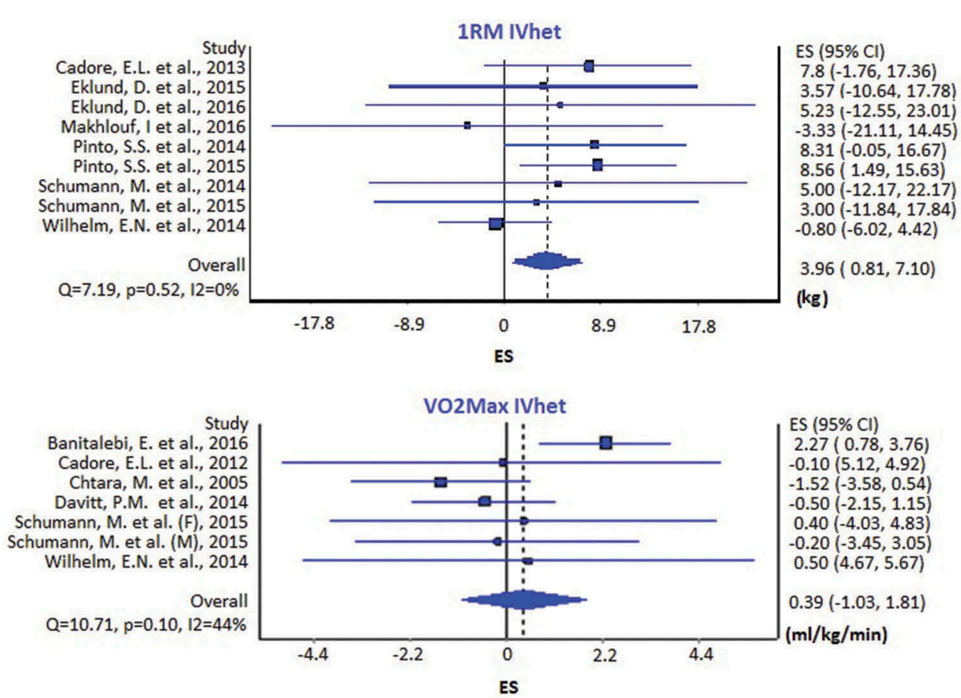

Figure 2. Forrest plot of 1RM and VO_{2max} variables.

Table 3. Subgroup analyses based on covariates for 1RM.

1RM	Effect Size	95% CI	I^2
Overall	3.96	0.81 to 7.10	0%
Gender stratified			
Males only	1.37	−2.80 to 5.55	0%
Females only	7.84	2.74 to 12.88	0%
Age stratified (mean)			
<50	6.11	0.74 to 11.48	0%
>50 years	2.82	−4.10 to 9.70	56%
Training level stratified			
Trained (only one study)	-	-	-
Untrained	4.19	1.00 to 7.38	0%

I^2 = measure of heterogeneity between studies

Table 4. Subgroup analyses based on covariates for VO2 Max.

VO_2 Max	Effect Size	95% CI	I^2
Overall	0.39	−0.10 to 1.81	44%
Gender stratified			
Males only	−0.89	−2.55 to 0.77	0%
Females only	1.02	−1.70 to 3.75	83%
Age stratified (mean)			
<50	0.40	−1.33 to 2.14	63%
>50 years	0.19	−3.41 to 3.79	0%
Training level stratified			
Trained	−1.52	−3.58 to 0.54	0%
Untrained	0.82	−0.50 to 2.14	25%

I^2 = measure of heterogeneity between studies

analysis for 1RM strength. Upper body 1RM strength was not included in the meta-analysis, because out of the identified and screened articles, only one met the predetermined eligibility criteria. Moreover, in some cases upper body 1RM strength measures included different muscle groups (e.g. elbow flexors, bench press), which could not be combined in the same analysis. The secondary outcome measure included aerobic capacity, namely VO_2max and VO_2peak.

When we compared the effectiveness of SE and ES training sequences on muscular strength, we found a significantly different effect size of 3.96 kg (95%CI: 0.81 to 7.10 kg), indicating the superiority of the strength-prior-to-endurance order as shown in the Forrest plot (Figure 2).

However, the training sequence had no impact on aerobic capacity with a pooled estimate of the difference between the sequences to be 0.39 ml.kg.min^{-1} (95%CI: −1.03% to 1.81 ml.kg.min^{-1}). We have also carried out subgroup analyses to see the changes in pooled estimates based on age, gender and training status. We classified the papers that used all males or all females and did a stratified meta analyses. Also, we used the mean age of the participants in each study to stratify them as studies with younger participants (under 50 years) and older participants (over 50 years). Likewise, we also found that some studies used trained participants for their trials while most others used untrained healthy individuals. So, we did stratified subgroup analyses. 1RM was significantly higher in studies that were carried out only on females. Young, female and untrained also had relatively higher 1RM changes (Table 3). There were no major changes and VO_2 was non-significant throughout all stratum (Table 4).

Sensitivity analyses carried out using inverse variance heterogeneity effects models yielded similar estimates. Random effects models were not used as there was no significant heterogeneity between studies. Publication bias was also assessed by funnel plots, which indicated funnel shape distributions, thus there might not be any publication bias evident in the current analyses.

Discussion

The principal finding of this meta-analysis reveals that SE training order is superior to ES sequence for 1RM strength development. Thus, it is plausible that when endurance training immediately precedes the strength training stimulus, the accumulation of acute local or systemic fatigue interferes with the long-term strength adaptations. This finding has important practical implications, because maximal strength is a major determinant of athletic performance as well as daily functioning. In fact, optimizing strength adaptations is especially important for health-related fitness (e.g. rehabilitation, elderly), because muscular strength is closely related to health outcomes and has a greater impact on wellbeing and mortality risk (Mitchell et al., 2012). Moreover, strength training responses and maximal strength indices are good indicators of sport performance in elite athletes (Beattie et al., 2017).

The underlying mechanisms of this interference remain to be elucidated, although both neuromuscular and metabolic processes can attenuate adaptations. One of the current authors has shown along with others that a prior aerobic exercise session significantly reduced the number of repetitions that could be performed in the back squat exercise, without impacting the activation of the involved muscles or muscle groups (Reed et al., 2013; Tan, Coburn, Brown, & Judelson, 2014). This evidence points to acute interference of metabolic rather than neuromuscular nature, compromising the quality of the training session and in turn diminishing chronic adaptations.

It has to be noted that these investigations used lower body endurance training protocols (stationary bicycle and elliptical trainer, respectively) in the concurrent session and only reported reduced performance in the back squat and not in the bench press exercise. Moreover, half-squat performance was impacted to a greater extent after cycling compared to running exercise, further indicating muscle group specificity in exercise interference (Panissa et al., 2015). Hence, the available information supports the notion of local, as opposed to systemic effects during concurrent training, that is attenuated responses are only apparent in the muscle groups that are the most active during the preceding aerobic exercise.

The current meta-analysis only examined lower body strength adaptations in concurrent training, therefore it is possible that no order effect would be evident when predominantly lower body endurance exercise is followed by upper body strength training. However, investigations that describe upper body strength performance and adaptation following upper body endurance training are lacking.

Lastly, no order effect was found for maximal aerobic capacity. When examining changes in aerobic capacity as a result of same-session concurrent training, it is important to consider whether a prior resistance training stimulus enhances or attenuates the subsequent aerobic performance, affecting long-term adaptations. Based on the principle of training specificity, resistance training does not contribute to improved aerobic capacity, especially beyond what is already gained from endurance training in a concurrent training program (Knuttgen, 2007). Therefore, our finding is not surprising, because most studies agree that aerobic capacity is neither compromised nor enhanced with the inclusion of strength training in a combined training program (Nelson, Arnall, Loy, Silvester, & Conlee, 1990; Wilson et al., 2012). Nevertheless, strength training is frequently added to routine endurance training to enhance performance in elite athletes, such as long distance runners and cyclists.

Indeed, combining strength with endurance training has been shown to enhance indices of endurance performance, such as running economy (Beattie et al., 2017), however, it did not impact maximal aerobic capacity in cyclists (Psilander, Frank, Flockhart, & Sahlin, 2015). These findings were corroborated at the cellular level, as markers of mitochondrial biogenesis were altered during rehabilitation irrespective of the order of strength and endurance exercise modes (MacNeil, Glover, Bergstra, Safdar, & Tarnopolsky, 2014).

We also have to note that studies are smaller and varying quality in terms of the bias assessment. High quality studies that are larger with longer follow up may provide higher level of evidence. However, our meta analyses could bring underpowered studies to provide a statistically powered estimation of the sequence effect.

Concurrent training is a complex field with various other contributing factors, such as exercise mode and intensity, muscle groups trained (upper vs. lower body) and subject characteristics (elite athletes vs. sedentary, young vs. old), along with inter-individual variations. Moreover, the interaction of these factors would likely affect the contribution of each component to the resulting training adaptations. Although we believe that training sequence can have an immediate impact on training practices, the understanding gained from our meta-analysis in this multifactorial area is still limited, thus further high-powered studies and meta-analyses are necessary to shed light on this intricate subject.

Conclusion

In conclusion, according to the current meta-analysis, if the primary goal is to increase lower body muscular strength it is highly recommended to perform resistance exercise before endurance training in the same session concurrent training program. However, for maximal aerobic capacity the exercise sequence has no impact on the ensuing adaptations, consequently the order of execution may be selected based on practical considerations or personal preferences. Moreover, considering the available evidence, the separation of endurance exercise and resistance exercise sessions preferably by 24hrs whenever it is realistic, could be a useful strategy to optimise concurrent training adaptations and avoid acute interference (Baar, 2014; Cantrell et al., 2014; Eklund, Häkkinen, et al., 2016; Robineau, Babault, Piscione, Lacome, & Bigard, 2016). This recommendation is based on investigations on both acute and chronic strength training responses to concurrent training. First, it has been demonstrated that strength training performance is compromised for at least six to eight hours following endurance training (Reed et al., 2013; Robineau et al., 2016; Sporer & Wenger, 2003). It is conceivable that the required recovery time is even longer, because according to the authors' knowledge no studies are available that analyzed strength training performance between eight and 24 hours post-endurance exercise. This advice may also be corroborated at the molecular level, because several hours is necessary for adenosine monophosphate (AMP) activated kinase (AMPK) activity to return to baseline following endurance exercise; otherwise it may interfere with mammalian target of rapamycin (mTOR) signaling, which plays a crucial role in resistance training adaptations (Baar, 2014; Fyfe et al., 2014). On the contrary, some chronic studies that separated endurance and resistance training session to alternate days did not find reduced strength adaptations compared to resistance training alone (Cantrell et al., 2014; Karavirta et al., 2011).

Disclosure statement

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