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SYSTEMATIC REVIEW

Maximizing Adaptations in Concurrent Training: An Umbrella Review of Meta-analyses

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Abstract

Background Concurrent training (CT), the combination of resistance training (RT) and endurance training (ET), is widely used in athletic and clinical settings. However, concerns about a potential interference effect have prompted ongoing debate regarding its impact on strength, power, hypertrophy, and aerobic capacity.

Methods A systematic search was conducted in PubMed, Web of Science, SPORTDiscus, and PsycNet following PRISMA guidelines and the four-eyes principle (28th February 2025). Main outcomes included aerobic capacity, muscle strength, power, and hypertrophy. Subgroup analyses were performed based on training modality, performance level, age, resistance training load, and endurance intensity.

Results Seventeen meta-analyses comprising 144 individual studies and 1492 healthy participants were included. Umbrella data revealed comparable improvements in aerobic capacity for CT and ET. CT revealed significantly greater strength adaptations compared with ET (standardized mean difference [SMD] 0.59; $p<0.001$). Compared with RT, CT significantly improved aerobic capacity (SMD 0.77; $p=0.02$), while strength, power, and hypertrophy outcomes were comparable. No significant effects of training sequence were found; however, trends suggest performing RT before ET may favor strength (SMD 1.69; $p<0.001$) and hypertrophy (SMD 0.83; $p=0.36$) gains.

Conclusion CT improves both aerobic capacity and strength-related outcomes, making it a valuable strategy for comprehensive fitness development for recreationally trained individuals. While no relevant differences were found regarding the training sequence, performing RT before ET may enhance strength and hypertrophy adaptations. However, data from highly trained to elite athletes remain scarce and warrant further investigation.

PROSPERO Registration Number CRD42025646460.

1 Introduction

Endurance training (ET) improves cardiovascular and metabolic function, notably by increasing maximal oxygen uptake (VO_2max), enhancing mitochondrial function, and optimizing substrate utilization [1, 2]. In contrast, resistance training (RT) primarily induces neuromuscular adaptations, including enhanced motor unit recruitment and muscle hypertrophy, leading to greater maximal strength [3, 4]. In both athletic and recreational settings, these training modalities are rarely performed in isolation but are often combined within the same training cycle [5, 6]. While this concurrent training (CT) approach aims to elicit broad physiological gains, it may also produce competing adaptations—a phenomenon known as the interference effect [7, 8].

The interference effect is thought to stem from molecular signaling conflicts between endurance- and resistance-induced adaptations. In short, endurance exercise activates adenosine monophosphate-activated protein kinase (AMPK), an energy sensor promoting catabolic pathways, while RT stimulates the mammalian target of rapamycin complex 1 (mTORC1), driving muscle protein synthesis and anabolic growth [9, 10]. However, AMPK can inhibit mTORC1 signaling both directly and via upstream regulators like tuberous sclerosis complex 2 (TSC2), potentially dampening the hypertrophic responses to resistance exercise [11, 12]. Notably, the timing and sequence of training may influence the activation of these pathways. Performing ET first may elevate AMPK activity at the onset of a subsequent resistance exercise, thereby reducing downstream anabolic signaling [13]. In contrast, starting a session with resistance exercises may allow mTORC1 signaling to peak before AMPK-mediated inhibition occurs [14].

Steffen Held and Lena Wolf were equally involved in the work.

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Key Points

Combining resistance and endurance training in the same plan improves aerobic fitness just as well as endurance training alone, while giving even stronger muscle and strength benefits than endurance training only.

Compared with resistance training alone, the combined approach boosts cardiovascular fitness while matching gains in strength, power, and muscle size.

Doing resistance training before endurance training may further increase muscle growth and strength without reducing endurance improvements.

Emerging evidence indicates that training order can influence strength and hypertrophy outcomes, with RT performed before ET often yielding more favorable strength and hypertrophy adaptations, likely due to reduced neuromuscular fatigue and a more anabolic environment [13–17]. While these strength-related mechanisms are supported by acute studies, their relevance for long-term adaptation remains uncertain. Several meta-analyses have examined different aspects of CT, including effects on strength and hypertrophy [6, 18], the compatibility of high-intensity interval training with resistance exercise [19], and the role of exercise sequence [17]. However, findings are often fragmented and inconsistent. Recent reviews [18, 20] differ in their inclusion criteria, analytical methods, and conclusions. A systematic synthesis of meta-analytic evidence is therefore needed to clarify whether training order meaningfully influences CT outcomes and modulates the interference effect across performance domains.

An umbrella review provides a powerful approach by synthesizing and evaluating findings from existing meta-analyses, thereby revealing consistent patterns, methodological limitations, and key gaps in the literature [21–23]. Unlike traditional meta-analyses that are based on individual trials, umbrella reviews capture broader trends and offer more conclusive insight relevant to applied training contexts [24]. Therefore, this review adopts an umbrella framework to clarify how CT influences key performance outcomes and how its structure can be optimized to reduce interference while enhancing adaptation.

2 Methods

2.1 Search and Screening Procedures

This umbrella review was conducted in accordance with the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) and was registered in PROSPERO (CRD42025646460) [25, 26]. The literature search and screening processes were independently conducted by two researchers (LW and SH). Four health-related, biomedical, and psychological databases (PubMed, Web of Science, PsycNet, and SPORTDiscus) were screened from inception until February 28, 2025. Relevant search terms and operators were combined with Boolean conjunctions (OR/AND) and applied to three search levels (Table 1). In addition, tracking of cited articles and manual searching of relevant articles were also carried out. Duplicates were removed and the remaining studies underwent manual screening. The remaining meta-analyses were screened using (i) titles, (ii) abstracts, and (iii) full texts for potentially eligible articles. If differences existed in the identification of meta-analyses, a decision was made in consultation with a third-party independent reviewer (EI).

2.2 Inclusion and Exclusion Criteria

The following inclusion criteria were applied based on the PICOS approach: (population [P], intervention [I], comparators [C], main outcome [O], and study design [S]).

Population (P): Studies were included if they investigated healthy participants without physical impairments that could affect performance outcomes in the respective exercise tests. No restrictions were placed on sex or training status, provided participants were free from musculoskeletal, cardiovascular, or neurological conditions that might interfere with performance assessment.

Intervention (I): The primary intervention had to be CT, defined as the combination of ET and RT within the same training period. Studies with various CT configurations (e.g., different exercise modes, frequencies, and intensities) were included, provided that CT was the primary intervention.

Table 1 Search strategy

Search level	Search terms with Boolean operators
Search #1	("concurrent training" OR "concurrent exercise" OR "combined training" OR "combined exercise" OR "concurrent strength and endurance" OR "combined strength and endurance" OR "concurrent resistance and endurance" OR "combined resistance and endurance”)
Search #2	#1 AND ("meta analysis" OR "systematic”)
Search #3	#2 NOT ("elderly" OR "child*" OR "patient" OR "disease" OR "syndrome" OR "cerebral palsy" OR "injur*" OR "sedentary" OR "obese" OR "animals" OR "supplementation" OR "validity" OR "cancer" OR "diabet*" OR "stroke")

Comparators (C): Studies were included if they compared CT with at least one of the following: ET alone, RT alone, or CT with different exercise sequences (i.e., resistance first vs endurance first).

Outcomes (O): Studies were eligible if they reported at least one of the following primary outcome measures: aerobic capacity ($\dot{V}O_2$max or $\dot{V}O_2$peak), maximal strength (one-repetition maximum [1RM], maximal voluntary contraction [MVC], or maximal torque), power performance (countermovement jump [CMJ], height or other power-related metrics), and muscle hypertrophy (changes in muscle cross-sectional area [CSA] or thickness assessed via imaging techniques).

Study design (S): Only controlled intervention studies with a pre-post design were included to ensure methodological rigor and allow for valid comparisons of training effects.

Studies were excluded if they met any of the following criteria: not published in a peer-reviewed journal, not published in English, did not investigate isolated CT but combined it with additional interventions such as blood flow restriction training, whole-body vibration training, electrical muscle stimulation or nutritional supplementation (e.g., creatine, protein, or ergogenic aids).

2.3 Quality of Meta-Analyses

The methodological quality of the included systematic reviews was assessed using the AMSTAR (A MeaSurement Tool to Assess systematic Reviews) checklist [27]. Two independent reviewers (LW and SH) evaluated each study based on the 11 AMSTAR criteria, covering aspects such as study design, data extraction, risk-of-bias assessment, and synthesis methods. Discrepancies between reviewers were resolved through discussion or by consulting a third reviewer when necessary. Studies were classified as high, moderate, or low quality based on their AMSTAR scores.

2.4 Data Extraction

Relevant data, necessary for calculating effect sizes, were extracted independently by two researchers (LW and SH) using a standardized extraction Excel spreadsheet adapted from the Cochrane Collaboration [28]. Standardized mean differences (SMDs) as pairwise effect sizes on relevant outcomes were extracted along with the number of participants assessed in each group. Relevant outcome parameters were (i) $\dot{V}O_2$max and $\dot{V}O_2$peak for aerobic capacity; (ii) CMJ and squat jump (SJ) for power performance; (iii) 1RM such as leg press, squat, knee extension, bench press or biceps curl for strength, and (iv) the CSA of the upper leg muscles, for hypertrophy. If these points and variability measures were not reported in the full-text article, the authors were contacted. If parameters were only presented in figures, WebPlotDigitizer Version 4 (Free Software Foundation, Boston, MA, USA) was used to extract means with standard deviations [29]. In addition to these outcomes, relevant information on author, year, number of participants, interventional data (weeks, frequency, duration per session, type of intervention), and control condition were also extracted.

2.5 Statistical Analysis

The SMD and 95% confidence intervals (95% CI) were calculated for all training interventions as a measure of treatment effectiveness. SMDs were calculated as the differences between means divided by the pooled standard deviations (trivial: $SMD < 0.2$, small: $0.2 \leq SMD < 0.5$, moderate: $0.5 \leq SMD < 0.8$, large $SMD \geq 0.8$) [30]. The direction of the effect sizes was harmonized to ensure interpretability (21). Overall, the following three pairwise comparisons were analyzed: (i) endurance versus concurrent training (ET vs CT); (ii) resistance versus concurrent training (RT vs CT), and (iii) exercise order during CT (i.e., RT followed by ET [RE] vs ET followed by RT [ER]) (order, sequence comparison). The umbrella-based analyses were conducted using random effects models [31]. Since individual meta-analyses can include overlapping primary studies, we also applied random-effects models at the level of each single study. Thus, we extracted the original data from all individual studies incorporated into the meta-analyses and subjected these data to random effects modeling for further analysis. Moreover, we conducted subgroup analyses to examine the effect of (i) training modality (simultaneous, same day, or different day), (ii) training status (untrained vs trained), (iii) age group (< 45 years vs ≥ 45 years), (iv) resistance training load, and (v) endurance training intensity (low, moderate, or high) on the interference effect of ET and RT in healthy adults. The Q-statistics were used to interpret potential heterogeneity [31] and inconsistency and were further quantified by I^2 [32]. To identify potential undue influence from individual meta-analyses, leave-one-out analyses were conducted, where each meta-analysis was sequentially removed, and the overall intervention effect and CIs were re-estimated. This process ensured the robustness of the findings. Potential publication bias was examined with a funnel plot [33]. All calculations and presentational figures were made using the R software (version 4.1.1; The R Foundation for Statistical Computing) employing the packages 'meta' [34], 'metafor' [35].

3 Results

3.1 Study Characteristics and Quality

To minimize heterogeneity in our results, two meta-analyses were excluded after screening and study selection (Fig. 1), as most or all of the included studies did not meet our predefined inclusion criteria [36, 37]. Consequently, 17 meta-analyses [15, 17–20, 38–49] were included in the final analysis, comprising a total of 144 individual studies [7, 14, 50–191]. The full list of selected studies, with corresponding study details, is displayed in Supplementary Table S1 (see Electronic Supplementary Material [ESM]). Details on the corresponding meta-analyses are given in Table 2. Overall, 1492 healthy participants were examined. Included trials enrolled on average 21 ± 10 participants per study (range 10–64 participants) with an average age of 31 ± 15 years (range 16–73 years). The mean intervention duration was 10.4 ± 4.3 weeks (range 4–25 weeks). Of the studies included, 73, 75, and 11 investigated the comparison between ET and CT, RT and CT, and exercise order during concurrent training, respectively. The average meta-analysis quality revealed an AMSTAR score of 10.4 ± 2.3 (range 6–15).

3.2 Umbrella Data

3.2.1 Endurance Versus Concurrent Training

The umbrella-based pairwise comparison between endurance and concurrent training revealed relevant higher strength adaptations of CT compared with ET (Fig. 2, SMD 0.59; $p < 0.0001$). To assess the robustness of this finding, a leave-one-out sensitivity analysis was conducted. Omitting

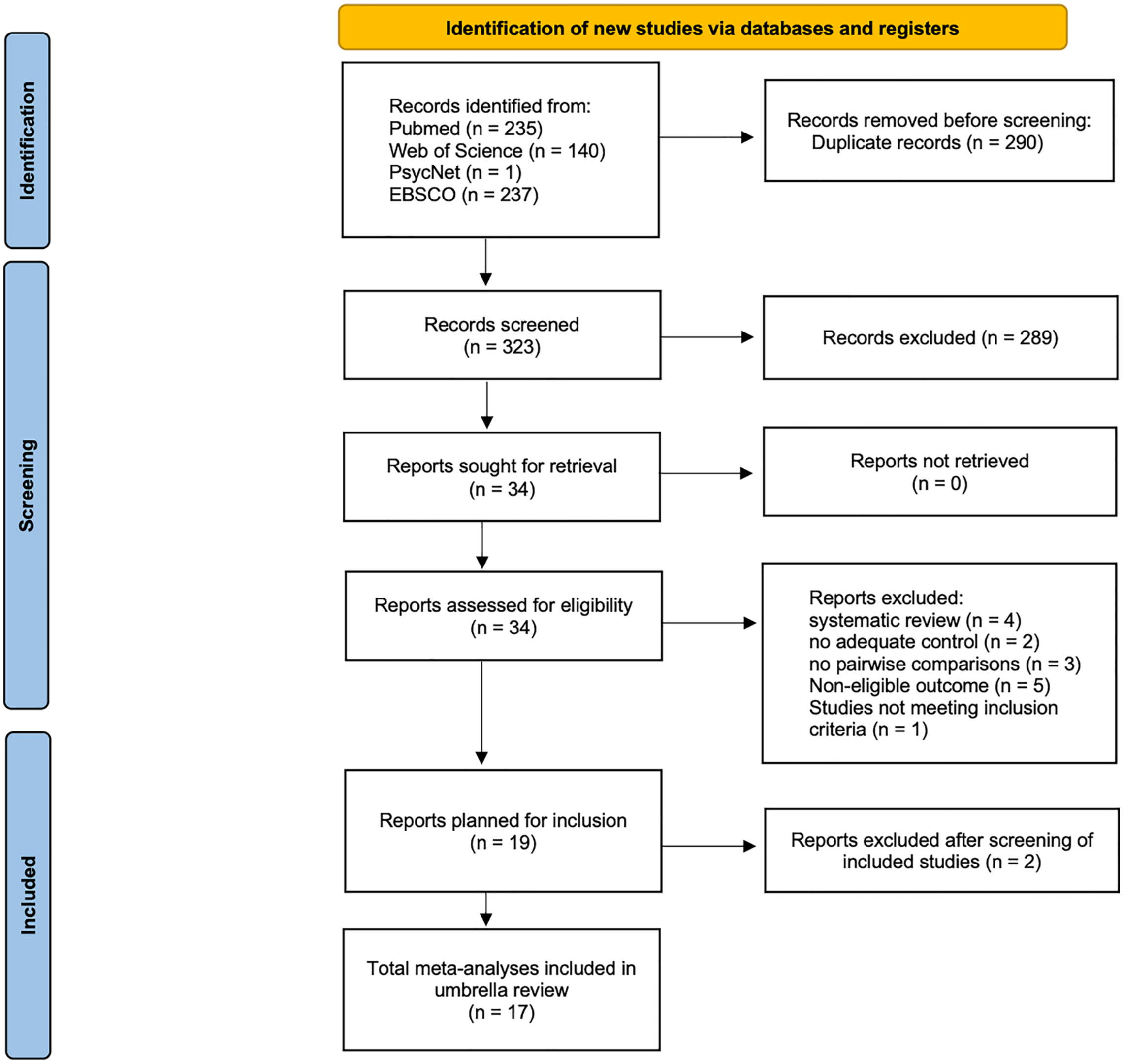


Fig. 1 PRISMA 2020 flow diagram of the search process and the study selection

Table 2 Overview of included meta-analyses comparing concurrent training (CT) with resistance training (RT), endurance training (ET), or different exercise orders (RT before ET vs ET before RT). Meta-analyses are presented with information on comparison type, sample characteristics, investigated outcomes, summary of key results, and AMSTAR quality scores. Outcomes include maximal strength, muscle hypertrophy, muscle power, and aerobic capacity

Study	Comparison	Sample	Outcome	Results	AMSTAR
Schumann et al. [20]	CT vs RT	43 included studies, healthy adults	**Maximal strength**: Both isometric and isoinertial measurements were accepted; **Explosive strength**: Any form of jump test, isometric RFD, or dynamic power measurements were considered eligible; **Muscle hypertrophy**: Objective measurements of whole-muscle cross-sectional area or muscle thickness (e.g., ultrasound, computed tomography or magnetic resonance imaging) were required. In addition, segmental lean mass as determined by DXA was accepted if values were reported separately for segments that were engaged in training	No negative effect through CT on hypertrophy and muscle power, but muscle strength (especially when in same session); regardless of training form, frequency, training status, or age	10.5
Lundberg et al. [18]	CT vs RT	15 included studies, healthy adults	**Hypertrophy:** muscle fiber type (magnetic resonance imaging, computed tomography, muscle biopsies)	Less muscle hypertrophy through CT, more through running than through cycling	8
Monserdà-Vilaró et al. [38]	CT vs RT	25 included studies, healthy adults, aged 20–71 years	**Hypertrophy**: at the whole-muscle level (using ultrasonography, computed tomography, or magnetic resonance imaging) and/or at the muscle fiber level (using histological assessment of muscle biopsies)	More muscle hypertrophy through RT	9
Kang et al. [39]	CT vs RT	7 included studies, team sports players, aged > 13 years	**Muscle strength/ power**: lower-body 1RM of half squat, counter movement jump or squat jump; **Aerobic capacity**: VO_2max/peak or Yo-Yo test	CT increases muscle strength more but has no effect on muscle power and endurance	10.5
Petré et al. [40]	CT vs RT	27 included studies, healthy normal-weight adults, aged 20–38 years	**Muscle strength:** 1RM of leg press or squat	No effect when untrained/ moderately trained; trained: greater increase in muscle strength with RT than with CT, especially when ET and RT are in the same session	8
Pagaduan et al. [41]	CT vs RT	10 included studies, aged 18–30 years	**Muscle power**: counter movement jump	Better vertical jump performance after CT than after RT	6.5
Sabag et al. [19]	CT vs RT	13 included studies, healthy adults, aged 18–34 years	**Muscular strength**: dynamic RM measurements; **Hypertrophy**: changes in lean muscle mass via biopsy, ultrasonography, computed tomography, dual x-ray absorptiometry, magnetic resonance imaging and/or densitometry	No negative effect of CT on the upper body; lower-body gains are smaller than with RT alone, more pronounced with cycling than with running, and greater with shorter rest periods	9.5

Table 2 (continued)

Study	Comparison	Sample	Outcome	Results	AMSTAR
Pito et al. [42]	CT vs RT/ET	21 included studies, healthy adults	**Muscle strength:** 1RM upper and lower limb **Aerobic capacity**: VO_2max/peak	Similar results from CT compared with RT or ET in strength and endurance parameter	13
Khalafi et al. [43]	CT vs RT/ET	49 included studies, middle-aged to older adults, aged 55–88 years	**Aerobic capacity**: VO_2max/peak; **Lower- and upper-body muscular strength**: one RM to 10RM tests during isoinertial contractions, or peak torque during isometric dynamometry or isokinetic dynamometry at 30–60°/s	CT increased VO_2max/peak compared with RT; CT increased lower- and upper-body muscular strength compared with ET. No differences in VO_2max/peak between CT and ET, or in lower-body and upper-body muscular strength between CT and RT	11
Huiberts et al. [44]	CT vs RT/ET	59 included studies, healthy adults, aged 18–50 years	**Muscle strength:** 1RM upper (bench press) and lower body (squat and deadlift), all out (pull ups) **Aerobic capacity**: VO_2max/peak	CT small changes in males (not females); VO_2max improvements	12.5
Trowell et al. [45]	CT vs ET	25 included studies, ‘distance’ or ‘endurance’ runners of any training status, aged > 15 years	**Running performance**: kinematic, kinetic or electromyography outcome measures captured during running; **Muscle strength:** lower body muscle force, strength or power outcome measures; **Stiffness:** lower body muscle–tendon stiffness outcome measures	CT training was found to significantly improve knee flexion, ankle plantar flexion, knee extension and squat strength more than ET alone, suggesting an increased force-generating capacity in the triceps surae, quadriceps, hamstrings, and gluteal muscle groups	11
Gao and Yu [46]	RE vs ER	19 included studies	**Muscle strength & power:** lower limb strength **Aerobic capacity**: VO_2max	Order has no effect on VO_2max. RE results in better improvement in lower limb strength than ER, especially in elderly, females, duration > 8 weeks, > 2 sessions per week	15
Eddens et al. [15]	RE vs ER	10 included studies, healthy adults	**Muscle strength**: 1RM (leg press, squat, leg-extension exercise); **Hypertrophy**: muscle fiber cross-sectional area by histochemical analysis or measures of whole muscle volume or thickness by magnetic resonance imaging or ultrasound; **Muscle power**: counter movement jump **Aerobic capacity**: measurement of peak oxygen consumption during, or maximal workload at the end of, an incremental test to volitional exhaustion; **Body fat percentage**: dual-energy X-ray absorptiometry scans or skinfold techniques	RT before ET is beneficial for lower-body dynamic strength, while ET before RT offers no advantage	10.5
Murlasits et al. [17]	RE vs ER	13 included studies	**Muscle strength**: 1RM lower body **Aerobic capacity:** VO_2max/peak	RT before ET is better for strength adaptation, with no effect on aerobic capacity	12

Table 2 (continued)

Study	Comparison	Sample	Outcome	Results	AMSTAR
Chen et al. [47]	CT vs RT	40 included studies, healthy adults, aged 18–45 years	**Hypertrophy**: MCSA: lean body mass, lean lower body mass, thigh cross-sectional area, lean leg mass, thigh thickness; **Muscle strength**: 1RM (half squat, leg press, leg extension) quadriceps MVC; **Muscle power**: counter movement jump, 30 m sprint, 20 m sprint, drop jump, peak power	HIIT running in CT minimizes negative effects on lower limb strength and MCSA	11
Chen et al. [48]	CT vs RT	11 included studies, healthy adults, aged 18–40 years	**Muscle strength**: 1RM half squat; **Muscle power**: counter movement jump	CT and RT produce comparable effects	11
Prieto-González et al. [49]	CT vs ET	20 included studies, healthy adults (endurance runners), aged 18–45 years	**Muscle strength**: 1RM; **Aerobic capacity**: VO_2max	CT improves specific performance more than ET (RT targets vertical jump, 1RM, lactate threshold, and peak velocity)	12

CT concurrent training, *DXA* dual energy X-ray absorptiometry, *ER* resistance after endurance training, *ET* endurance training, *MCSA* muscle cross-sectional area, *MVC* maximum voluntary contraction, *RE* endurance after resistance training, *RFD* rate of force development, *RM* repetition maximum, *RT* resistance training, *VO_2max* maximal oxygen uptake

individual studies did not meaningfully alter the significant advantage of CT, with effect sizes ranging from 0.59 to 0.62 (all $p < 0.01$), confirming that the results were not driven by any single study. In contrast, aerobic capacity (SMD 0.05; $p = 0.46$) and power adaptations (SMD 0.21; $p = 0.17$) revealed only trivial to small effect sizes for the ET versus CT comparison (Fig. 2). Sensitivity analyses for aerobic capacity further supported these results, demonstrating stability in the effect estimates (SMD range − 0.03 to 0.06) and consistently low heterogeneity (I^2 range 0–18.8%) regardless of study exclusion. Overall, I^2 (0%) revealed no relevant heterogeneity for all outcome parameters.

3.2.2 Resistance Versus Concurrent Training

Regarding the umbrella-based pairwise comparison between resistance versus concurrent training, positive effects of aerobic capacity adaptations (SMD 0.77; $p = 0.004$) during CT compared with RT could be observed (Fig. 3). In contrast, power (SMD 0.21; $p < 0.0001$), strength (SMD 0.17; $p < 0.0001$) and hypertrophy (SMD − 0.04; $p < 0.0001$) revealed significant but only trivial effects between RT and CT (Fig. 3). To evaluate the stability of these findings, a leave-one-out sensitivity analysis was performed. For hypertrophy, the results proved highly robust, with effect sizes remaining trivial (SMD range − 0.08 to − 0.01) and heterogeneity remaining low (I^2 range 0–27.6%) regardless of study exclusion. In contrast, strength and power adaptations showed greater sensitivity to individual outliers. Specifically, omitting Kang et al. [39] shifted the strength effect size from 0.17 to − 0.12 and drastically reduced heterogeneity (I^2 dropped to 5.8%), whereas omitting Huiberts et al. [44] increased the effect size to 0.24. Similarly, for power, the exclusion of Pagaduan et al. [41] reduced the effect size to near zero (0.03), while omitting Schumann et al. [20] increased it to 0.38. Consequently, I^2 demonstrated no relevant heterogeneity for hypertrophy ($I^2 = 5.1\%$), but relevant heterogeneity regarding power and strength data (Fig. 3, $I^2 \geq 89.8\%$). Thus, while the trivial impact of CT on hypertrophy is a highly stable finding, the data for strength and power are influenced by specific outliers. However, even accounting for these fluctuations, the differences generally remained within the trivial-to-small range, suggesting that the interference effect of CT on these parameters is likely of limited practical magnitude.

3.2.3 Exercise Order

The umbrella-based pairwise comparison of the exercise order during concurrent training revealed large effect size with large standard error for strength (SMD 1.69; $p < 0.0001$) and hypertrophy (SMD 0.83; $p = 0.057$) adaptations in favor of RE (Fig. 4). In contrast, aerobic capacity

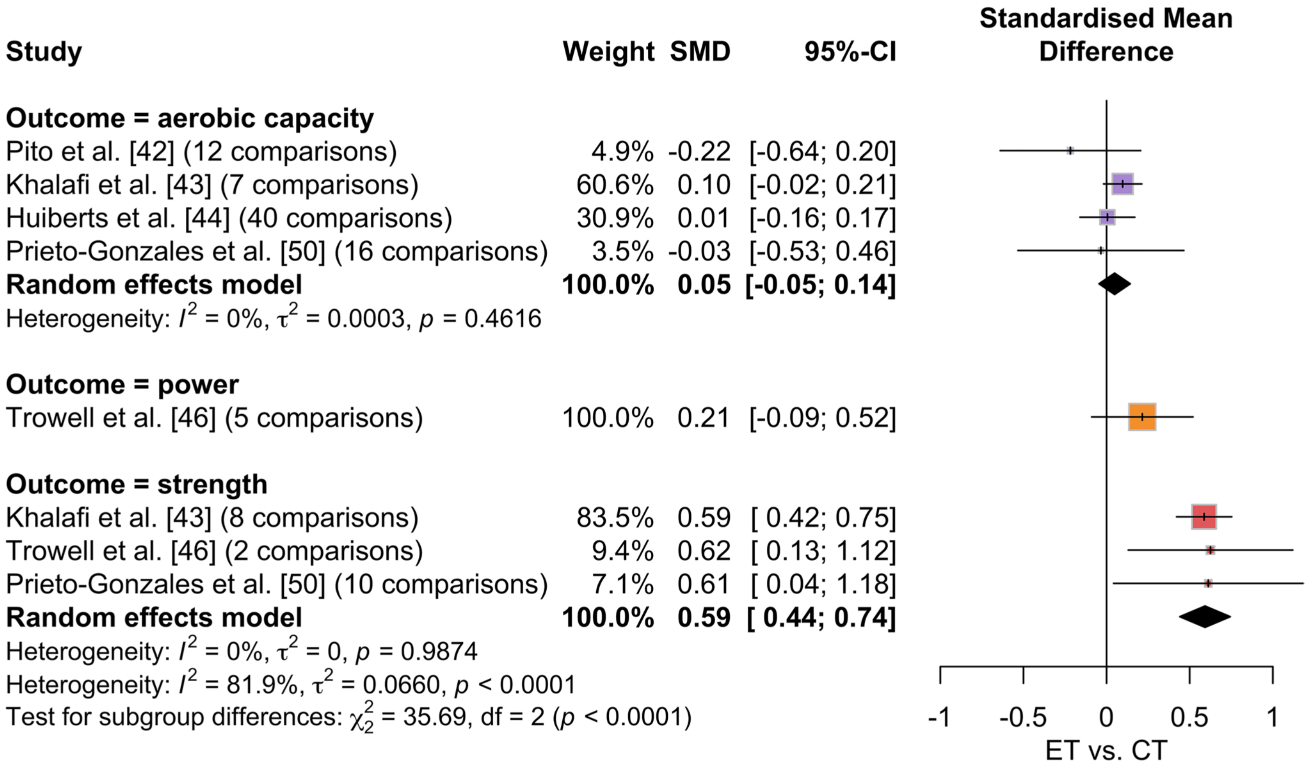


Fig. 2 Umbrella forest plots of pairwise comparisons between endurance and concurrent training (ET vs CT). Aerobic capacity (violet), power (orange) and strength (red) data are presented separately. Effect sizes (standard mean difference, SMD) with 95% confidence intervals (CI) of each meta-analysis are given in grey. In addition, I^2 values are given as indices of heterogeneity for each pairwise comparison

(SMD 0.14; $p = 0.034$) umbrella data revealed only trivial effects regarding the exercise order. To further explore the stability of these estimates, sensitivity analyses were conducted. For strength, the omission of Gao and Yu [46] resolved the heterogeneity ($I^2 = 0\%$) and increased the effect size to SMD = 2.53, suggesting that while the magnitude varies, the direction of the effect favoring RE remains consistent. Conversely, for aerobic capacity, the exclusion of Murlasits et al. [17] shifted the trivial positive effect to a trivial negative effect (– 0.05) and eliminated heterogeneity ($I^2 = 0\%$). In addition, I^2 demonstrated relevant heterogeneity for the aerobic capacity, strength, and hypertrophy data (Fig. 4). Overall, the data indicate a favorable trend for RE-first sequencing regarding strength adaptations. Regarding aerobic capacity, the effects appear consistently trivial, regardless of specific study inclusion.

3.3 Individual Study Data

3.3.1 Endurance Versus Concurrent Training

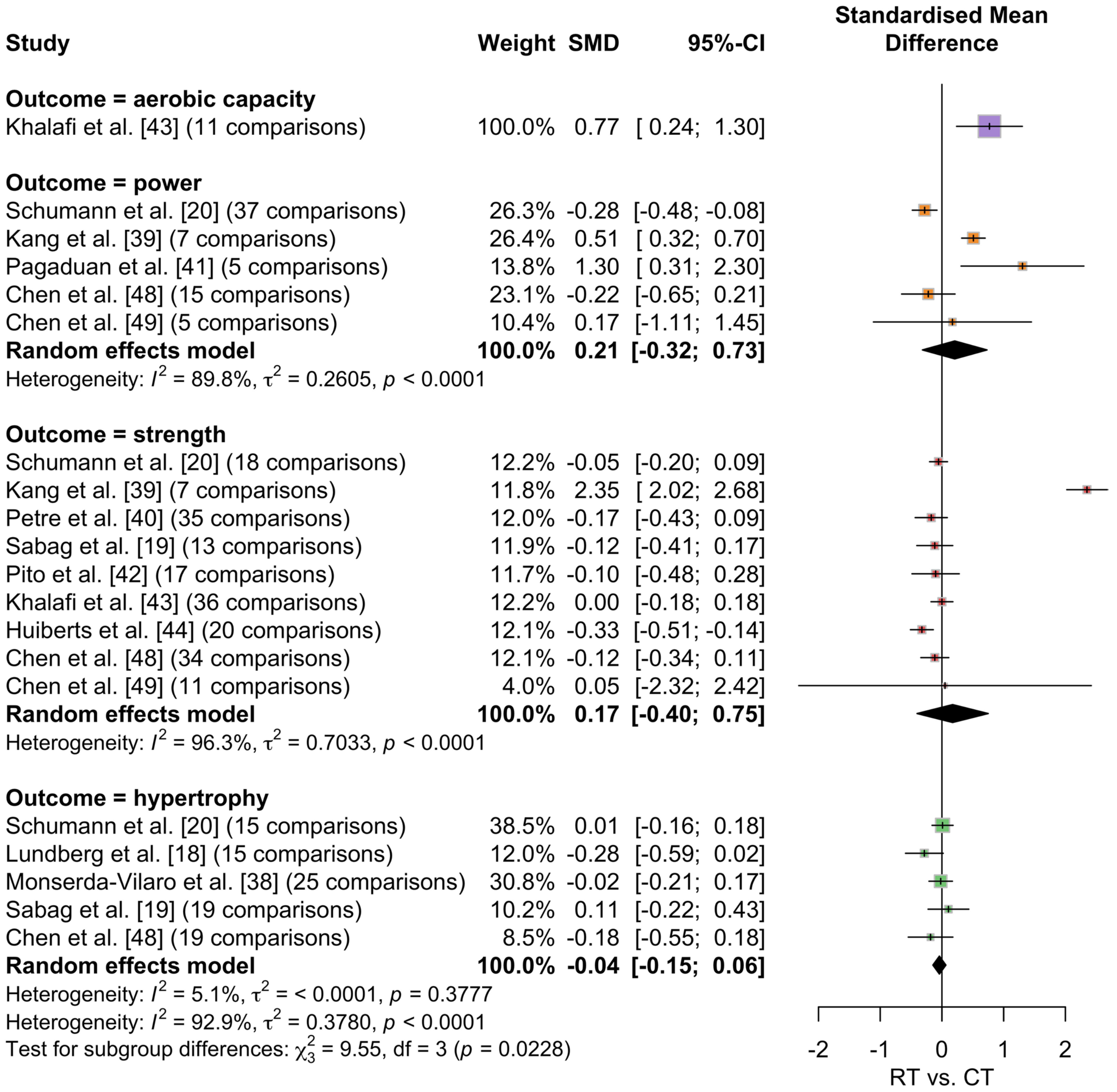
The pairwise meta-analysis comparing endurance versus concurrent training showed significantly greater strength adaptations in CT (SMD 0.91; $p \leq 0.001$). However, heterogeneity analysis ($I^2 = 80.7\%$) indicated substantial variability (Fig. 5A). In contrast, the random-effects model found no significant effects for aerobic capacity (SMD 0.02; $p = 0.67$) and power (SMD 0.25; $p = 0.21$), with only trivial to small effect sizes. Thereby, heterogeneity analysis ($I^2 \leq 23.1\%$) for these outcomes revealed no meaningful variance (Fig. 5A).

3.3.2 Resistance Versus Concurrent Training

The pairwise meta-analysis comparing resistance versus concurrent training demonstrated significantly greater aerobic capacity improvements in CT (SMD 0.78; $p = 0.02$) (Fig. 5B). In contrast, power (SMD 0.00; $p = 0.99$), strength (SMD 0.19; $p = 0.03$), and hypertrophy (SMD 0.09; $p = 0.22$) showed only trivial to small effect sizes. Heterogeneity analysis indicated no meaningful variance for hypertrophy ($I^2 = 0.0\%$) but significant heterogeneity ($I^2 \geq 67.0\%$) for aerobic capacity, power, and strength (Fig. 5B).

3.3.3 Exercise Order

The pairwise meta-analysis comparing exercise order in CT found no significant effects on aerobic capacity (SMD 0.05; $p = 0.58$), power (SMD 0.11; $p = 0.58$), or strength (SMD



Study	Weight	SMD	95%-CI
Outcome = aerobic capacity			
Khalafi et al. [43] (11 comparisons)	100.0%	0.77	[0.24; 1.30]
Outcome = power			
Schumann et al. [20] (37 comparisons)	26.3%	-0.28	[-0.48; -0.08]
Kang et al. [39] (7 comparisons)	26.4%	0.51	[0.32; 0.70]
Pagaduan et al. [41] (5 comparisons)	13.8%	1.30	[0.31; 2.30]
Chen et al. [48] (15 comparisons)	23.1%	-0.22	[-0.65; 0.21]
Chen et al. [49] (5 comparisons)	10.4%	0.17	[-1.11; 1.45]
Random effects model	**100.0%**	**0.21**	**[-0.32; 0.73]**
Heterogeneity: $I^2 = 89.8\%$, $\tau^2 = 0.2605$, $p < 0.0001$			
Outcome = strength			
Schumann et al. [20] (18 comparisons)	12.2%	-0.05	[-0.20; 0.09]
Kang et al. [39] (7 comparisons)	11.8%	2.35	[2.02; 2.68]
Petre et al. [40] (35 comparisons)	12.0%	-0.17	[-0.43; 0.09]
Sabag et al. [19] (13 comparisons)	11.9%	-0.12	[-0.41; 0.17]
Pito et al. [42] (17 comparisons)	11.7%	-0.10	[-0.48; 0.28]
Khalafi et al. [43] (36 comparisons)	12.2%	0.00	[-0.18; 0.18]
Huiberts et al. [44] (20 comparisons)	12.1%	-0.33	[-0.51; -0.14]
Chen et al. [48] (34 comparisons)	12.1%	-0.12	[-0.34; 0.11]
Chen et al. [49] (11 comparisons)	4.0%	0.05	[-2.32; 2.42]
Random effects model	**100.0%**	**0.17**	**[-0.40; 0.75]**
Heterogeneity: $I^2 = 96.3\%$, $\tau^2 = 0.7033$, $p < 0.0001$			
Outcome = hypertrophy			
Schumann et al. [20] (15 comparisons)	38.5%	0.01	[-0.16; 0.18]
Lundberg et al. [18] (15 comparisons)	12.0%	-0.28	[-0.59; 0.02]
Monserda-Vilaro et al. [38] (25 comparisons)	30.8%	-0.02	[-0.21; 0.17]
Sabag et al. [19] (19 comparisons)	10.2%	0.11	[-0.22; 0.43]
Chen et al. [48] (19 comparisons)	8.5%	-0.18	[-0.55; 0.18]
Random effects model	**100.0%**	**-0.04**	**[-0.15; 0.06]**
Heterogeneity: $I^2 = 5.1\%$, $\tau^2 = < 0.0001$, $p = 0.3777$			

Heterogeneity: $I^2 = 92.9\%$, $\tau^2 = 0.3780$, $p < 0.0001$

Test for subgroup differences: $\chi^2_3 = 9.55$, df = 3 ($p = 0.0228$)

Fig. 3 Umbrella forest plots of pairwise comparisons between resistance and concurrent training (RT vs CT). Aerobic capacity (violet), power (orange), strength (red) and hypertrophy (green) data are presented separately. Effect sizes (standard mean difference, SMD) with 95% confidence intervals (CI) of each meta-analysis are given in *grey*. In addition, I^2 values are given as indices of heterogeneity for each pairwise comparison

0.19; $p = 0.35$), with only trivial effect sizes (Fig. 5C). In contrast, hypertrophy (SMD 0.87; $p = 0.36$) showed a large positive effect for RT before ET (RE vs ER), though accompanied by substantial standard errors. Heterogeneity analysis indicated no meaningful variance for aerobic capacity and power ($I^2 = 0.0\%$), while strength and hypertrophy exhibited significant heterogeneity ($I^2 \geq 90.2\%$; Fig. 5C).

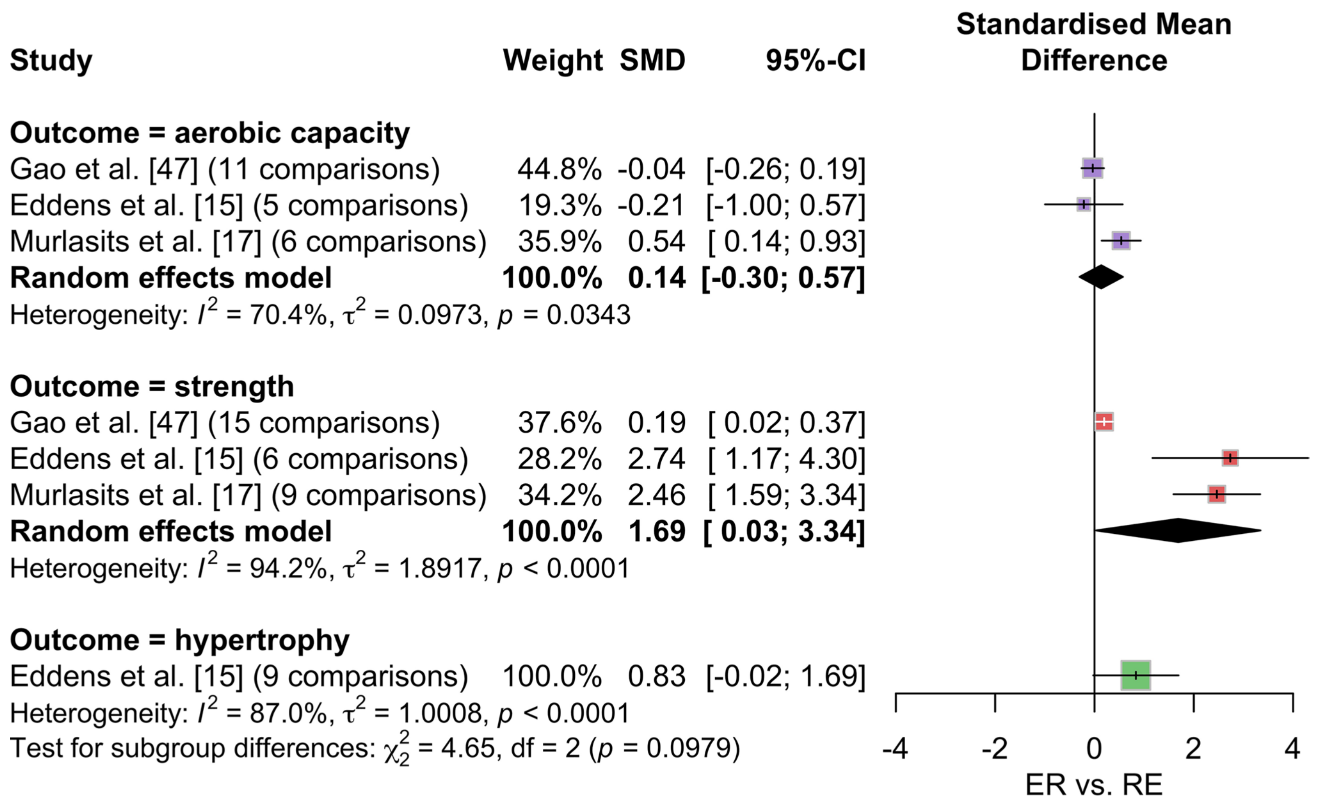


Fig. 4 Umbrella forest plots of pairwise comparisons of exercise order during concurrent training, i.e. resistance training followed by endurance training (RE) vs endurance training followed by resistance training (ER) (order). Aerobic capacity (violet), strength (red) and hypertrophy (green) data are presented separately. Effect sizes (standard mean difference, SMD) with 95% confidence intervals (CI) of each meta-analysis are given in grey. Effect sizes with 95% CI and significance levels of the separate random effect models are given in black. In addition, *Q*-statistics and I^2 are given as indices of heterogeneity for each pairwise comparison

3.3.4 Subgroup Analysis

Subgroup analysis identified significant effects for strength adaptations in the ET versus CT comparison, specifically in relation to resistance training load. A significant subgroup effect ($p = 0.05$) was observed, with strength gains increasing progressively from moderate (SMD 0.64; $p = 0.505$), to mixed (SMD 0.78; $p \leq 0.001$), to high resistance training loads (SMD 1.35; $p \leq 0.001$; Fig. 6). Additionally, ET intensity showed a significant subgroup effect for the ET versus CT comparison ($p = 0.02$; Fig. 7); however, the observed effect sizes were trivial to small (SMD ≤ 0.26). Apart from these, no other significant subgroup differences were detected across all outcome parameters and pairwise comparisons ($0.06 \leq p \leq 0.98$), including (i) training modality (simultaneous, same day, or different day), (ii) training status (untrained vs trained), (iii) age group (< 45 years vs ≥ 45 years), (iv) resistance training load, and (v) endurance training intensity (low, moderate, or high).

3.4 Risk of Bias

The funnel plots revealed no significant publication bias for ET versus CT (Fig. 8A); RT versus CT (Fig. 8B) and exercise order during CT comparisons (Fig. 8C).

4 Discussion

This umbrella review synthesized meta-analytic evidence on CT, comparing it to isolated ET and RT, while additionally examining the impact of exercise order. The findings indicate that (i) aerobic capacity adaptations did not differ meaningfully between isolated ET and CT, while (ii) strength improvements were clearly greater with CT compared with ET, and power gains showed a small, non-significant advantage; (iii) higher resistance training loads within CT further enhanced strength gains compared with ET; (iv) in contrast, when comparing RT and CT, aerobic capacity benefits were superior in CT, whereas (v) strength, power, and hypertrophy adaptations were largely comparable, suggesting that CT does not compromise neuromuscular development and thus

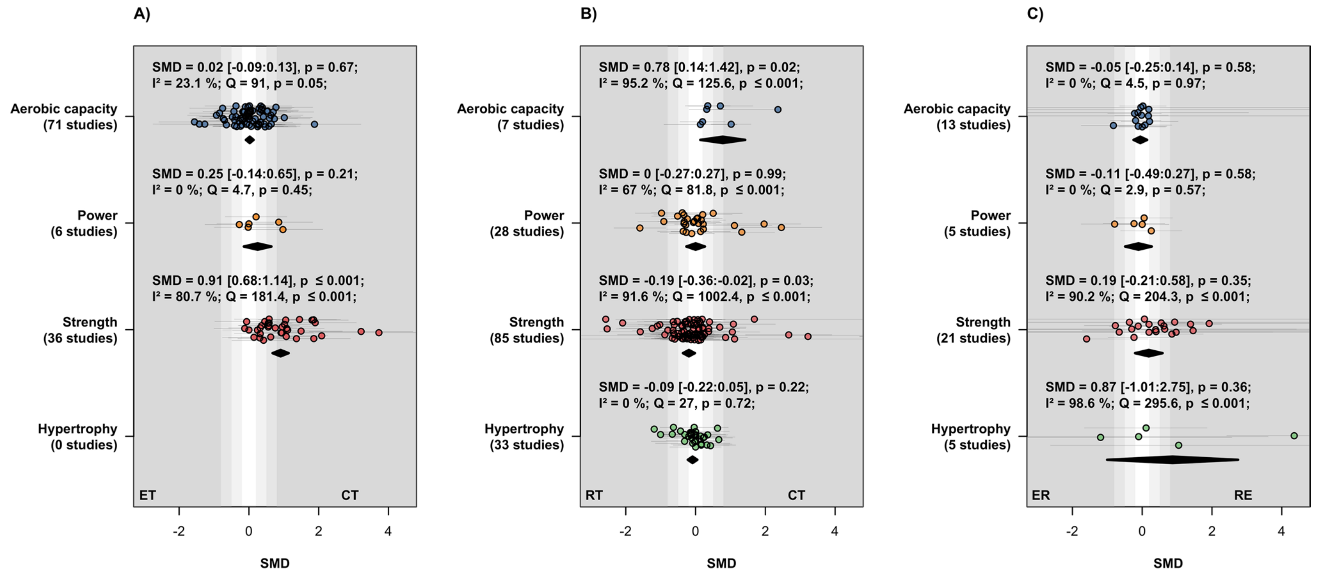


Fig. 5 Adapted forest plots of pairwise comparisons between (**A**) endurance vs concurrent training (ET vs CT); (**B**) resistance vs concurrent training (RT vs CT) and (**C**) exercise order during concurrent training, i.e. resistance training followed by endurance training vs endurance training followed by resistance training (order). Aerobic capacity (violet), power (orange), strength (red) and hypertrophy (green) data are presented separately. In addition, a corresponding number of studies are given for each outcome parameter. Effect sizes (standard mean difference, SMD) with 95% confidence intervals (CI) of individual studies are given in grey. Effect sizes with 95% CI and significance level of the separate random effect models are given in black. In addition, *Q*-statistics and I^2-statistics are given as indices of heterogeneity for each pairwise comparison

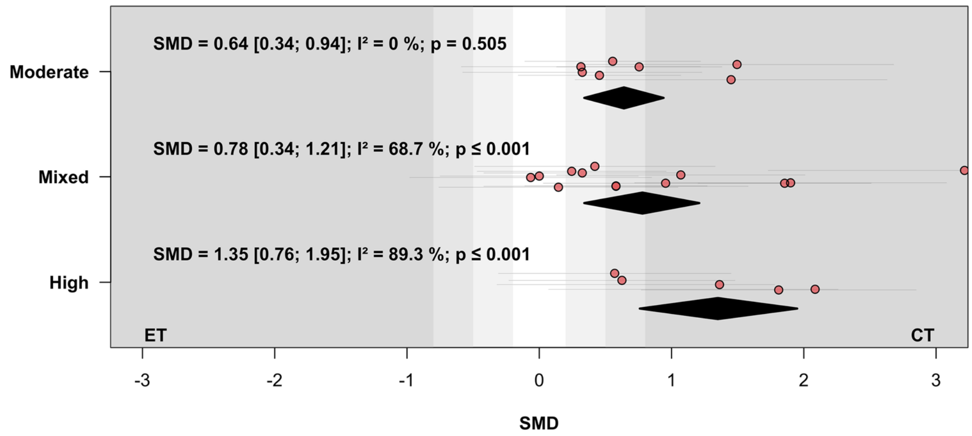


Fig. 6 Adapted forest plot showing a subgroup analysis of strength adaptations comparing endurance training (ET) and concurrent training (CT). The analysis stratifies subgroup effects by resistance training load in the CT setting. Individual values for each study are indicated in red. Effect sizes are presented as standardized mean differences (SMD) with 95% confidence intervals (CI). Heterogeneity is indicated by I^2

challenges the classical interference hypothesis; (vi) exercise order had no impact on aerobic capacity; (vii) but performing RT before ET was associated with greater hypertrophy effects and possibly enhanced strength, though accompanied by substantial heterogeneity and standard errors. Overall, these results suggest that CT can be strategically structured to optimize multiple physiological adaptations without compromising strength or hypertrophy, provided that training variables are carefully managed.

4.1 Endurance Versus Concurrent Training

Our findings suggest that, based on both individual studies and umbrella-level meta-analytic evidence, adaptations in aerobic capacity are comparable between ET alone and CT. However, CT appears to elicit potentially superior improvements in strength compared with ET alone. The observed effects on power were small and not statistically significant, indicating that claims of superiority should be interpreted cautiously. Notably, no data on hypertrophy were available for this comparison. These findings align with previous meta-analyses examining the compatibility

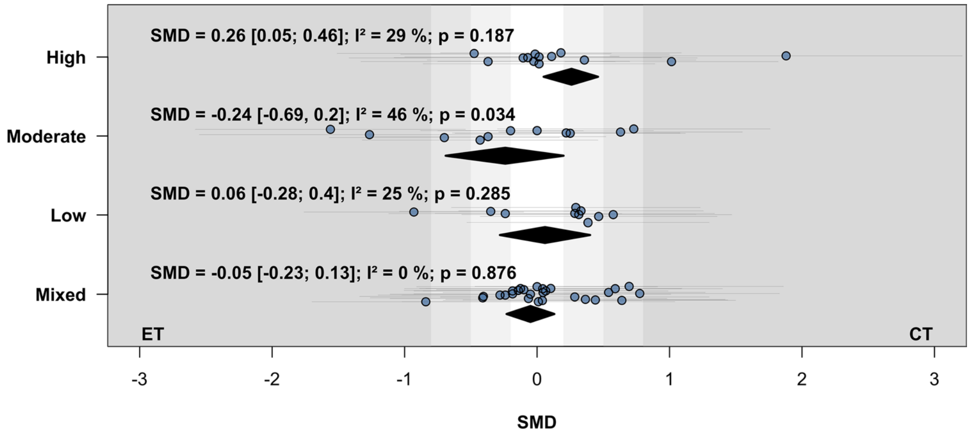


Fig. 7 Adapted forest plot showing a subgroup analysis of aerobic capacity adaptations comparing endurance training (ET) and concurrent training (CT). The analysis stratifies subgroup effects by endurance training intensity. Individual values for each study are indicated in red. Effect sizes are presented as standardized mean differences (SMD) with 95% confidence intervals (CI). Heterogeneity is indicated by I^2

of concurrent strength and endurance training, particularly regarding the interference effect and its impact on muscular adaptations [43, 45].

The observed similarities in aerobic capacity adaptations suggest that adding RT does not compromise cardiovascular improvements. This is consistent with prior research showing that ET adaptations, including VO_2max and running economy, are not negatively impacted by concurrent RT [6, 42, 43, 128, 192]. Some studies even indicated that CT can enhance endurance performance by improving neuromuscular efficiency and reducing energy cost during submaximal efforts [1].

However, our subgroup analyses suggest a slight advantage for CT when combined with high-intensity ET, though the observed effect size was small. This finding is particularly relevant considering previous evidence indicating that high-intensity interval training may interact differently with RT compared with traditional moderate-intensity ET [20, 193].

A key regulator of muscle adaptations to ET is peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC-1α), a transcriptional coactivator that is activated through both AMPK-dependent and AMPK-independent mechanisms. The latter includes activation by p38 mitogen-activated protein kinase (p38 MAPK) in response to metabolic stress like ET but also RT [194, 195]. Besides inducing oxidation and angiogenesis, PGC-1α plays a crucial role in mitochondrial biogenesis through co-activation of transcription factors such as nuclear respiratory factor 1 (NRF-1), overall leading to improved mitochondrial function, and thus contributes to an increase in endurance capacity [2, 196]. Interestingly, preliminary studies show that PGC-1α is activated differently depending on intensity and volume after acute endurance exercises in animal models [197, 198]. In addition, a course of kinetic PGC-1α activation after intensive interval exercise was observed in humans [199, 200]. However, the kinetics of PGC-1α activation after continuous low-intensity endurance exercise and the comparison with high-intensity intervals have not yet been investigated. Yet, chronic training studies with humans also indicate that short, intensive training units induce a higher activation of PGC-1α than low-intensity continuous exercise

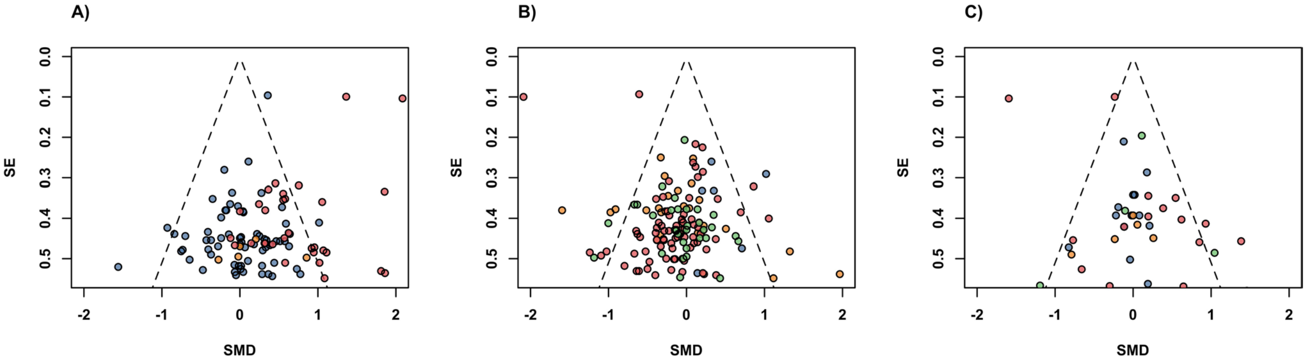


Fig. 8 Funnel plots depicting the assessment of publication bias for pairwise comparisons. The comparisons include **A** endurance training (ET) vs concurrent training (CT), **B** resistance training (RT) vs CT, and **C** exercise order during CT, specifically RT followed by ET (RE) vs ET followed by RT (ER). Effect sizes (standard mean difference, SMD) and standard errors (SE) are shown for aerobic capacity (violet), power (orange), strength (red), and hypertrophy (green)

[201]. The potential benefits of CT in this context may be attributed to a more robust activation of the mTORC1 pathway, along with an upregulation of transcriptional factors through PGC-1α. This, in turn, enhances aerobic metabolism by promoting mitochondrial biogenesis, oxidative capacity, and angiogenesis. Additionally, CT induces neuromuscular adaptations, including an increased proportion of type IIa muscle fibers, which improve fatigue resistance and enhance force output during high-intensity exercise [3, 4, 197]. Although these effects may be small, they could prove decisive in high-performance sports. However, the current lack of sufficient data from highly trained to elite athletic populations precludes the ability to draw definitive conclusions.

Additionally, our subgroup analyses revealed that strength adaptations progressively increased from moderate to mixed to high-load resistance training within CT protocols. This suggests that higher resistance training loads may amplify strength gains even when combined with ET, likely by enhancing neuromuscular recruitment of type II muscle fibers and mechanical overload with stronger activation of the mTORC1 pathway. This finding aligns with previous research indicating that training load is a critical factor in mitigating interference effects [8, 202]. Notably, all other subgroup comparisons failed to reveal significant differences, indicating that factors such as endurance training modality, frequency, and training background did not substantially alter strength outcomes in CT settings.

Conversely, our findings highlight a clear advantage of CT over endurance-only training for improving strength, while effects on power were not statistically significant. Sensitivity analyses confirmed the robustness of these strength gains, demonstrating that the advantage of CT remains stable and significant regardless of individual study inclusion. This is in line with recent meta-analyses showing that ET alone does not optimize neuromuscular adaptations necessary for maximal force production [20, 43, 45, 193]. While ET primarily induces mitochondrial and capillary density adaptations, RT leads to increases in muscle CSA and neuromuscular efficiency, both of which are essential for strength and power development [3, 4]. The enhanced strength and power adaptations observed in CT groups may be attributed to the synergistic benefits of RT, which counteract the catabolic effects of endurance exercise [8, 202]. These findings suggest a smaller impact of AMPK on mTORC1 and underline the beneficial effects of CT. However, the subgroup analysis revealed no significant differences between the intensities of RT on power performance during CT. A critical factor in this context is the type of power exercise performed, along with the number of repetitions, sets, and the intensities used. Recent studies suggest that exercises such as the squat jump tend to require lower intensities compared with movements like the hang power clean [203]. Furthermore, RT can be classified into traditional strength training (characterized by slow to moderate movement execution) and weightlifting training (characterized by explosive, high-velocity execution). Since power training demands the fastest possible muscular contractions, weightlifting training appears to be superior to traditional strength training in developing power [204]. CT protocols have predominantly utilized low to moderate loads and movement velocities, with limited incorporation of weightlifting-specific exercises or techniques. This methodological approach may partially account for the minimal differences often observed between CT and ET in the literature. To date, the integration of Olympic lifts or other explosive resistance exercises within CT paradigms remains largely underexplored in scientific research.

The absence of hypertrophy data in the ET versus CT comparison remains a notable limitation. This gap likely stems from the predominant focus of endurance-centric studies on cardiovascular and metabolic adaptations rather than morphological changes. Furthermore, since pure ET is generally not expected to induce significant muscle growth and excessive hypertrophy may even be considered detrimental to the power-to-weight ratio in distance sports, researchers seldom prioritize specific hypertrophy assessments in these study designs. Previous meta-analyses of CT suggest that hypertrophic responses depend on the interaction between training volume, intensity, and recovery periods [6, 20, 48, 202]. Given that ET alone does not typically induce significant hypertrophy, it is plausible that CT, which includes RT, could promote greater increases in muscle mass. However, due to the lack of available data in our analysis, no definitive conclusion can be drawn at this stage.

Another important factor is the influence of training status on adaptation patterns. Huiberts and colleagues [44] demonstrated that training responses to CT may differ based on an individual's prior strength or endurance training background. Their meta-analysis found that untrained endurance athletes exhibited blunted VO_2max gains with CT compared with endurance-only training, whereas trained endurance athletes and strength-trained individuals did not display significant differences in aerobic adaptations. This suggests that baseline training status may modulate the degree of adaptation interference in CT settings. Furthermore, performance capacity can be categorized either generally or specifically as strength- or endurance-oriented. Currently, general performance levels may be classified using McKay et al.'s framework; however, this model provides only broad descriptors for each performance tier without specifying objective performance parameters [205]. A similar limitation applies to classifications of specific strength performance. At present, these are predominantly theoretical in nature, such as the model proposed by Santos Jr. et al., and lack empirical validation [206]. In contrast, endurance performance in cycling has been better characterized, with reference values derived from secondary analyses of existing datasets. However, many of the included studies did not report VO_2max values, or assessments were conducted using a cycle ergometer, thereby limiting the applicability of VO_2max-based classifications in these contexts [207]. However, our own subgroup analyses did not detect significant differences between individual subgroups, suggesting that the impact of prior training status on CT adaptations may be smaller than previously assumed. While some trends in the data hint at possible moderating effects, the lack of statistically significant differences indicates that factors such as training volume, intensity, and modality may play a more decisive role than training history alone. Further research with larger, well-controlled samples with an exact declared performance level is necessary to clarify whether prior endurance or strength training status meaningfully influences the CT response.

4.2 Resistance Training Versus Concurrent Training

A growing body of evidence suggests that CT can enhance aerobic capacity more effectively than RT alone, while producing comparable adaptations in strength, power, and hypertrophy**.** Our findings support this perspective, as both the umbrella-based meta-analytic data and individual study-level analyses demonstrated that adding ET to a RT regimen does not meaningfully impair neuromuscular adaptations.

The principal signal transduction cascade for muscular strength, power, and hypertrophy involves the activation of mTORC1. mTORC1 functions as a central regulator of skeletal muscle hypertrophy, its activation being elicited by mechanical stress induced through RT. Acting antagonistically to AMPK, mTORC1 phosphorylates ribosomal protein S6 kinase 1 (S6K1) and eukaryotic translation initiation factor 4E-binding protein 1 (4EBP1), thereby inducing anabolic processes such as stimulating myofibrillar protein synthesis and promoting muscle hypertrophy [208, 209]. The potential interference effect occurs when AMPK inhibits mTORC1 both directly and indirectly by phosphorylating TSC2, a critical negative regulator of mTORC1 [9–11]. The results of this umbrella-based meta-analysis challenge the notion of an interference effect [7] and align with recent meta-analyses indicating that strength and hypertrophy gains are largely preserved in CT programs, provided that training parameters are well controlled [6, 18, 20, 38, 42, 43, 193].

The superior improvements in aerobic capacity with CT compared with RT are well documented in the literature. RT alone provides limited cardiovascular stimulus and is generally insufficient to elicit substantial VO_2max improvements [1, 187]. Conversely, CT enhances both neuromuscular and metabolic efficiency, leading to improved oxygen utilization and overall endurance performance [8, 128]. Muscle fiber shifts from IIx to IIa may be beneficial for both endurance and resistance improvements [111]. This suggests that athletes requiring both endurance and strength capabilities may benefit from CT strategies that optimize both physiological domains.

In contrast to early hypotheses regarding interference effects on strength, power, and hypertrophy, our findings indicate no meaningful differences between CT and RT alone for these outcomes. Several meta-analyses have shown that hypertrophy and strength gains in CT programs are comparable to those in RT-only protocols, provided that training variables such as intensity, volume, and recovery are properly managed [6, 38, 40, 202]. Our results further reinforce these findings, suggesting that neuromuscular adaptations are not inherently compromised by the inclusion of ET, particularly when appropriate programming decisions are made. Notably, sensitivity analyses revealed that the trivial impact of CT on hypertrophy is a highly stable finding, whereas strength and power outcomes showed greater sensitivity to specific outliers, though generally remaining within the trivial-to-small range. Interactions between molecular pathways may have a lesser impact than previously assumed, highlighting the significance of additional regulatory factors such as nutrition and hormonal signaling. White et al. [211] demonstrated an AMPK-independent activation of mTORC1 by testosterone through the downregulation of regulated in development and DNA damage response 1 (REDD1), a well-established inhibitor of mTORC1. In contrast, estrogen has been shown to activate mTORC1 via an alternative signaling pathway [210–212]. Further research is needed to examine hormonal influences in CT programs.

Importantly, none of our subgroup analyses revealed significant differences between CT and RT across different training modalities. This suggests that factors such as ET type, frequency, and prior training status do not substantially alter strength, power, or hypertrophy outcomes when RT and ET are combined. This finding aligns with recent evidence indicating that CT adaptations are highly dependent on program design rather than an unavoidable physiological interference effect [17, 20, 47].

Interestingly, our findings contrast with earlier meta-analyses suggesting that CT may impair strength and hypertrophy outcomes compared with RT alone [6, 19, 44]. However, more recent research suggests that such impairments are mainly observed when ET is performed at high volumes or intensities, leading to higher transcript levels for aerobic metabolism, excessive fatigue, and reduced RT performance [20, 197]. Given that our data did not reveal a relevant difference in neuromuscular adaptations between CT and RT, this reinforces the importance of strategic training design, particularly in terms of training load management, to optimize strength adaptations within a CT framework.

Similar to the existing endurance studies and meta-analyses, research involving highly trained to elite athletes remains notably limited. There is a pronounced gap in the literature concerning national-level or international-level athletes who engage in one or two daily training sessions, in which strength training is strategically coordinated within their overall training regimen. Moreover, studies that integrate specific power-oriented exercises, such as Olympic weightlifting movements, with endurance components are currently lacking. As a result, it is currently not possible to draw definitive conclusions regarding the effects of ET on the specific physiological and performance adaptations of high-performance strength athletes.

4.3 Exercise Order in Concurrent Training

The sequencing of RT and ET within a CT program has been widely debated, as exercise order may influence neuromuscular and cardiovascular adaptations [15, 17]. However, our findings suggest that the order of training does not significantly impact aerobic capacity. Both our umbrella-based meta-analytic data and individual study-level analyses indicate that VO_2max improvements are comparable regardless of whether ET or RT is performed first. This aligns with previous research demonstrating that aerobic adaptations are primarily driven by training intensity and volume rather than sequencing effects [15, 17, 46, 193].

Although aerobic adaptations appear to be independent of exercise order, our data indicate that hypertrophic responses are enhanced when RT precedes ET. This pattern was observed consistently across both umbrella-level data and individual studies**,** suggesting that prioritizing RT may optimize muscle growth in CT programs. These findings align with molecular and physiological mechanisms, which were described previously [8, 202]. Performing RT first ensures that muscular contractions occur under a more anabolic environment, maximizing hypertrophic adaptations before potential interference from endurance-induced molecular signaling occurs [15].

The effect of exercise order on strength adaptations appears to be more nuanced. Our analysis suggests that performing RT before ET is beneficial for maximizing strength adaptations, supporting the idea that fatigue induced by prior ET may impair force production during subsequent resistance exercises [16, 17]. Although sensitivity analyses indicated that the magnitude of this benefit is heavily influenced by individual outliers, the positive trend favoring the resistance-first sequence remained consistent. However, individual study-level data only reveal a trivial positive effect of RT-first sequencing**,** suggesting that while performing RT first may be optimal, the practical implications of this advantage may be relatively small in real-world training applications. Previous research has similarly found that any potential strength deficits induced by ET-first sequencing may be mitigated with adequate recovery and training periodization [15, 20].

Another explanation for the order-dependent differences in strength and hypertrophy could be the duration and intensity of the ET exercise. High-intensity ET (e.g., high-intensity interval training or prolonged aerobic sessions) before RT has been shown to increase fatigue and reduce force output, potentially compromising strength development [193]. Conversely, low-intensity endurance exercise prior to RT does not appear to impair strength gains to the same extent [17]. This suggests that training structure, including rest periods and endurance intensity, may play a critical role in moderating the effects of exercise order on strength adaptations. Baar [13] recommends a recovery period of at least 3 h after ET, as AMPK levels rise and fall rapidly post-exercise. In contrast, mTORC1 activity remains elevated for a much longer period after RT, showing no impact on ET outcomes [13]. Given the fatigue and reduced force output induced by high-intensity interval training, performing RT prior to ET, with sufficient recovery periods, may be crucial for optimizing training outcomes. However, our subgroup analyses did not reveal significant differences between training protocols, indicating that factors such as endurance intensity and sequencing may have a less pronounced impact on CT adaptations than previously assumed.

Overall, studies on high-intensity training in highly trained athletes over an extended period, with recovery times of at least 3 h, remain limited. A study by Coffey et al. [213] examined the early molecular response in well trained resistance and endurance athletes, finding an increase in AMPK, mTORC1, and p38 MAPK when training in a non-familiar activity but not in their habitual training. Notably, p38 MAPK acted as an activator of PGC-1α [213]. These findings suggest short-term differences in training adaptations of previously trained muscles, raising the question of whether long-term adaptations could occur while minimizing the interference effect when CT is systematically integrated into the training regimen of highly trained individuals.

In addition to the lack of studies involving highly trained to elite athletes, there is a significant gap in the literature regarding the optimal sequencing of training sessions and the appropriate time intervals between them. Specifically, there is a need to investigate the activation of molecular signaling pathways following various combinations of training modalities, such as low-intensity RT followed by high-intensity endurance exercise, and vice versa. Furthermore, the precise recovery duration required between training sessions, depending on training intensity and volume, remains largely unknown. It is also unclear which recovery strategies, such as sleep, nutritional intake, or active recovery methods, should be implemented to effectively support adaptive responses. Consequently, the current body of evidence is insufficient to provide practice-oriented, evidence-based recommendations for training management in high-performance athletes.

4.4 Limitations

Despite the strengths of this umbrella review, we acknowledge several limitations. First, the methodological heterogeneity and varying quality of the included meta analyses likely influenced our findings. Differences in inclusion criteria, statistical approaches, and study selection introduce variability that limits the direct comparability of results. Second, the overlap of primary studies across multiple meta analyses poses a risk of data redundancy. To effectively mitigate this risk and prevent biased conclusions, we explicitly included an analysis based on individual studies in addition to the umbrella based approach. Third, the diversity of training protocols regarding intensity, volume, and frequency restricts the ability to derive universal recommendations. However, our funnel plot analyses revealed no indication of publication bias. This suggests that the reported effects are robust despite these methodological variations. Finally, a restriction exists regarding generalizability and population characteristics. Most samples involve healthy adults classified as recreational or untrained (tiers 0–2) according to McKay et al.'s framework [205]. Data pertaining to well-trained athletes (tier 3) or highly trained to elite competitors (tiers 4–5) are notably scarce. Furthermore, the average duration of the included interventions was approximately 10 weeks. Consequently, the findings primarily capture early-phase adaptations, restricting conclusions regarding long-term physiological responses.

4.5 Future Research Directions

To address the identified limitations, future research should prioritize rigorous primary studies using standardized inclusion criteria and statistical methodologies. Specifically, we recommend the use of individual participant data meta-analyses to provide deeper insights into how training variables interact with individual responses. Furthermore, researchers must investigate the long-term effects of CT. Most current studies are limited to durations of approximately 10 weeks, capturing only the initial phase of adaptation. Traditionally, the rapid strength gains observed during this period are attributed primarily to neural adaptations, such as improved motor unit recruitment, increased firing rates, and enhanced inter-muscular coordination [214]. This distinct temporal phasing is conceptually supported by Coffey and Hawley [5], who illustrate how adaptation responses evolve from generic signals in the untrained state to highly specific phenotypes over time. However, recent findings challenge this strict dichotomy by demonstrating that significant skeletal muscle hypertrophy also predominates in the early stages of resistance training [215]. It remains unclear how the interplay between these early neural and morphological adaptations evolves during prolonged CT and whether interference effects manifest differently over time. Given the influence of training load and exercise order on strength and hypertrophy, future studies should also explore optimal periodization strategies to maximize the benefits of CT. Beyond training variables, additional physiological and environmental factors require closer examination. Since AMPK acts as a key energy sensor and protein synthesis relies on amino acid availability, nutrition represents a crucial variable that future investigations must strictly control. Similarly, sex hormones such as testosterone and estradiol play a significant role in these pathways but remain underrepresented in current research. Moreover, this review could not fully account for health conditions. Future work should analyze how obesity and metabolic disorders like type 2 diabetes mellitus affect these signaling pathways. This is particularly relevant for aging populations. Crucially, existing data predominantly feature participants with lower performance levels according to McKay et al.'s framework [205]. Consequently, we cannot exclude potential interference effects in highly trained individuals. Research on elite athletes and world-class competitors requires precise synchronization of training intensity, duration, and timing. Future studies must also reflect practical training loads where high endurance volumes contrast with lower strength training volumes. Finally, to extend the applicability of findings beyond general fitness settings, scientists must specifically target older adults, clinical populations, and elite athletes in future trials.

4.6 Practical Implications for Athletes and Coaches

Based on the findings of this umbrella review, CT serves as a highly effective strategy for recreationally trained individuals to improve aerobic capacity and neuromuscular performance simultaneously. Coaches can confidently prescribe CT for muscle growth since sensitivity analyses confirmed the absence of interference effects on hypertrophy as a highly robust finding unaffected by individual study outliers. Consequently, adding endurance sessions to a resistance training program does not inherently compromise muscle growth in recreational athletes. To maximize strength gains during CT, practitioners should prioritize high load resistance training over moderate loads. Although the magnitude of strength benefits varies across studies, the advantage of high loads remains a consistent key variable for securing physiological adaptations. Exercise sequence plays a role when specific neuromuscular adaptations are the primary goal. Performing RT before ET is recommended to optimize strength and hypertrophy outcomes. While the precise magnitude of this benefit fluctuates depending on specific study contexts, the positive trend favoring the RT-first sequence remains consistent. Conversely, the sequence appears negligible for aerobic development. These recommendations apply primarily to healthy and recreationally trained adults. In high-performance settings, where the margin for adaptation is smaller, the interference effect might be more pronounced, requiring a more individualized approach to mitigate residual fatigue.

5 Conclusion

This umbrella review provides comprehensive meta-analytic evidence on the effects of CT compared with ET or RT alone, as well as on the influence of exercise order. Aerobic capacity adaptations did not differ meaningfully between ET and CT, indicating no evidence of interference. In contrast, strength improvements were significantly greater with CT compared with ET alone, particularly when higher RT loads were applied. Power gains showed a small, non-significant advantage with CT. When comparing RT and CT, aerobic capacity was superior with CT, whereas strength, power, and hypertrophy outcomes were largely comparable. These findings challenge the classical interference hypothesis, at least in recreationally trained populations. Exercise order did not influence aerobic outcomes, but RT-first sequencing was associated with greater hypertrophy and, to a lesser extent, strength, albeit with substantial variability across studies. Overall, CT can be strategically designed to optimize multiple performance outcomes without compromising neuromuscular adaptations, provided that training variables such as load and sequencing are carefully managed. However, the generalizability to highly trained and elite athletic populations remains uncertain and requires further research.

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Declarations

Conflicts of Interest Steffen Held, Lena Wolf, Ludwig Rappelt, Wilhem Bloch, Lars Donath, Florian Micke, Stephan Geisler, and Eduard Isenmann have no conflicts of interest relevant to the content of this review and are in accordance with journal policy.

Data Availability Statement The datasets generated during and/or analyzed during the current study are available in the article and its supplementary material. Additional data are available from the corresponding author on reasonable request.

Author Contributions Design of the study: SH, EI, LW. Literature search: LW, SH. Data screening and extraction: LW, SH. Statistical analyses: SH. Manuscript preparation and editing: SH, LW, EI, LR, WB, FM, LD, SG. All authors read and agreed to the submitted version. All authors read and approved the final version of the article.

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