The effects of repeated-sprint training on physical fitness and physiological adaptation in athletes

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The Effects of Repeated-Sprint Training on Physical Fitness and Physiological Adaptation in Athletes: A Systematic Review and Meta-Analysis

ABSTRACT

Background: Repeated-sprint training (RST) is a common training method for enhancing physical fitness in athletes. To advance RST prescription, it is important to understand the effects of programming variables on physical fitness and physiological adaptation.

Objectives: To (1) quantify the pooled effects of running RST on changes in 10 and 20 m sprint time, maximal oxygen consumption (VO_{2max}), Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) distance, repeated-sprint ability (RSA), countermovement jump (CMJ) height, and change of direction (COD) ability in athletes, and, (2) examine the moderating effects of program duration, training frequency, weekly volume, sprint modality, repetition distance, number of repetitions per set, and number of sets per session on changes in these outcome measures.

Methods: Pubmed, SPORTDiscus, and Scopus databases were searched for original research articles up to July 4, 2023, investigating RST in healthy, able-bodied athletes, between 14–35 years of age, and a performance calibre of trained or above. RST interventions were limited to repeated, maximal running (land-based) sprints of $\leq$ 10 s duration, with $\leq$ 60 s recovery, performed for 2−12 weeks. A Downs and Black checklist was used to assess the methodological quality of the included studies. Eligible data were analysed using multi-level mixed-effects meta-analysis, with standardised mean changes determined for all outcomes. Standardised effects (Hedges G [G]) were evaluated based on coverage of their confidence (compatibility) intervals (CI), using a strength and conditioning specific reference value of $G = 0.25$ to declare an improvement (i.e., $G > 0.25$) or impairment (i.e., $G < -0.25$) in outcome measures. Applying the same analysis, the effects of programming variables were then evaluated against a reference RST program, consisting of three sets of 6 × 30 m straight-line sprints performed twice per week for six weeks (1200 m weekly volume).

Results: 40 publications were included in our investigation, with data from 48 RST groups (541 athletes) and 19 active control groups (213 athletes). Across all studies, the effects of RST were compatible with improvements in VO_{2max} (G: 0.56; 90% CI: 0.32 to 0.80), YYIR1 distance (0.61; 0.43 to 0.79), RSA decrement (-0.61; -0.85 to -0.37), linear sprint times (10 m: -0.35; -0.48 to -0.22, 20 m: -0.48; -0.69, to -0.27), RSA average time (-0.34; -0.49 to -0.18), CMJ height (0.26; 0.13 to 0.39), and COD ability (-0.32; -0.52 to -0.12). Compared to the reference RST program, the effects of manipulating training frequency (+1 session per week), program duration (+ 1 extra training week), RST volume (+200 m per week), number of reps (+ 2 per set), number of sets per session (+1 set) or rep distance (+ 10 m per rep) were either non-substantial or comparable with an impairment in at least one outcome measure per programming variable.

Conclusions: Running-based RST improves speed, intermittent running performance, VO_{2max}, RSA, COD ability, and CMJ height in trained athletes. Performing three sets of 6 × 30 m sprints, twice per week for six weeks is effective for enhancing physical fitness and physiological adaptation. Additionally, since our findings do not provide conclusive support for the manipulation of RST variables, further work is needed to better understand how programming factors can be manipulated to augment training-induced adaptations.

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Key Points

- Repeated-sprint training (RST) elicits moderate improvements maximal oxygen consumption, yo-yo intermittent recovery test level 1 (YYIR1) distance, and repeated-sprint ability (RSA) decrement, as well as small improvements in 10 and 20 m linear sprint times, RSA average time, countermovement jump height, and change of direction ability.
- Compared to three sets per session, performing four sets per session may further enhance intermittent running performance (i.e., YYIR1 distance). Combined with a low number of repetitions (4–6 reps), this is a more effective training strategy to enhance physical performance rather than long series of exhaustive efforts (e.g., two sets of 10–12 reps).
- There was limited evidence to recommend increased training frequency (+1 session per week), program duration (+ 1 extra training week), RST volume (+200 m per week), number of reps (+ 2 per set) or rep distance (+ 10 m per rep) as beneficial to changes in physical qualities.

1.0 INTRODUCTION

Repeated-sprint training (RST) involves maximal-effort, short-duration sprints (≤ 10 s), interspersed with brief (≤ 60 s) recovery periods [1]. Existing evidence suggests that it improves several physical qualities relevant to sports competition, including speed, countermovement jump (CMJ) height and intermittent running performance [2]. Physical adaptations from RST can be achieved with as few as 6 × 10–20 min sessions over two weeks [3], which makes it particularly suitable in team sport environments, where there is a need for time-efficient, multi-component training methods. Furthermore, RST can be used to help prepare athletes for the intermittent, high-intensity demands of competition, with its frequent accelerations, decelerations and changes of direction [4-6]. While RST is a potent training method, the magnitude of adaptations may depend on the methods of prescription as it is well documented that the manipulation of programming variables influences adaptation to other methods of training (e.g., resistance training) [7].

Our recent work has demonstrated that RST induces a considerable acute physiological, neuromuscular, perceptual, and performance demand in athletes [8]. For example, average heart rate and oxygen consumption (VO_2) correspond to approximately 90% and 70–80% of max, respectively, while sessions are typically perceived as ’very hard’ and cause a reduction in CMJ height of ~4–5% [8]. Therefore, RST could provide an effective stimulus to enhance aerobic capacity, but this is yet to be quantitively synthesised. A high level of aerobic fitness is essential for enhanced recovery between intermittent bouts of high-intensity exercise and has been associated with the ability to perform more work during team-sport competition [9, 10]. Due to the maximal intensity at which RST is performed, it also exerts a considerable demand on the metabolic system, demonstrated by blood lactate concentrations over 10 $mmol \cdot L^{-1}$ [8]. However, variation in the prescription of programming variables can influence the internal (i.e., psycho-physiological stress) and external (i.e., physical performance output) training load of RST, which subsequently have the potential to cause diverse training adaptations [11, 12]. It is therefore important to understand how the manipulation of programming variables affects the adaptations to RST in athletes.

Programming variables are the core, individual components of a training program (e.g., frequency of sessions, number of repetitions, sprint distance, etc.). In isolation and combination, they influence the exercise stimulus and the magnitude of physiological, neuromuscular, and musculoskeletal adaptations. Furthermore, the chronic effects of manipulating RST variables on physical adaptation are diverse. For example, when an average weekly sprint volume of ~800 m was completed during a six-week, shuttle-based RST intervention [13], significant improvements in 10 m sprint time, repeated-sprint ability (RSA) average time, and change of direction (COD) ability were achieved. Conversely, no change in these outcomes, as well as maximal oxygen consumption (VO_{2max}) and CMJ height, were observed when a volume of 1200 m per week was prescribed over a six-week, straight-line RST program [14]. There were no significant differences in adaptation were found when sprint modality (straight-line vs shuttle RST) [3, 15] and training frequency (1 vs 2 sessions per week) [16] were also compared. Due to the diverse responses observed throughout the literature, it is therefore important to determine the moderating effects of programming variables on chronic RST outcomes.

Since a review by Taylor et al. [2], conducted in 2014, there has been a large increase in the available evidence on RST adaptations, and the moderating effects of programming variables on chronic changes in physical performance are yet to be quantitively synthesised. An updated review therefore seems timely and can provide practitioners with a greater understanding of the influence of RST prescription. Accordingly, our systematic review and meta-analysis aims to (1) quantify the pooled effects of running RST on changes in 10 and 20 m sprint time, VO_{2max}, Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) distance, RSA, CMJ height, and COD ability in athletes, and, (2) examine the moderating effects of program duration, training frequency, weekly volume, sprint modality, repetition distance, number of repetitions per set, and number of sets per session on changes in these outcome measures.

2.0 METHODS

2.1 Search Strategy

Our study was conducted per the ‘Preferred Reporting Items for Systematic Reviews and Meta-analyses’ (PRISMA) guidelines [17] and registered on Open Science Framework (DOI: 10.17605/OSF.IO/RVNDW). A systematic search of the literature was conducted to find original research articles investigating the chronic effects of RST. The latest search was performed on July 4, 2023, using the electronic databases Pubmed, SPORTDiscus, and Scopus. No restrictions were imposed on the article language or the publication date. Relevant keywords for each search term were identified through pilot searching of titles/abstracts/full-texts of previously known articles. Key search terms were grouped and searched within the article title, abstract, and keywords using the search strategy outlined in Supplementary Tables S1 – S3.

Following the initial search of the literature, results were exported to Covidence (www.covidence.org, Melbourne, Australia) and duplicates were removed. The titles and abstracts were then independently screened by two authors (FT, JW), who were not blinded to journal names or manuscript authors. Full texts of the remaining articles were then screened by the same two authors to determine their final inclusion-exclusion status. Any disagreement between the two authors was resolved by a third author (AT). Furthermore, reference lists of all eligible articles and relevant reviews [2, 18] were searched to retrieve any additional studies. Figure 1 displays the strategy for the study selection process used in our review.

-- Insert Figure 1 near here --

2.2 Inclusion-Exclusion Criteria

The inclusion and exclusion criteria can be found in Table 1. Pilot scoping of the literature identified that two weeks (six sessions) was the shortest running-based RST program administered for this population, thus criteria 5 was determined accordingly.

Table 1. Study inclusion-exclusion criteria.

-- Insert Table 1 near here --

2.3 Selection of Outcome Measures and Programming variables

The outcome measures were selected based on consultation with elite sport practitioners and pilot scoping of the literature that identified the most common markers of physical fitness and physiological adaptation in athletes following a RST intervention, which also had a sufficient number of samples to quantitively synthesise. These outcome measures were: 10 m sprint time, 20 m sprint time, CMJ height, COD ability (i.e., time taken to complete the 5–0–5 test, T-test, modified T-test, 20 m agility test, zig-zag 20 m test, Illinois agility test), intermittent running performance (i.e., YYIR1 distance), RSA (mean time and percentage sprint decrement, as defined by Fitzsimons [19] and Glaister et al. [20]) and VO_{2max} recorded during a graded exercise test with gas analysis on a motorised treadmill.

The primary programming variables recorded for the moderator meta-analysis were: program duration, average (i.e., across the intervention) training frequency, average weekly RST volume, sprint modality (i.e., straight-line, 180° shuttle or multi-directional), average number of repetitions per set, average number of sets per session and average sprint repetition distance. Secondary programming variables recorded, but not included in the moderator meta-analysis due to insufficient diversity in the data were: average inter-repetition rest duration, inter-repetition rest modality, inter-set rest duration and inter-set rest modality.

2.4 Extraction of Study Information

Mean and standard deviation data were extracted directly from tables and the text of the included studies. To obtain data from studies where information was provided in figures, graph digitising software (WebPlotDigitizer, version 4.3, USA) was used. For studies where sprint duration was provided instead of sprint distance, the sprint distance was estimated using evidence from our previously published work and based on the average time taken to complete the prescribed distance [12]. With regards to sprint modality, shuttle repeated-sprints were defined as RST where one or more 180° COD were performed. Multi-directional repeated-sprints involved RST where COD were performed with angles other than 180°. For rest modality, ‘passive’ included protocols where participants were required to walk back to a two-way start line (sprints alternating from both ends) in preparation for the next sprint. Where information relating to exercise protocols could not be found within the study or clarification was required, authors were contacted. The Participant Classification Framework [21] was used to define the training and performance calibre of the athletes included in our investigation (Supplementary Table S2).

2.5 Assessment of Reporting Quality and Risk of Bias

To assess the reporting quality and risk of bias within the studies included in our review, two authors (FT and JW) independently evaluated the literature using a modified version of the Downs and Black index [22]. This method is valid for assessing the methodological reporting quality of both randomised and non-randomised interventions, and has been used extensively in systematic reviews pertaining to sport science [8, 23, 24]. If there was an absence of clear information to assess an item on either scale, it was scored as 0. Any disagreements between the two authors were resolved by discussion or a third author (AT).

2.6 Overall Certainty of Evidence

The overall certainty of evidence for each outcome was assessed by two authors (FT and JW) using the Recommendation, Assessment, Development and Evaluation (GRADE) tool [25]. The GRADE domains included inconsistency, heterogeneity, risk of bias, imprecision, indirectness, and publication bias, and were rated as ‘not serious’, ‘serious’ and ‘very serious’ as per the Cochrane recommendations. The overall certainty of evidence was then categorised as ‘very low’, ‘low’, ‘moderate’ or ‘high’ based on the level of confidence that the true effect was similar to the estimated effect for each outcome. Any disagreements between the two authors were resolved by discussion or a third author (AT).

2.7 Data Analysis

Meta-analysis was performed using the “metafor” (Viechtbauer, 2010) and “clubSandwich” (Pustejovsky, 2022) packages in the *R* programming language (R Core Team, 2021). The included studies reported outcomes across several subgroups (from repeated measures taken on the same sample). To account for this hierarchical structure, particularly the within-subject correlation, data were analysed using multi-level mixed-effects meta-analysis. Here, dependency was accounted for by replacing the variance with the variance-covariance matrix of the estimates for outcomes under the same study. Block-diagonal covariance-matrices were estimated with an assumed correlation of $r = 0.50$ [12].

To conduct the meta-analysis, a simple model (intercept-only), using restricted maximum likelihood, was constructed to serve as a baseline model. In this model, we treated each study as a random effect, and grouped them within studies. Meta-regression was then used to determine how different programming variables influenced the outcomes, by adding the programming variables to the baseline model as fixed effects. The programming variables included were: training frequency (continuous, linear: sessions per week), program duration (continuous, linear: number of weeks), sprint modality (categorical: straight-line, 180° shuttle or multidirectional), sets per session (continuous, linear), repetitions per set (continuous, linear), repetition distance (continuous, linear) and weekly training volume (continuous, linear). Where continuous RST programming variables were altered across a study's intervention, the average value was used in our analyses [3, 13, 14, 16, 26-42]. For example, if six repetitions per set were applied in week one, but eight repetitions per set were applied in week two, the average number of repetitions across the intervention was set at seven per set. Therefore, as this occurred in 25 RST groups, some caution should be taken when interpreting the moderating effects of these programming variables.

Within the meta-regression, factors were re-scaled so that the reference (intercept) effect represented the response to the most common prescription of each programming variable found in our studies. Specifically, the reference response involved three sets of 6 × 30 m straight-line repeated sprints, performed twice per week for six weeks for a total weekly volume of 1200 m. The effects of programming variables were then evaluated at a magnitude deemed to be practically relevant for training prescription: performing one more session per week, one more week per program, one more set per session, two more repetitions per set, 200 m volume per week, and sprinting 10 m further per repetition. The effects of each programming variables were estimated while keeping all other factors constant. Maximum Likelihood and Correct Akaike Information Criteria were used to select the best model. We then explored different combinations of the programming factors in linear form and determined the importance value of each predictor by summing the weights and dividing it by the probabilities of the models where the variables appear. This importance value represents the overall support for each variable across all the candidate models. Finally, conclusions were made about the predictors by considering their relative weights and looking at all possible models. This helped us make informed inferences about the programming factors.

Standardised mean changes corrected for small sample bias (Hedges G) were analysed for all outcomes. Additionally, to aid the practical context of our results and accounting for the consistency of data collection methodology between different studies for 10 and 20 m sprint (s), VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$) and YYIR1 (m), mean changes (i.e., raw units) were additionally analysed where appropriate. Uncertainty was expressed using 90% confidence intervals (CI), calculated based on a *t*-distribution, with denominator degrees of freedom given by the inner level of the random effects structure. Prediction intervals (PI) were computed alongside the estimates to convey the likely range of the true change in similar future studies. Between-study heterogeneity was estimated with Cochran's Q and Higgins & Thompson's I^2 statistics.

To provide interpretations on the effect of RST on changes in our outcomes and the moderating effects of programming variables, we visually scaled standardised effects (Hedges G) against threshold values reported specific to strength and conditioning outcomes. These were 0.25, 0.50, and 0.75 for small, moderate, and large effects, respectively [43]. Coverage of the upper and lower CI against these thresholds was considered when interpreting RST effects. When the upper and lower CI fell entirely or predominantly outside the trivial region (i.e., ≥ -0.25 [impairment], ≥ 0.25

[improvement]) we declared an effect substantial. When the upper and lower CI were inside the region bound by a trivial impairment and a trivial improvement (i.e., -0.25 to 0.25), the effect was deemed as non-substantial. If there was equal coverage between a non-substantial change and at least a small improvement or impairment, the effect was declared compatible with both (a trivial change and a substantial impairment/ improvement). When the width of the CI crossed both a small improvement and a small impairment (i.e., ≤ -0.25 and ≥ 0.25), the effect was deemed inconclusive. To facilitate consistent interpretation of standardised effects, the sign of time-based estimates and their CI were reversed, such that a negative value was indicative of an impairment and vice-versa.

3.0 RESULTS

Following the screening process (Figure 1), 40 publications were included in our investigation, with data from 48 RST groups and 19 active control groups. Across all studies, there were 754 athlete inclusions (541 from RST groups).

3.1 Study Characteristics

The most common study design across all studies was parallel-group, controlled trials (n = 27 studies, 68%), while parallel-group, non-controlled trials were represented in 13 (32%) studies. Where a control group was used, participants maintained 'regular' training throughout the intervention (i.e., active control group). Random allocation of participants was conducted in 33 (82%) of studies. The most investigated sport across all studies was soccer (n = 20, 50%), followed by basketball (n = 9, 23%), futsal, volleyball, and a mixture of sports (i.e., athlete were involved in a variety of different sports (n = 2, 5% respectively). Field hockey, tennis, handball, rugby, and taekwondo were represented in one study each. Nineteen (47.5%) studies involved highly trained/national level athletes, and 21 (52.5%) studies involved trained/development level athletes. Twenty-five (62.5%) studies involved adult athletes, while 15 (37.5%) studies involved youth athletes. Female athletes were represented in only four (10%) studies. A summary of the participants and study characteristics of included publications are provided in Supplementary Table S6.

3.2 Outcomes for the Assessment of Reporting Quality and Risk of Bias

Supplementary Table S4 summarises the outcomes of the modified Downs and Black scale for the assessment of reporting quality and risk of bias. Results ranged from 8−12, with a mean score of 10.5 ± 0.9.

3.3 Outcomes for the Overall Certainty of Evidence

The GRADE tool for assessing the overall certainty of evidence is presented in Supplementary Table S5. The certainty of evidence was downgraded to moderate (i.e., we believe that the true effect is probably close to the estimated effect) for 10 m sprint, 20 m sprint, VO_{2max}, RSA average, RSA decrement, CMJ height, and COD ability.

3.4 Study Outcomes

A summary of the training protocols and study outcomes of included publications are provided in Supplementary Table S7. A RST program duration of six weeks was most implemented (n = 13 RST groups, 27%), while the most assigned training frequency was twice per week (n = 27, 56%). The average weekly training volume across all RST groups was 1200 m. Across all RST sessions (n = 567), the most common prescription for each programming variable were straight-line sprints (n = 268 RST sessions, 47%), performed over 30 m (n = 224, 40%), with a passive inter-repetition recovery (n = 521, 92%) lasting 20 s (n = 333, 59%). Three sets (n= 340, 60%) of six repetitions (n = 220, 39%) were most implemented. Multi-set protocols were prescribed across 537 sessions, with a passive inter-set recovery (n = 465, 87%) lasting four minutes (n = 295, 55%) most prescribed in these instances. The complete distribution of RST prescription across all sessions is presented in Figure 2.

-- Insert Figure 2 near here --

Figure 2. The distribution of RST prescription across all 567 sessions. Data are given as the total number of protocols represented (percentage). [range]. Note: 'various' indicates sessions that were prescribed with different combinations of a programming variable (e.g., 20 m sprints in set one, and 30 m sprints in set two).

3.5 Meta-Analysed Effects of Repeated-Sprint Training

The meta-analysed effects of RST on physical adaptation are presented in Table 3 (standardised units) and Table 4 (raw units). Individual forest plots for each outcome are presented in Figures 3–10. Repeated-sprint training elicited moderate improvement in VO_{2max}, YYIR1 distance, and RSA decrement, as well as small improvements in short sprint performance (10 & 20 m sprint times), RSA average time, CMJ height and COD ability. Coverage of the prediction intervals for these effects suggested compatibility with improvements across the range of RST programs similar to those included in our meta-analysis, although 20 m sprint time, VO_{2max}, RSA, CMJ height and COD ability may have some compatibility with no substantial change.

Table 2. Meta-analysed effects of repeated-sprint training on physical adaptation (standarised units).

-- Insert Table 2 near here --

Table 3. Meta-analysed effects of repeated-sprint training on physical adaptation (raw units).

-- Insert Table 3 near here --

-- Insert Figure 3 near here --

Figure 3. The effects of repeated-sprint training on 10 m sprint time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 4 near here --

Figure 4. The effects of repeated-sprint training on 20 m sprint time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 5 near here --

Figure 5. The effects of repeated-sprint training on VO_{2max}. * = $ml \cdot kg^{-1} \cdot min^{-1}$. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 6 near here --

Figure 6. The effects of repeated-sprint training on distance achieved in the Yo-Yo Intermittent Recovery Test Level 1. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 7 near here --

Figure 7. The effects of repeated-sprint training on repeated-sprint ability average time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 8 near here --

Figure 8. The effects of repeated-sprint training on repeated-sprint ability decrement. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 9 near here --

Figure 9. The effects of repeated-sprint training on countermovement jump height. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

-- Insert Figure 10 near here --

Figure 10. The effects of repeated-sprint training on change of direction ability. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

3.6 Moderating Effects of Study Design

There was a further small improvement 10 m sprint time (G: -0.48; 90% CI: -0.93 to -0.03) and further moderate improvement in VO_{2max} (0.57; 0.13 to 1.00) for randomised studies when compared to non-randomised studies. Conversely, compared to non-randomised studies, there was a small impairment in RSA decrement (0.34; -0.14 to 0.82) and moderate impairment in YYIR1 distance (-0.50; -0.90 to -0.10) for randomised studies. There was no substantial difference in RSA average time between randomised and non-randomised studies (-0.22; -0.55 to 0.10) and CMJ height (0.09; -0.16 to 0.33), and the differences between 20 m sprint time (-0.11; -0.64 to 0.41) and COD ability (-0.06; -0.46 to 0.35) were inconclusive.

3.7 Moderating Effects of Programming Variables on the Effects of Repeated-Sprint Training

The moderating effects of programming variables on the RST outcomes when compared to the reference training program are presented in Figure 11. The efficacy of manipulating a single moderator was considered for all measures as a group, where compatibility with impairment in at least one outcome (including any effects that were inconclusive) was considered as insufficient for recommendation. The effects of manipulating training frequency (+1 session per week), program duration (+ 1 extra training week), RST volume (+200 m per week), number of reps (+ 2 per set), number of sets per session (+1 set) or rep distance (+ 10 m per rep) were either non-substantial or comparable with an impairment in at least one outcome measure per programming variable

-- Insert Figure 11 near here --

Figure 11. The moderating effects of programming variables on physical adaptation compared to the reference training program, consisting of three sets of 6 × 30 m straight-line repeated-sprints, performed twice per week for six weeks (1200 m weekly volume). The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

3.8 Model Selection

A comparison of univariate meta-regression models, naïve multivariate models, and the unconditional models for the effects of programming variables on the RST outcomes are provided in Supplementary Tables S8 – S13. In these tables, importance is a measure of how often a moderator appears relative to all candidate models, with higher values representing greater importance. The top five models for each outcome (excluding intercept-only models) are provided in Supplementary Tables S14 – S21. The number of repetitions per set appears in the top model for predicting change in five outcomes; 20 m sprint time, YYIR1 distance, RSA decrement, CMJ height and COD ability. Additionally, weekly volume and training frequency appear in the top models for predicting change in 10 m sprint time and RSA average time, respectively.

4.0 DISCUSSION

From 754 athlete inclusions across 48 intervention groups and 19 active control groups, our systematic review and meta-analysis demonstrates that RST enhances a range of physical qualities that are fundamental to sports performance. Pooled effect estimates indicate that RST causes a moderate improvement in VO_{2max}, YYIR1 distance, and RSA decrement, as well as small improvements in10 and 20 m linear sprint time, RSA average time, CMJ height, and COD ability in athletes. Our meta-analysis is also the first to isolate the effects of manipulating programming variables on the physical adaptations to RST. Performing three sets of 6 × 30 m straight-line sprints with 20 s of passive inter-repetition rest, twice per week for six weeks, is an effective program to achieve the established benefits of RST. However, caution should be taken when manipulating programming variables, as the current evidence is suggestive of impairment in some physical qualities. Since our findings do not provide conclusive support for the manipulation of RST variables, further work is needed to better understand how programming factors can be manipulated to augment training-induced adaptations. Overall, our results support the application of RST as a time-efficient conditioning method that concurrently improves an array of distinct physical qualities.

A practical way to consider heterogeneity within meta-analysis is via a prediction interval, which provides the likely effect size of a new (similar) study based on the included studies and informs practitioners about the expected results in future training interventions [44]. Accordingly, prediction intervals for the meta-analysed effects of RST on physical adaptation are reported in Tables 2 and 3, and Figures 3−10. These largely concur with our interpretations of the effect size, which are based on the point estimate and coverage of the upper and lower CI against threshold values reported specific to strength and conditioning outcomes. However, as is typical with prediction intervals, they are often wider than our CI's and therefore suggest less certainty in some outcomes. Specifically, based on our prediction intervals, the outcomes may have some compatibility with no substantial change. Given that none of our prediction intervals were compatible with an impairment in any outcome measure, practitioners can take confidence when interpreting our findings, which suggest a largely beneficial effect of RST for a multitude of physical qualities.

Our meta-analysis presents evidence of a substantial effect of running-based RST on aerobic capacity in athletes. From eight RST groups, there was a mean improvement from baseline of 4.0%, which equated to an increase in VO_{2max} of 2.2 $ml \cdot kg^{-1} \cdot min^{-1}$, from an average baseline of 52.9 $ml \cdot kg^{-1} \cdot min^{-1}$ (Figure 5). A considerable improvement (i.e., a standardised effect of ≥ 0.25) in aerobic capacity was observed in seven of the eight RST groups included in our investigation (Figure 5), with considerably greater improvements found compared to active control groups, which recorded an average decline in VO_{2max} of -1.2 $ml \cdot kg^{-1} \cdot min^{-1}$. [31, 33, 45-48]. Evidence about the underlying physiological reasons for how increases in VO_{2max} are achieved with RST is lacking, but its brief duration may be insufficient to elicit significant increases in cardiac output, which tends to respond best to prolonged bouts of sub-maximal exercise [49-51]. Rather, RST induced improvement in VO_{2max} is more likely to arise from an enhanced ability to extract and utilise oxygen due to increased muscle oxidative handling capacity (i.e., a greater arterio-venous oxygen difference) [50, 52]. We also found a substantial effect of RST on YYIR1 distance and RSA, two physical performance tests that require a large aerobic contribution [1, 53]. These findings demonstrate that RST improves the ability to perform intermittent bouts of high-intensity running and sprinting. Thus, for practitioners who wish to develop high-intensity running ability in athletes, RST should be considered a productive method of conditioning.

A meta-analysis of the effects of RST on trained participants was conducted in 2014 by Taylor et al. [2]. Since that time, 32 new studies have been included in our review, but several findings remain similar, despite the addition of new studies. These include the magnitude of improvement in linear sprint times, CMJ height, and intermittent running performance. For the first time, we also investigated the effect of RST on COD ability, which is a key physical component of many sports [5]. We found evidence for a small improvement, however, there was also compatibility with no substantial change. The wide disparity between COD tests included in our analysis (see section 2.3 for details) may have affected the precision of this outcome. Improvement in explosive physical qualities following RST likely arises from both neuromuscular and morphological adaptations. Neural adaptations may involve greater muscle fibre recruitment, firing frequency, and motor unit synchronisation [54, 55], while morphological changes could include a shift toward type IIa muscle and an increase muscle cross-sectional area [56, 57]. Collectively, our findings lend further support to the application of RST as a multi-component training method.

4.1 Moderating Effects of Programming Variables

As per sound training theory and in particular principles such as progressive overload, practitioners implementing RST will naturally seek to manipulate programming variables to maximise training outcomes across a program. We previously demonstrated that the manipulation of programming variables such as rest duration, rest modality, sprint modality, number of repetitions, and sprint distance have a substantial effect on acute RST demands[8]. Since training load is a causal component of both acute and chronic training effects [58],it is reasonable to assume that the manipulation of programming factors may indeed influence RST outcomes.

To examine the effects of program duration, training frequency, weekly volume, repetition distance, number of repetitions per set, and number of sets per session on 10 and 20 m sprint time, VO_{2max}, YYIR1 distance, RSA, CMJ height, and COD ability, we used a multiple, multi-level mixed meta-regression against a reference program of three sets of 6 × 30 m straight-line sprints performed twice per week for six weeks. The effects of a single programming factor on a given outcome were then evaluated while holding all others constant. However, we opted for a pragmatic decision framework when interpreting moderators, considering each ‘as a whole’ on the entire set of outcome measures. For example, if the effects of a programming variable were compatible with at least a small improvement [$G >$ or < 0.25] in at least one outcome measure and not compatible with an impairment in any other, we intended to recommend its implementation for enhancing the effects of RST. However, if at least one programming factor was compatible with an impairment or inconclusive, we opted to not recommend its implementation based on the available evidence, even if some outcome measures showed compatibility with an improvement. Indeed, this was the case for our present findings.

It was not possible to include other programming factors such as sprint mode, rest mode, and rest duration within the multiple meta-regression models owing to limited heterogeneity in the range of levels for each variable. Therefore, these programming factors were mostly exampled via univariate meta-regression and qualitative synthesis. As such, consideration should be given to the likely lower strength of evidence and therefore recommendations via the aforementioned programming factors.

4.1.1 Program Duration

Short RST programs are an effective strategy to enhance physical performance. Considerable improvements were found across all outcomes and in all studies that implemented a two-week [3, 59, 60] and four-week [26, 29, 30, 38, 40, 61-63] RST intervention. Changes in enzyme activity related to aerobic and anaerobic metabolism can arise within two weeks of high-intensity training [64], which may subtend rapid improvements in physical performance. A short block of RST could be applied immediately before the competitive season to prepare athletes for the intensity of competition or briefly inserted into the in-season training period to enhance fitness. Compared to the reference training program that consisted of a six-week duration, there were no substantial benefits of performing an additional week of RST (i.e., seven weeks). Therefore, it would seem that most adaptations to RST occur in the first six weeks of a RST program and then plateaux [52, 65]. Furthermore, longer program durations (10−12 weeks) that were employed in three studies [28, 34, 66], did not provide any meaningful benefits on physical performance and are often not feasible in practice given the condensed and concurrent training demands of many sports.

4.1.2 Training Frequency

By manipulating session frequency, practitioners can appropriately manage weekly RST volume, with considerably lower average weekly volumes achieved when one (530 m) and two (1120 m) sessions per week were prescribed, compared to three (1610 m) and four (2100 m). Implementing one RST session per week is an effective in-season strategy to enhance sprint times, intermittent running performance, CMJ height, and COD ability [16, 28, 35]), or at the least, maintain such attributes [15, 67]. Two sessions per week is most common, and also most effective at eliciting the established benefits of RST. This prescription could be suitable during the preparation period when training opportunities are regular and higher volumes of sprinting are accumulated. Compared to the reference program that consisted of two sessions per week, an additional RST session per week (i.e., three sessions) causes an impairment in COD ability, without any conclusive benefits on other physical qualities. While, three sessions per week has been effectively applied during ‘shock’ two-week mesocycles of RST [3, 60], our results lead us to suggest that they are not recommended under other circumstances.

4.1.3 Training Volume

The application of RST can help prepare athletes for the high-speed demands of competition, but considering that RST is performed at or close to maximal intensity, controlling the volume of sprinting is important to ensure appropriate management of fatigue, as well as improvements in fitness. A wide range of weekly RST volumes (300–3150 m) were implemented across the studies in our investigation. Compared to the reference training program that consisted of 1200 m of weekly volume, there were no substantial effects of an additional 200 m of volume per week. It therefore appears that this programming manipulation is too modest to elicit meaningful benefits. Around 1200 m of volume per week appears is conducive for improving physical performance, but smaller weekly training volumes (< 800 m) could be prescribed at the beginning of a RST program to gradually expose athletes to maximal velocity or used during the in-season period to maintain sprint exposure.

4.1.4 Number of Sprint Repetitions

The number of sprint repetitions per set regularly appeared as a top five model for predicting future changes in performance (Supplementary Tables S14 – S21) and is commonly associated as a programming variable with high relevance across many of our RST outcomes (Supplementary Tables S8 – S13). However, compared to the reference training program that consisted of six repetitions per set, an additional two repetitions per set was not associated with any positive effects, and instead, had comparability with a small impairementsp in VO_{2max}. While this effect was non-susbtantial, it can be assumed that the prescription of four or more reps per set could lead to a substantial impairement. This evidence is further supported by visual inspection of the univariate meta-regression bubble plots (Supplementary Figures S1 – S8), which suggest that a greater number of repetitions per set has negative influence on physical fitness and physiological adaptation. While the number of repetitions is an important programming variable to consider for RST prescription, our results suggest that the prescription of 4–6 repetitions is most effective.

Improvements across all outcomes were also observed in the majority of studies that prescribed less than six repetitions per set on average [13, 14, 16, 26-30, 33, 35, 37-40, 68]. Previous synthesis has suggested a lower number of successive repetitions (e.g., 4–6 repetitions) can allow for the quality of each sprint to be maintained while inducing a considerable cardiorespiratory response [12, 69], which together with the findings from our study, lend support to the prescription of lower repetition sets. However, it is relevant to note, that our findings do not suggest that low RST volumes are more effective at improving performance. Rather, training sessions could be designed to incorporate small groups of repetitions performed over multiple sets (e.g., 4 sets of 5 repetitions). If larger repetition sets are prescribed, rest redistribution may permit the maintenance of acute sprint performance and internal physiological load [69]. Furthermore, velocity loss thresholds can account for individual differences in RSA, and the capacity to recover between repetitions [69]. Future research may wish to determine the effects of these prescriptive methods on changes in physical qualities.

4.1.5 Number of Sets

It was common to alter the number of sets per session across the training program, which usually involved an initial period of a lower number of sets per session, corresponding with lower training volumes, and progression to a higher number of sets and greater training volumes [3, 13, 14, 16, 27, 28, 31-37, 68]. The current evidence demonstrates that two and three sets are effective at achieving the established benefits of RST, but one set may be insufficient. Compared to the reference training program that consisted of three sets per session, performing one more set per session (i.e., four sets) causes a substantial improvement in intermittent running performance, as well as minor, non-substantial improvements in 10 and 20 m sprint times. Together with the evidence on the effect of the number of repetitions, these findings suggest that four sets of low repetitions (e.g., 4−6 reps) could be a more effective training strategy than long exhaustive sets (e.g., 2 sets of 10−12 reps). Although, given that our review did not directly compare these strategies, further investigation is needed. To maintain the time-efficient nature of RST when a higher number of sets are implemented, shorter inter-set rest times (e.g., two minutes) can be applied, without detriment to adaptation [27, 28, 32]. It can also be practical to integrate sets between technical drills, thus multiple sets can be completed across a training session.

4.1.6 Sprint Distance

Longer sprint distances have previously been associated with greater physiological demands and increased within-session fatigue [12]. These augmented internal responses to an acute exercise session could be expected to enhance the chronic physiological adaptations to a RST program. However, compared to the reference training program that consisted of a 30 m repetition distance, the effects of sprinting for an additional 10 m per repetition were non-substantial. It therefore seems that a sprint distance of 30 m is most suitable for the all-round development of physical performance in athletes during RST. While there was no conclusive evidence to suggest that longer sprint distances (e.g., 40 m) enhance chronic outcomes, they can increase exposure to faster running speeds, higher training volumes [36, 45, 47, 59, 60] and greater metabolic stress [12]. Therefore, they may be beneficial to achieve process-oriented training goals, such as increased sprint volume exposure or to train under fatigue in team sport athletes (e.g., players not selected for the weekly competitive fixture, or during late-stage return-to-play following injury). Furthermore, it may be logical to assume that increasing repetition distance could improve maximum velocity, however, we did not find enough available data to assess this outcome. Conversely, it could be more practical to implement shorter repetition distances (e.g., 15–25 m) during competition phases, where a reduced sprint volume is desirable. The movement demands of specific sports, where the distance of sprint efforts varies considerably [4], should also be considered when prescribing repetition distance.

4.1.7 Sprint Modality

Visual inspection of univariate meta-regression bubble plots (Supplementary Figures S1 – S8) suggests that the adaptations to RST are largely independent of sprint modality and each respective modality (straight-line, shuttle and multi-directional) demonstrates the ability to enhance physical performance. Subsequently, sprint modality is associated with the least importance for influencing RST outcomes when compared to the other programming variables (Supplementary Table S8 – S13). Both straight-line and shuttle-based RST are associated with an improvement in VO_{2max} (Supplementary Figure S3), but given the width of the CI's, the effect of straight-line RST was more uncertain, and of a smaller magnitude compared to shuttle-based RST. Furthermore, the meta-regression bubble plots rely on univariate analysis, and therefore, the influence of other programming variables may affect this outcome. For example, shuttle-based sprints were more commonly implemented with longer sprint distances (> 30 m) [13, 15, 27, 28, 37, 40, 45, 47, 59, 60, 70-72]. It could have been expected that shuttle-based RST would improve COD ability to a greater extent than straight-line sprints and while there was some evidence for this to occur (Supplementary Figure S8), given the uncertainty of the effect (i.e., the width of the CI), and univariate analysis, this effect remains inconclusive. Original investigations are therefore required to compare the effects of straight-line, shuttle, and multi-directional sprints on COD ability, as well as other RST outcomes.

The different repeated-sprint modalities offer practitioners a variety of training options to challenge athletes in different ways. Shuttle-based RST can be implemented to emphasise change of direction while potentially optimising aerobic adaptations. Protocols with multiple changes of direction per repetition could be effective at improving COD ability, acceleration and deceleration, however, repetition distance should be limited to maintain the intensity of each effort. Straight-line sprints should be prescribed if the goal is to expose athletes to higher speed, here, it would be logical to gradually progress the repetition distance and volume of sprinting so athletes can become accustomed to maximal velocity efforts. One study [40] alternated between straight-line and shuttle-sprints across each session of the training program, which could be a practical strategy to incorporate both formats within a mesocycle.

4.1.8 Rest Duration

Most RST sessions applied across our studies were implemented with a 20 s inter-repetition rest duration (n = 330, 59% of sessions) and a 4 min inter-set rest duration (n = 283; 55% of sessions). One study [32] investigated the effects of inter-repetition rest duration on physical adaptation, with greater improvement in 20 m sprint time shown by the 30 s rest group compared to the 15 s rest group, as well as similar improvement in RSA decrement. Furthermore, enhanced sprint performance was more common in studies that prescribed longer inter-repetition rest durations (i.e., ≥ 30 s) [32, 34, 39, 61], compared to shorter rest times (≤ 20 s) [27, 28, 32, 46], but the effects of rest duration on our other outcomes is equivocal. A 30 s inter-repetition rest period has previously been shown to mitigate within-session fatigue and maintain repetition quality [12], which may explain why longer rest times augment sprint performance. We therefore recommend that longer rest times are prescribed if practitioners wish to prioritise the development of speed during RST, particularly when longer sprint distances (> 30 m) are implemented. While a 4 min inter-set rest period was most common, there is currently a lack of evidence to support the prescription of a particular inter-set rest time in relation to RST adaptations.

4.1.9 Rest Modality

Passive rest was prescribed across most training programs, implemented in 509 (92%) and 453 (88%) of all training sessions for inter-repetition rest, and inter-set rest, respectively. Two studies

[27, 28] incorporated both passive and active rest into their RST program. In these interventions, passive rest was prescribed alongside shorter inter-repetition rest times (14 s) and active recovery was prescribed in conjunction with longer inter-repetition rest times (23 s), which involved a slow jog [27, 28]. One study [46] incorporated eight minutes of sport-specific drills between sets as a form of inter-set active recovery, which was effective at increasing VO_{2max} and RSA average time by 5.4% and 3.7%, respectively, but there was no change in 20 m sprint time or CMJ height. Given the lack of long-term training interventions that have utilised active recovery or compared rest modalities, it would be misguided to present practical recommendations on this programming variable. Instead, we refer readers to our recent review [12] that guides the prescription of rest modality based on the acute responses to a RST session.

4.1.10 Limitations

There are several considerations when interpreting our findings. First, the inclusion of non-randomised and non-controlled trials within the analyse may have increased the risk of bias and imprecision of the results. However, our approach allows for a more comprehensive aggregation of the available evidence on RST and we have assessed the overall risk of bias to be low. Second, all RST interventions were performed alongside usual training; and therefore, the true (isolated) effects of RST are unknown. Furthermore, our analysis did not compare the effects against other training methods (e.g., interval training, resistance training), which can cause similar or greater improvement in certain physical qualities [28, 46, 70]. Third, due to the absence of real-world anchors for practically significant changes in our outcomes (e.g., VO_{2max}), we relied on standardised effect sizes to examine the magnitude of change in our outcomes and the moderating effects of programming variables. Even though we attempted to make these thresholds more specific to strength and conditioning [43], we were not able to apply outcome-specific effect sizes (e.g., COD ability) due to a lack of reference across our entire range of meta-analysed physical qualities. Fourth, the effects of RST may vary according to an athlete's initial fitness. For example, in a study by Sanchez-Sanchez [73] RST had a likely trivial effect on intermittent running performance in high-aerobic fitness soccer players, but a possibly beneficial effect in low-aerobic fitness soccer players. Therefore, our reference training program and programming variable manipulations may have a greater effect in athletes with a low fitness level, but less of an effect in highly fit athletes who are closer to their genetic ceiling. Practitioners should consider the physiological profiles of their individual athletes when designing RST. Lastly, as mentioned, we were able to consider the effects of many programming factors in combination with one another on RST outcomes via multiple, multi-level mixed meta-regression. However, we had insufficient data to include sprint modality or rest duration and modality in these models. Our 'naïve' interpretation of these effects came from univariate analysis and qualitative synthesis only and as such, may not be definitive at present.

5.0 CONCLUSIONS

The quantification of training adaptations allows practitioners to understand the relationship between the training stimuli imposed and the adaptations achieved [2]. Our meta-analysis presents both new and updated evidence on the physical adaptations to RST in athletes. True to its reputation as a multi-component training method [2], our findings demonstrate that RST improves a range of physical qualities. Specifically, moderate improvements in VO_{2max}, YYIR1 distance, and RSA decrement were established, as well as small improvements in 10 and 20 m linear sprint times, RSA average time, CMJ height, and COD ability. The prescription of three sets of 6 × 30 m straight-line sprints, twice per week for six weeks, is an effective training program. Performing four sets per session is associated with additional improvement in intermittent running performance, and appears to be a more superior training strategy than long exhaustive sets (e.g., two sets of 10–12 reps). However, original investigations are needed to better understand how programming variables can be manipulated to augment training-induced adaptations as most of our findings could not differentiate their effects. The findings from our review and meta-analysis provide practitioners with the expected adaptations to RST in athletes and can be used to enhance the design of RST programs.

Study Registration

Open Science Framework. Registration DOI: 10.17605/OSF.IO/RVNDW

Declarations

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Jonathon Weakley completed the screening, data extraction and data analysis of all data within this manuscript. Fraser Thurlow and Minh Huynh created the tables and figures. All author’s contributed to the writing of the manuscript. All authors reviewed, refined and approved the final manuscript.

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Table 1. Study inclusion-exclusion criteria.

Criteria	Inclusion	Exclusion
1	Original research article available in any language, including randomised and non-randomised, controlled and non-controlled experimental studies.	Reviews, surveys, opinion pieces, books, periodicals, editorials, case studies, observational studies, non-academic/non-peer-reviewed text, articles that repeated the results from a different article.
2	Healthy, able-bodied, non-injured athletes, aged 14–35 years, of any gender. Athletes' performance calibre was 'trained' or above.	Special populations (e.g., clinical, patients), people with a physical or mental disability, or people considered to be injured or returning from injury. Non-athletic populations or athletes competing at recreational level. Athletes under the age of 14 or over the age of 35 years.
3	A RST intervention, involving maximal intensity sprints, with a mean work duration of ≤ 10 s or equivalent distance, and a rest duration of ≤ 60 s.	A training intervention involving submaximal intensity, with a work duration of > 10 s or equivalent distance, and a rest duration of > 60 s.
4	RST was performed as an independent experimental training intervention. Usual training practice was permitted.	Studies incorporated combined experimental training interventions that were outside of their usual training practice (e.g., RST plus plyometric training).
5	RST was performed as a running, land-based intervention on a flat surface.	RST was performed on a slope, treadmill, bicycle, ergometer or any other implement.
6	RST intervention duration of 2–12 weeks (minimum six sessions).	RST intervention duration of < 2 weeks, < 6 sessions, or > 12 weeks.
7	Studies must have reported ≥ 1 outcome measure (outcome measures are described in section 2.3)	No relevant outcome measures were reported.
8	RST group must have performed the intervention under normal conditions (e.g., usual nutritional intake, normoxia, absence of ergogenic aids). Placebos permitted.	RST was performed under altered or abnormal conditions (e.g., hypoxia, heat stress, ergogenic aids, different diet)
9	Control groups must have performed their usual sports training under normal conditions without any additional interventions. Placebos permitted.	Additional training interventions were given to the control groups, outside of their usual training practice.

Abbreviations: RST = repeated-sprint training; y = years; s = seconds.

Table 2. Meta-analysed effects of repeated-sprint training on physical adaptation (standarised units).

Outcome	Number of…		Pooled Effects (Hedges G)		
	Studies	Samples	Estimate	90% CI	90% PI
10 m sprint	15	22	-0.34	-0.47 to -0.21	-0.5 to -0.19
20 m sprint	9	14	-0.45	-0.69 to -0.21	-0.99 to 0.09
VO_{2max}	8	8	0.63	0.36 to 0.91	0.14 to 1.13
YYIR1 distance	16	22	0.60	0.43 to 0.77	0.24 to 0.96
RSA average	23	27	-0.34	-0.49 to -0.18	-0.78 to 0.11
RSA decrement	17	21	-0.63	-0.86 to -0.40	-1.36 to 0.09
CMJ height	20	25	0.27	0.14 to 0.39	0.14 to 0.39
COD ability	13	20	-0.32	-0.53 to -0.12	-0.85 to 0.20

Abbreviations: CI = confidence interval; PI = prediction interval; VO_{2max} = maximal oxygen consumption; RSA = repeated-sprint ability; CMJ = counter-movement jump; COD = change of direction; YYIR1 = Yo-Yo Intermittent Recovery Test Level 1.

Table 3. Meta-analysed effects of repeated-sprint training on physical adaptation (raw units).

Outcome	Number of…		Pooled Effects (Raw Units)		
	Studies	Samples	Estimate	90% CI	90% PI
10 m sprint (s)	15	22	-0.04	-0.05 to -0.02	-0.08 to 0.00
20 m sprint (s)	9	14	-0.06	-0.09 to -0.02	-0.14 to 0.03
VO_{2max} ($ml \cdot kg^{-1} \cdot min^{-1}$)	8	8	2.6	1.7 to 3.5	1.7 to 3.5
YYIR1 (m)	16	22	225	1534 to 296	3 to 447

Abbreviations: CI = confidence interval; PI = prediction interval; VO_{2max} = maximal oxygen consumption; YYIR1 = Yo-Yo Intermittent Recovery Test Level 1. Notes: Pooled effects (raw units) for RSA average time, RSA decrement, CMJ height and COD ability are unavailable due to the concerns of comparing results between different testing methods and protocols.

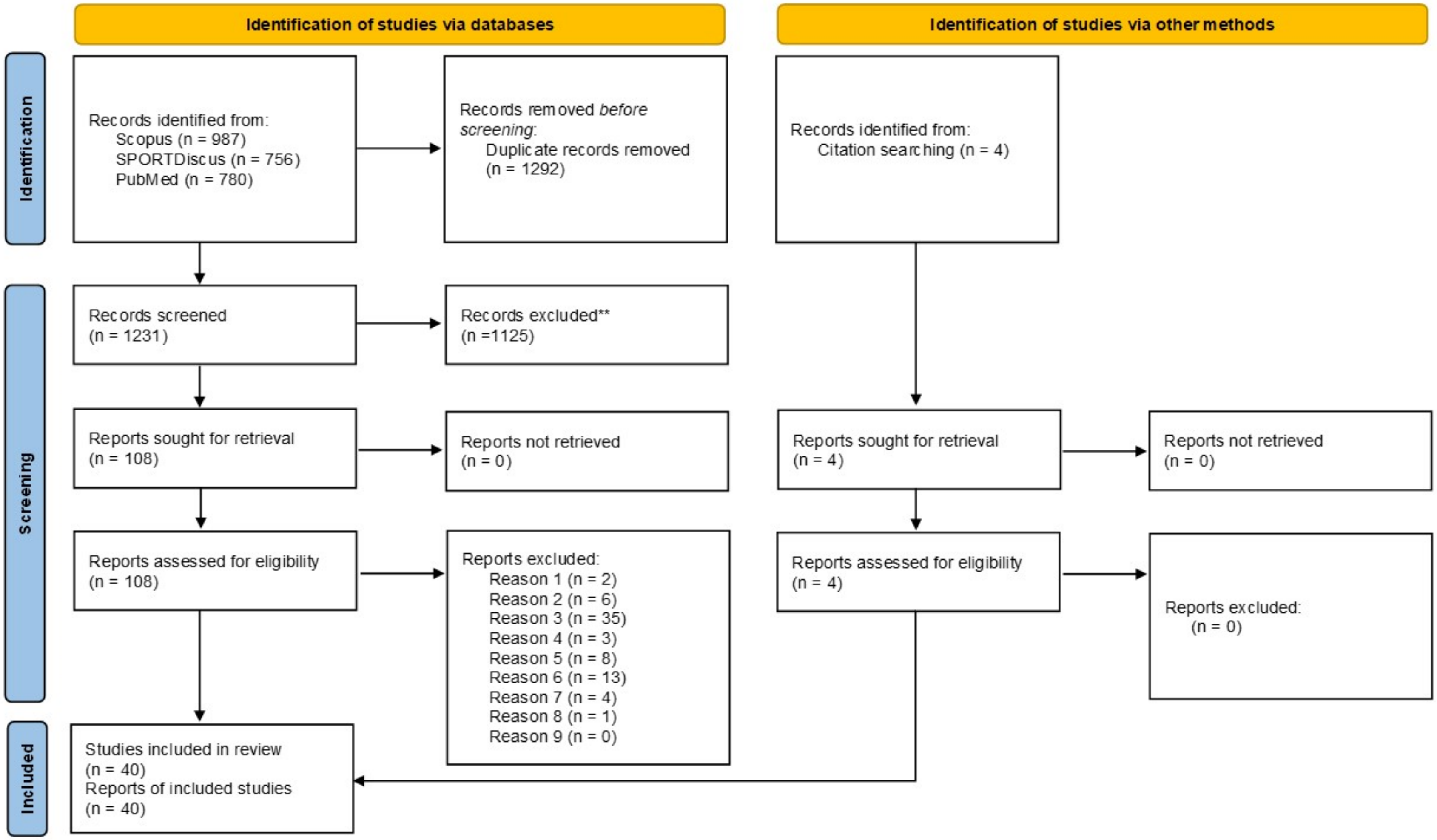


Figure 1. Study selection process

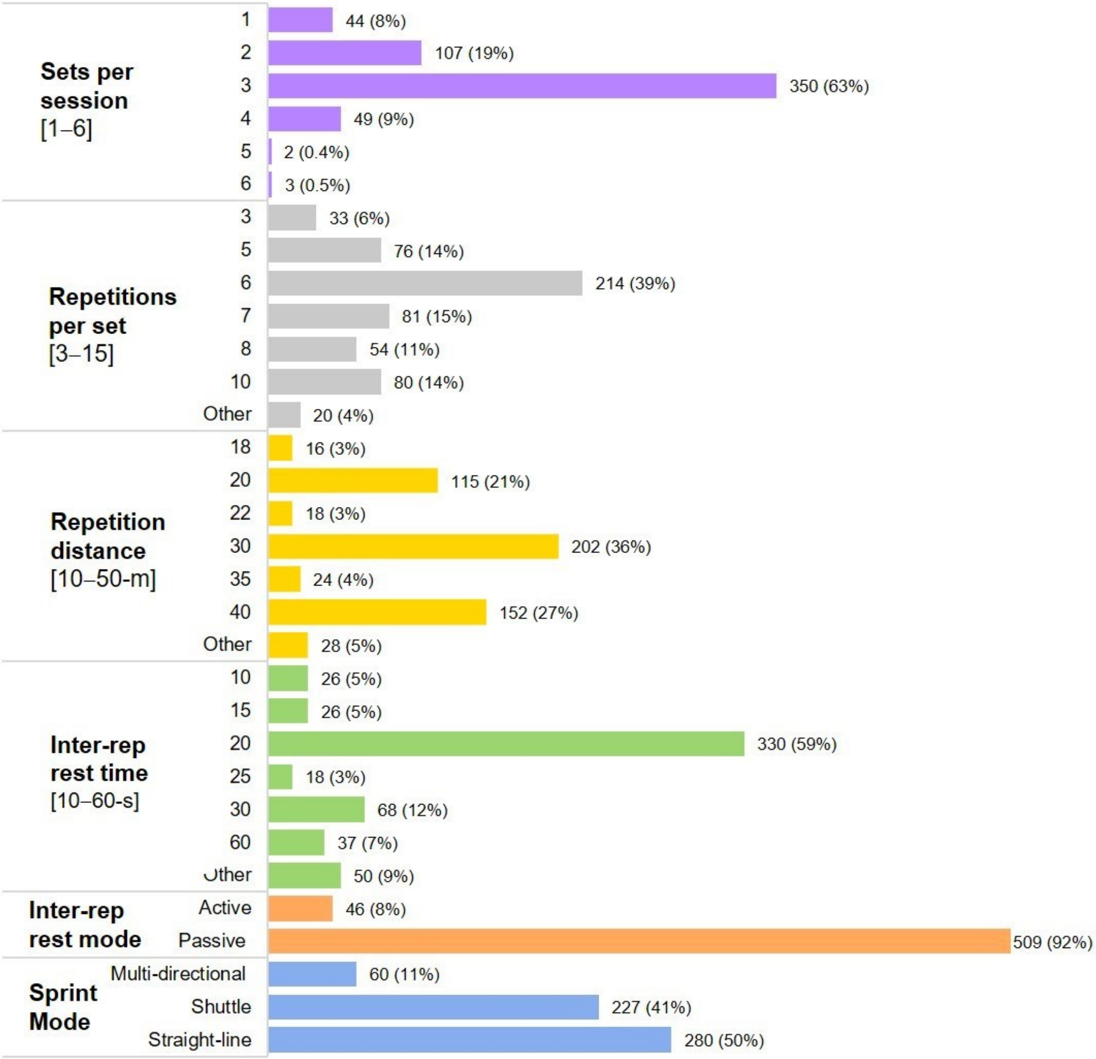


Figure 2. The distribution of RST prescription across all 567 sessions. Data are given as the total number of protocols represented (percentage). [range]. Note: 'various' indicates sessions that were prescribed with different combinations of a programming variable (e.g., 20 m sprints in set one, and 30 m sprints in set two).

Study	Study statistics		
	Pre-training (s)	Post-training (s)	Mean change (s)
Taylor, J, 2016 [3]	1.73	1.62	-0.11
Chtara, 2017 [13]	1.90	1.82	-0.08
Taylor, J, 2016 [3]	1.75	1.64	-0.11
Negra, 2022 [80]	1.85	1.76	-0.09
Michailidis, 2022 [63]	1.96	1.90	-0.06
Negra, 2022 [80]	1.90	1.82	-0.08
Beato, 2019 [60]	1.78	1.70	-0.08
Maggioni, 2018 [47]	1.87	1.82	-0.05
Beato, 2022 [15]	1.86	1.82	-0.04
Arede, 2022 [74]	1.88	1.81	-0.07
Buchheit, 2010 [28]	1.96	1.93	-0.03
Rey, 2019 [16]	1.84	1.81	-0.03
Krakan, 2020 [14]	1.88	1.86	-0.02
Arede, 2022 [74]	2.07	2.03	-0.04
Taylor, L, 2021 [39]	1.70	1.68	-0.02
Buchheit, 2008 [27]	1.88	1.86	-0.02
Rey, 2019 [16]	1.87	1.85	-0.02
Bravo, 2008 [70]	1.77	1.76	-0.01
Beato, 2022 [15]	1.80	1.79	-0.01
Beato, 2019 [60]	1.75	1.74	-0.01
Arede, 2022 [74]	2.18	2.17	-0.01
Le Scouarnec, 2022 [42]	2.12	2.12	0.00
Combined	1.87	1.83	-0.04
Prediction interval			

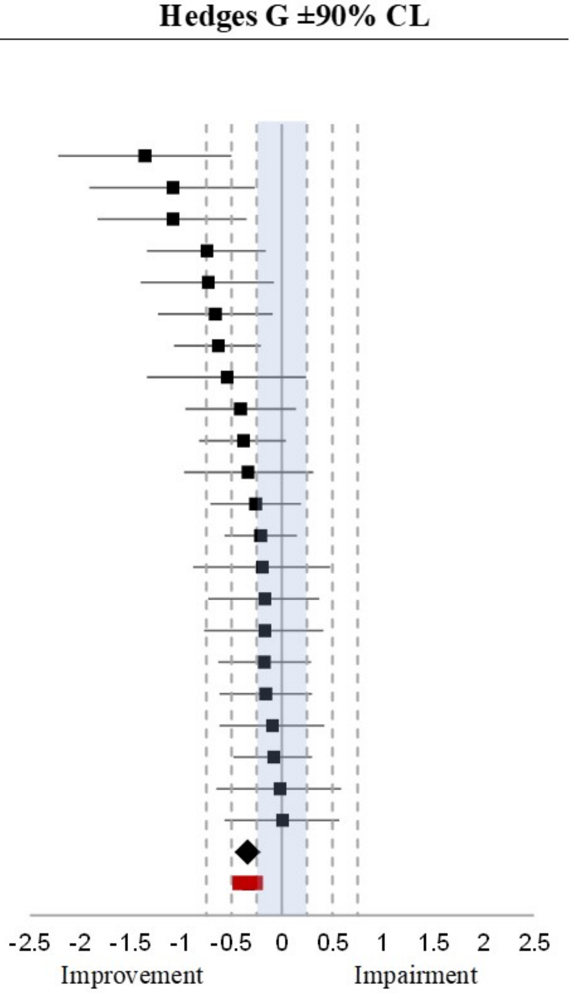


Figure 3. The effects of repeated-sprint training on 10 m sprint time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics		
	Pre-training (s)	Post-training (s)	Mean change (s)
Markovic, 2007 [34]	3.23	3.13	-0.10
Negra, 2022 [80]	3.37	3.20	-0.17
Taylor, 2016 [3]	3.03	2.91	-0.12
Taylor, 2016 [3]	2.96	2.85	-0.11
Negra, 2022 [80]	3.28	3.14	-0.14
Beato, 2019 [60]	2.96	2.90	-0.06
Iaia, 2017 [32]	3.30	3.25	-0.05
Rey, 2019 [16]	3.31	3.23	-0.08
Iaia, 2017 [32]	3.29	3.21	-0.08
Rey, 2019 [16]	3.28	3.23	-0.05
Beato, 2019 [60]	2.94	2.92	-0.02
Fernandez, 2012 [46]	3.20	3.20	0.00
Le Scouarnec, 2022 [42]	3.43	3.44	0.01
Maggioni, 2018 [47]	3.20	3.22	0.02
Combined	3.20	3.13	-0.07
Prediction interval			

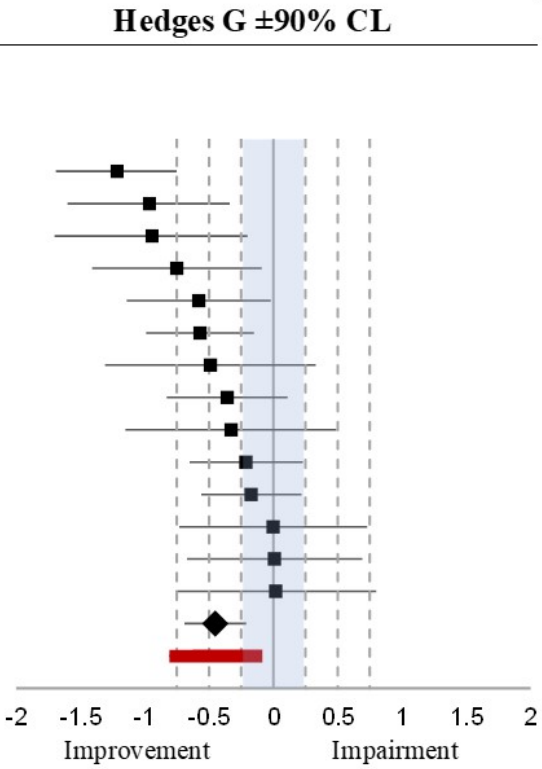
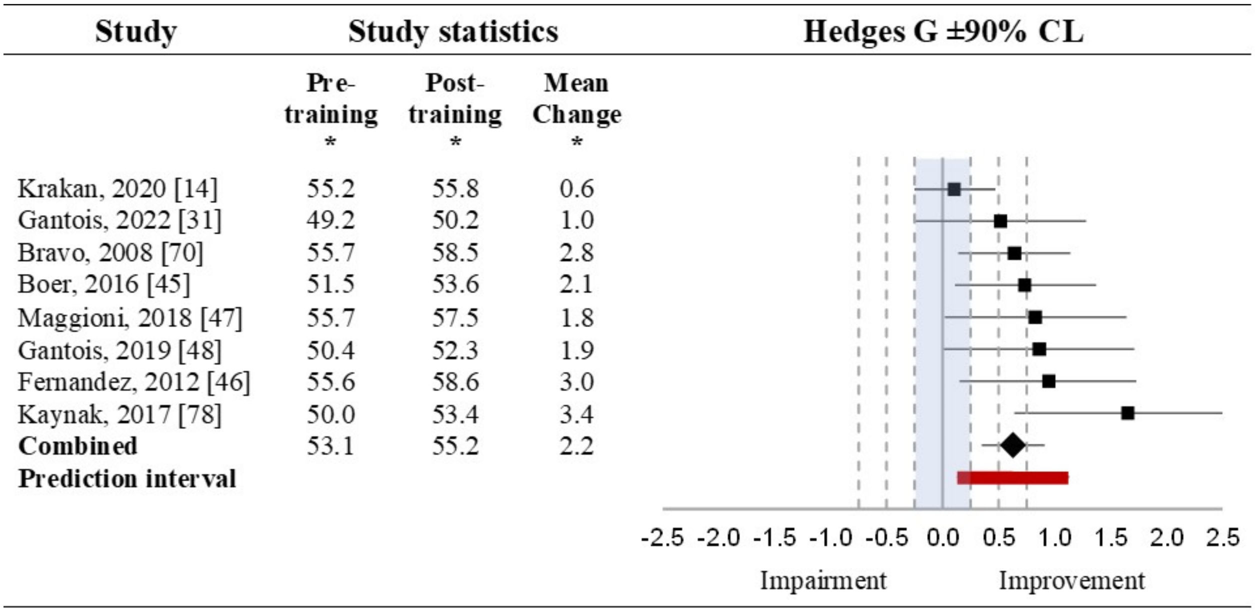


Figure 4. The effects of repeated-sprint training on 20 m sprint time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.



Study	Pre-training *	Post-training *	Mean Change *
Krakan, 2020 [14]	55.2	55.8	0.6
Gantois, 2022 [31]	49.2	50.2	1.0
Bravo, 2008 [70]	55.7	58.5	2.8
Boer, 2016 [45]	51.5	53.6	2.1
Maggioni, 2018 [47]	55.7	57.5	1.8
Gantois, 2019 [48]	50.4	52.3	1.9
Fernandez, 2012 [46]	55.6	58.6	3.0
Kaynak, 2017 [78]	50.0	53.4	3.4
Combined	53.1	55.2	2.2
Prediction interval			

Figure 5. The effects of repeated-sprint training on VO_{2max}. * = $ml \cdot kg^{-1} \cdot min^{-1}$. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics		
	Pre-training (m)	Post-training (m)	Mean change (m)
Sanchez, 2019 [73]	1764	1798	34
Sanchez, 2019 [73]	914	985	71
Haugen, 2015 [67]	1515	1612	97
Brini, 2018 [29]	1667	1852	185
Beato, 2022 [15]	2472	2604	132
Beato, 2019 [60]	1642	1822	180
Brini, 2020 [66]	1792	2065	273
Beato, 2019 [60]	1686	1811	125
Negra, 2022 [80]	860	1076	216
Beato, 2022 [15]	2500	2696	196
Maggioni, 2018 [47]	1350	1725	375
Attene, 2014 [41]	605	775	170
Taylor, J, 2016 [3]	1830	2270	440
Gatterer, 2014 [71]	1832	2216	384
Attene, 2016 [26]	1092	1441	349
Negra, 2022 [80]	1104	1404	300
Nedrehagen, 2015 [35]	1455	1677	222
Eniseler, 2017 [75]	2307	2480	173
Bravo, 2008 [70]	1917	2455	538
Attene, 2016 [26]	1105	1435	330
Taylor, J, 2016 [3]	1691	2183	492
Combined	1576	1828	252
Prediction interval			

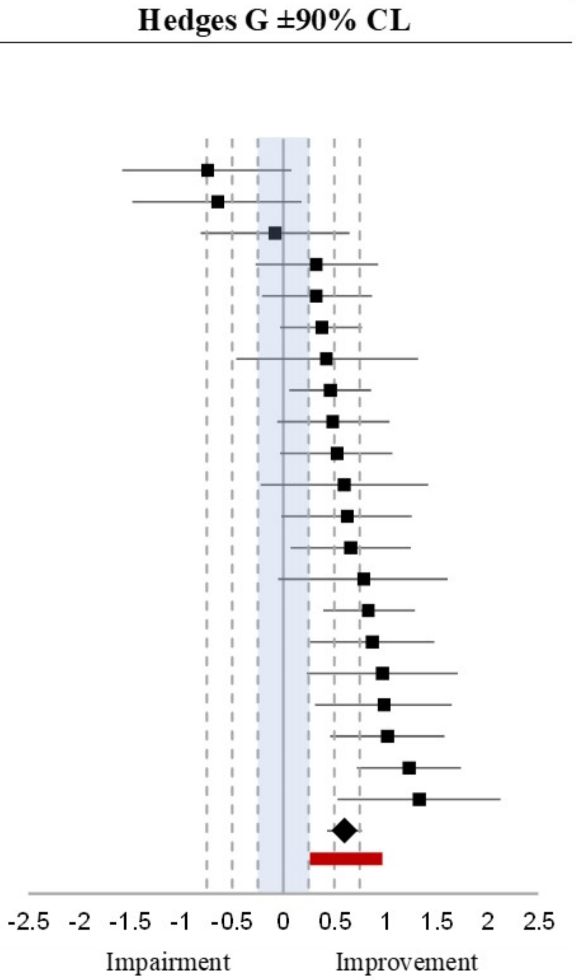


Figure 6. The effects of repeated-sprint training on distance achieved in the Yo-Yo Intermittent Recovery Test Level 1. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics Pre-training (s)	 Post-training (s)	 Mean change (s)
Michailidis, 2022 [63]	8.08	7.70	-0.38
Buchheit, 2010 [28]	6.35	6.18	-0.17
Kaynak, 2017 [78]	3.21	3.03	-0.18
Fernandez, 2012 [46]	5.3	5.10	-0.20
Suarez-Arrones, 2014 [72]	8.00	7.80	-0.20
Bravo, 2008 [70]	7.53	7.37	-0.16
Gantois, 2019 [31]	4.83	4.67	-0.16
Chtara, 2017 [13]	6.53	6.42	-0.11
Rey, 2019 [16]	4.20	4.08	-0.12
Sanchez, 2019 [73]	4.40	4.26	-0.14
Nedrehagen, 2015 [35]	7.79	7.68	-0.11
Rey, 2019 [16]	4.20	4.12	-0.08
Beato, 2019 [60]	7.46	7.40	-0.06
Lapointe, 2020 [40]	5.18	5.01	-0.17
Sanchez, 2019 [73]	4.77	4.76	-0.01
Haugen, 2015 [67]	2.98	2.98	0.00
Beato, 2022 [15]	7.46	7.40	-0.06
Beato, 2022 [15]	7.56	7.52	-0.04
Beato, 2019 [60]	7.50	7.48	-0.02
Buchheit, 2008 [27]	5.93	5.87	-0.06
Eniseler, 2017 [75]	7.13	7.13	0.00
Gatterer, 2014 [71]	7.60	7.60	0.00
Izquierdo, 2022 [77]	4.84	4.79	-0.05
Krakan, 2020 [14]	3.96	3.99	0.03
Nascimento, 2015 [79]	8.53	8.56	0.03
Soares-Caldiera, 2014 [38]	7.62	7.43	-0.19
Combined	6.11	6.01	-0.10
Prediction interval			

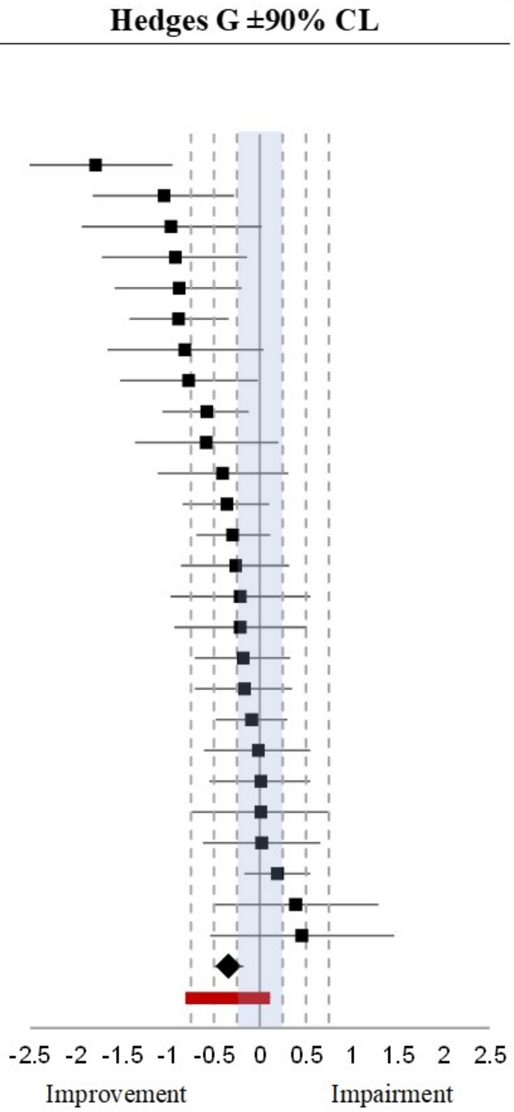


Figure 7. The effects of repeated-sprint training on repeated-sprint ability average time. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics		
	Pre-training (%)	Post-training (%)	Mean change (%)
Gantois, 2019 [31]	6.4	3.0	-3.4
Attene, 2016 [26]	11.4	7.0	-4.4
Attene, 2014 [41]	3.8	2.7	-1.1
Eniseler, 2017	5.5	4.8	-0.7
Iaia, 2017 [32]	5.9	4.1	-1.8
Suarez-Arrones, 2014 [72]	5.3	3.7	-1.6
Selmi, 2018 [37]	6.0	4.8	-1.2
Iaia, 2017 [32]	5.2	3.7	-1.5
Kaynak, 2017 [78]	9.5	6.1	-3.4
Buchheit, 2008 [27]	3.7	3.0	-0.7
Attene, 2016 [26]	10.3	7.3	-3.0
Rey, 2019 [16]	3.5	2.7	-0.8
Krakan, 2020 [14]	5.8	4.5	-1.3
Nascimento, 2015 [79]	4.8	3.5	-1.3
Rey, 2019 [16]	3.0	2.5	-0.5
Gatterer, 2014 [71]	5.2	4.6	-0.6
Izquierdo, 2022 [77]	4.8	4.5	-0.3
Lapointe, 2020 [40]	5.8	6.5	0.7
Sanchez, 2019 [73]	4.1	3.9	-0.2
Sanchez, 2019 [73]	2.6	3.0	0.4
Soares-Caldiera, 2014 [38]	6.3	5.2	-1.1
Combined	5.7	4.3	-1.3
Prediction interval			

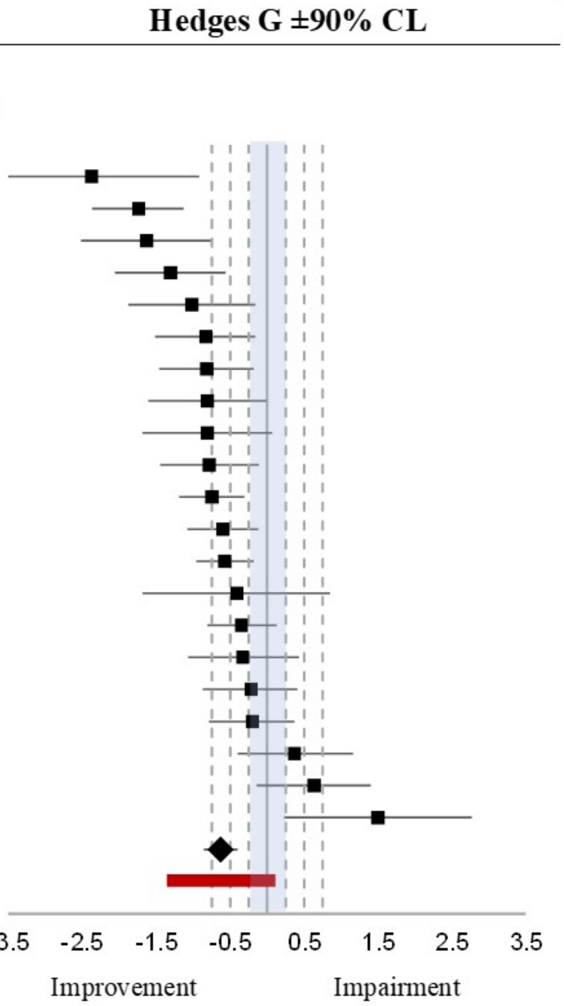


Figure 8. The effects of repeated-sprint training on repeated-sprint ability decrement. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics		
	Pre-training (cm)	Post-training (cm)	Mean change (cm)
Brini, 2020 [66]	43.9	39.0	-4.9
Nascimento, 2015 [79]	45.1	45.6	0.5
Soares-Caldiera, 2014 [38]	38.8	38.0	-0.8
Bravo, 2008 [70]	46.1	46.1	0.0
Arede, 2022 [74]	34.7	35.5	0.8
Ouergui, 2020 [36]	29.4	30.5	1.1
Taylor, J, 2016 [3]	41.9	42.5	0.6
Arede, 2022 [74]	25.2	26.4	1.2
Taylor, J, 2016 [3]	36.6	37.3	0.7
Krakan, 2020 [14]	40.0	40.9	0.9
Attene, 2016 [26]	29.6	31.3	1.7
Attene, 2016 [26]	29.2	31.0	1.8
Arede, 2022 [74]	22.1	23.4	1.3
Brini, 2020 [30]	35.8	37.4	1.6
Gantois, 2022 [31]	36.3	38.3	2.0
Maggioni, 2022 [47]	31.1	31.1	0.0
Fernandez, 2012 [46]	38.4	38.0	-0.4
Buchheit, 2010 [28]	35.5	38.0	2.5
Haugen, 2015 [67]	34.9	35.4	0.5
Boer, 2016 [45]	53.2	57.3	4.1
Izquierdo, 2022 [77]	30.9	33.8	2.9
Michailidis, 2022 [63]	31.1	34.3	3.2
Markovic, 2007 [34]	47.9	51.4	3.5
Buchheit, 2008 [27]	47.1	49.3	2.2
Gantois, 2019 [31]	34.5	37.9	3.4
Combined	36.8	38.0	1.2
Prediction interval			

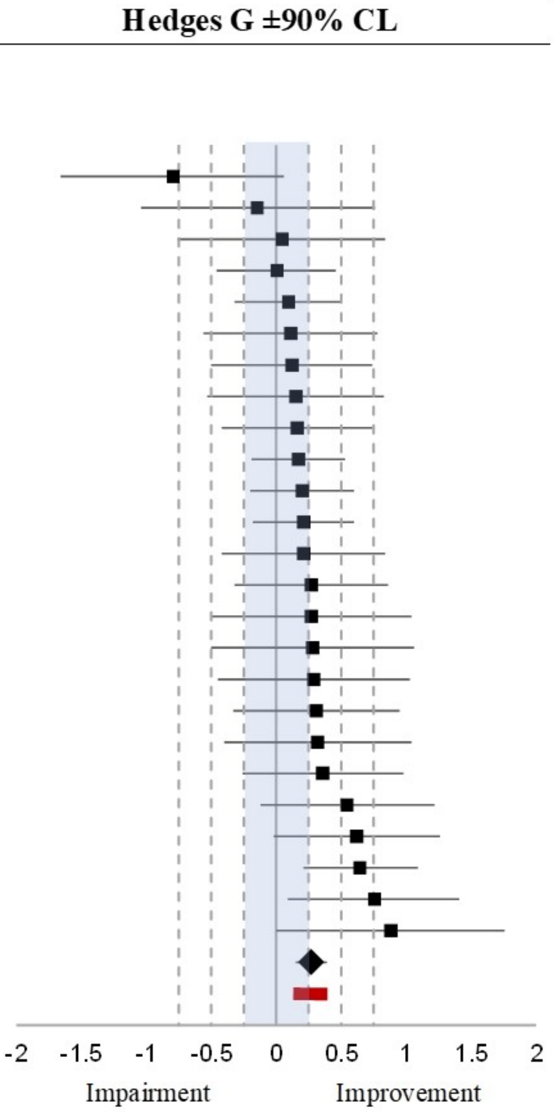


Figure 9. The effects of repeated-sprint training on countermovement jump height. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.

Study	Study statistics		
	Pre-training (s)	Post-training (s)	Mean change (s)
Buchheit, 2008 [27]	5.44	5.26	-0.18
Chtara, 2017 [13]	7.15	6.88	-0.27
Negra, 2022 [80]	2.48	2.33	-0.15
Beato, 2022 [15]	4.91	4.79	-0.12
Negra, 2022 [80]	2.47	2.36	-0.11
Boer, 2016 [45]	9.30	9.10	-0.20
Beato, 2022 [15]	4.75	4.65	-0.10
Taylor, J, 2016 [3]	15.55	15.30	-0.25
Arede, 2022 [74]	2.78	2.72	-0.06
Arede, 2022 [74]	3.07	3.01	-0.06
Ouergui, 2020 [36]	6.80	6.30	-0.50
Brini, 2020 [66]	10.21	9.86	-0.35
Brini, 2020 [30]	10.08	9.98	-0.10
Arede, 2022 [74]	3.13	3.10	-0.03
Beato, 2019 [60]	4.77	4.76	-0.01
Taylor, J, 2016 [3]	15.20	15.23	0.03
Michalidis, 2022 [63]	16.36	16.24	-0.12
Krakan, 2020 [14]	4.73	4.75	0.02
Maggioni, 2018 [47]	10.00	9.70	-0.30
Beato, 2019 [60]	4.70	4.73	0.03
Combined	7.19	7.05	-0.14
Prediction interval			

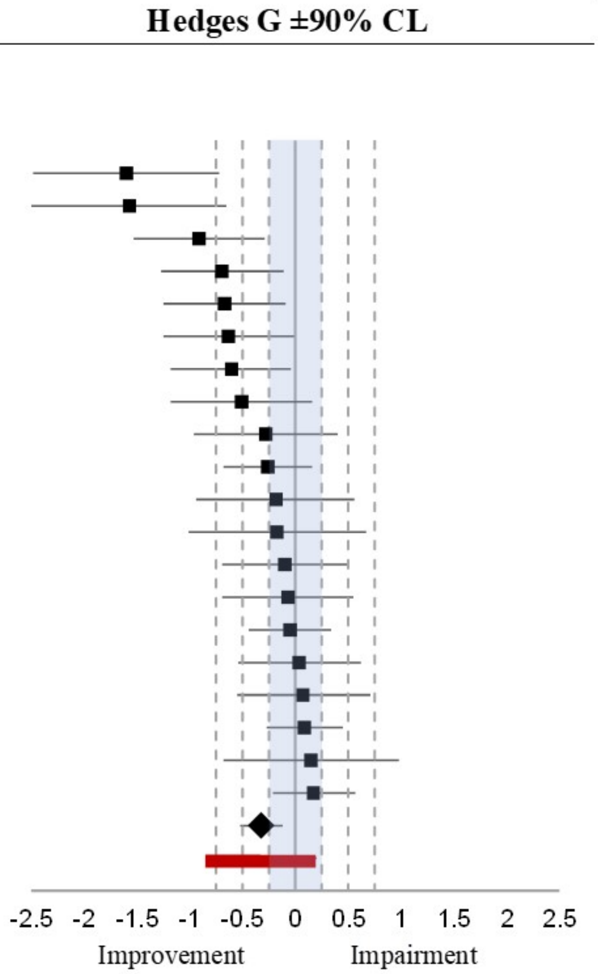
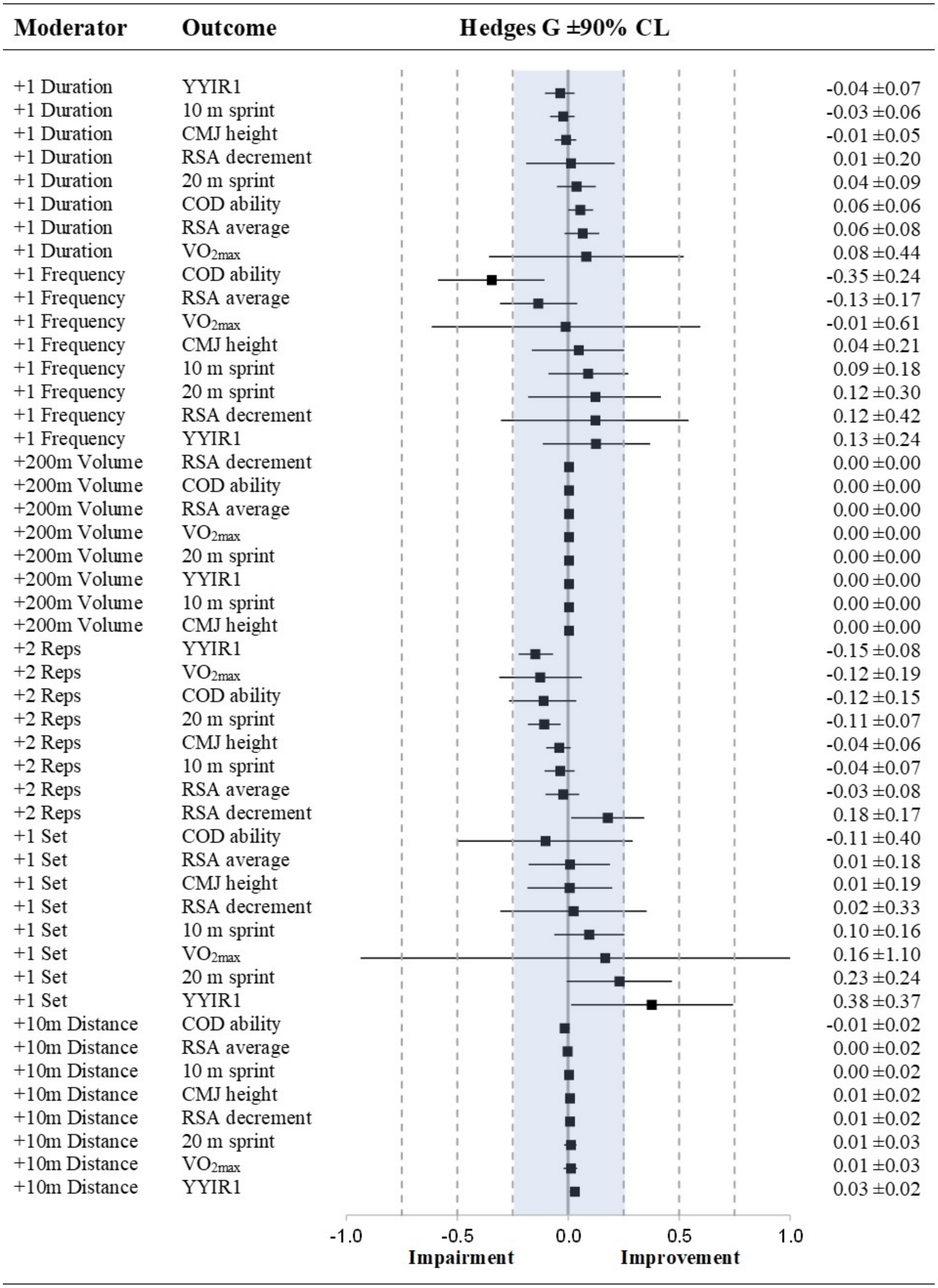


Figure 10. The effects of repeated-sprint training on change of direction ability. The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.



Moderator	Outcome	Hedges G ±90% CL
+1 Duration	YYIR1	-0.04 ±0.07
+1 Duration	10 m sprint	-0.03 ±0.06
+1 Duration	CMJ height	-0.01 ±0.05
+1 Duration	RSA decrement	0.01 ±0.20
+1 Duration	20 m sprint	0.04 ±0.09
+1 Duration	COD ability	0.06 ±0.06
+1 Duration	RSA average	0.06 ±0.08
+1 Duration	VO_{2max}	0.08 ±0.44
+1 Frequency	COD ability	-0.35 ±0.24
+1 Frequency	RSA average	-0.13 ±0.17
+1 Frequency	VO_{2max}	-0.01 ±0.61
+1 Frequency	CMJ height	0.04 ±0.21
+1 Frequency	10 m sprint	0.09 ±0.18
+1 Frequency	20 m sprint	0.12 ±0.30
+1 Frequency	RSA decrement	0.12 ±0.42
+1 Frequency	YYIR1	0.13 ±0.24
+200m Volume	RSA decrement	0.00 ±0.00
+200m Volume	COD ability	0.00 ±0.00
+200m Volume	RSA average	0.00 ±0.00
+200m Volume	VO_{2max}	0.00 ±0.00
+200m Volume	20 m sprint	0.00 ±0.00
+200m Volume	YYIR1	0.00 ±0.00
+200m Volume	10 m sprint	0.00 ±0.00
+200m Volume	CMJ height	0.00 ±0.00
+2 Reps	YYIR1	-0.15 ±0.08
+2 Reps	VO_{2max}	-0.12 ±0.19
+2 Reps	COD ability	-0.12 ±0.15
+2 Reps	20 m sprint	-0.11 ±0.07
+2 Reps	CMJ height	-0.04 ±0.06
+2 Reps	10 m sprint	-0.04 ±0.07
+2 Reps	RSA average	-0.03 ±0.08
+2 Reps	RSA decrement	0.18 ±0.17
+1 Set	COD ability	-0.11 ±0.40
+1 Set	RSA average	0.01 ±0.18
+1 Set	CMJ height	0.01 ±0.19
+1 Set	RSA decrement	0.02 ±0.33
+1 Set	10 m sprint	0.10 ±0.16
+1 Set	VO_{2max}	0.16 ±1.10
+1 Set	20 m sprint	0.23 ±0.24
+1 Set	YYIR1	0.38 ±0.37
+10m Distance	COD ability	-0.01 ±0.02
+10m Distance	RSA average	0.00 ±0.02
+10m Distance	10 m sprint	0.00 ±0.02
+10m Distance	CMJ height	0.01 ±0.02
+10m Distance	RSA decrement	0.01 ±0.02
+10m Distance	20 m sprint	0.01 ±0.03
+10m Distance	VO_{2max}	0.01 ±0.03
+10m Distance	YYIR1	0.03 ±0.02

Figure 11. The moderating effects of programming variables on physical adaptation compared to the reference training program, consisting of three sets of 6 × 30 m straight-line repeated-sprints, performed twice per week for six weeks (1200 m weekly volume). The shaded zone indicates a trivial effect. Dashed lines indicate small, moderate and large effects, respectively.