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SYSTEMATIC REVIEW

The Effect of Different Strength Training Modalities on Sprint Performance in Female Team-Sport Athletes: A Systematic Review and Meta-Analysis

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Abstract

Background There has been a rise in the participation, professionalism, and profile of female sports in recent years. Sprinting ability is an important quality for successful athletic performance in many female team sports. However, much of the research to date on improving sprint performance in team sports is derived from studies with male participants. Given the biological differences between the sexes, this may be problematic for practitioners when programming to enhance sprint performance in female team-sport athletes. Therefore, the aims of this systematic review were to investigate (1) the overall effect of lower body strength training on sprint performance, and (2) the effect of specific strength training modalities (i.e., reactive-; maximal-; combined-; special-strength) on sprint performance in female team-sport athletes.

Methods An electronic database search was performed using PubMed, MEDLINE, SPORTDiscus, CINAHL, The Cochrane Library, and SCOPUS to identify relevant articles. A random-effects meta-analysis was performed to establish standardised mean difference with 95% confidence intervals and the magnitude and direction of the effect.

Results Fifteen studies were included in the final analysis. The 15 studies represent a total sample size of 362 participants (intervention $n = 190$; control $n = 172$) comprising 17 intervention groups and 15 control groups. The overall effects revealed small improvements in sprint performance in favour of the experimental group over 0–10 m and moderate improvements over sprint distances of 0–20 m and 0–40 m. The magnitude of improvement in sprint performance was influenced by the strength modality (i.e., reactive-, maximal-, combined-, and special-strength) utilised in the intervention. Reactive- and combined-strength training methods had a greater effect than maximal- or special-strength modalities on sprint performance.

Conclusion This systematic review and meta-analysis demonstrated that, when compared with a control group (i.e., technical and tactical training), the different strength training modalities exhibited small to moderate improvements in sprint performance in female team-sport athletes. The results of a moderator analysis demonstrated that youth athletes (< 18 years) yielded a greater improvement in sprint performance compared with adults (≥ 18 years). This analysis also supports the use of a longer programme duration (> 8 weeks) with a higher total number of training sessions (> 12 sessions) to improve overall sprint performance. These results will serve to guide practitioners when programming to enhance sprint performance in female team-sport athletes.

1 Introduction

Sprinting ability is a foundational quality of athletic performance. Specifically, in team sports such as soccer and rugby, elite athletes are able to sprint faster than their lower-level counterparts [1, 2]. Speed, for these sports, may be directed linearly or in a sport-specific context which encompasses multi-directional and reactive movements (e.g., evasion of opponents; reaction to breaks in play). Linear sprinting can be divided into two distinct phases; acceleration and maximum velocity [3]. It has been previously contended that acceleration is of greater importance to team sports than maximum velocity [4]. For example, sprint distances of 0–5 m and 0–10 m in women's soccer represent 76% and 95% of total sprints [5]. Comparably, 81% of total sprints in men's Gaelic football were defined as acceleration efforts (e.g., change of ≥ 2 m s^{-2} over 1 s) [6]. However, maximum velocity may also play an important role for team-sport

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Key Points

Sprint performance in female team-sport athletes can be enhanced by strength training (i.e., reactive-, maximal-, combined-, and special-strength modalities). Compared with maximal- or special-strength programmes, reactive- and combined-strength training methods can have a greater effect on sprint performance.

The evaluation of moderating variables highlights that the effect of strength training on sprint performance can be influenced by age, programme duration, and total number of sessions.

Adaptations to training can be influenced by the natural hormonal fluctuations throughout the menstrual cycle. Careful methodological considerations should be applied to mitigate the impact of the menstrual cycle on overall training adaptations.

athletes. Clark et al. [7] reported that male American football players attain 94.5 ± 1.3% of their maximal velocity at 13.7 m during a linear speed assessment. The authors also reported that slower players reached a higher percentage of their maximal velocity when compared with faster players. Similarly, Barr et al. [8] observed that male rugby players reach 96% of their maximal velocity at 21 m. Therefore, it is evident that both acceleration and maximum velocity are important speed qualities in team sports.

Sprinting can be viewed as a multidimensional skill [9], suggesting that different techniques and training modes are required for improving overall sprint performance. Training to enhance sprint performance can be categorised into specific (i.e., free sprinting, technical training, resisted sprinting) and general training methods (i.e., reactive-; maximal-; explosive-strength) [3]. Previously, researchers [10–12] have suggested that the primary mechanical determinants of sprint performance are the neuromuscular capabilities (i.e., force and power outputs) and technique (i.e., the ability to apply ground reaction force [GRF] effectively) of the athlete. Further, Weyand et al. [13] identified that higher maximum velocities are associated with an enhanced ability to generate and transmit muscular force to the ground. In view of that, it is evident that the expression of force is an integral component of sprint performance and therefore the development of muscular strength is important.

Muscular strength is considered a key determinant with respect to improving an athlete's overall performance [14]. Muscular strength can be developed by employing various modalities such as maximal-; [15] explosive-; [16, 17] reactive-; [18, 19] and special-strength training [20], or a combination of modalities (see methods section for specific definitions of each modality). A strength training programme elicits a series of neuromuscular adaptations related to musculotendinous stiffness, motor unit recruitment, rate coding (firing frequency), motor unit synchronisation, and neuromuscular inhibition [21]. Rate of force development (RFD) (i.e., the rate of rise in contractile force at the onset of a muscular contraction) is also an important component of athletic performance [16, 17]. RFD can be increased following a period of explosive-, or maximal-strength training [16, 22, 23], with stronger athletes producing greater RFD than their weaker counterparts [24, 25]. Furthermore, a previous review [22] has highlighted that these training-induced changes in RFD are achieved through improvements in rapid muscle activation. Sprinting will typically involve faster muscular contraction times of 50–250 ms, which is lower than the time it takes (> 300 ms) to reach maximum force output in most muscles [16]. Therefore, increasing RFD through strength training methods may enhance sprinting ability by increasing the muscle's ability to generate more force, at a faster rate, in the earlier stages of muscle contraction. Additionally, improvements in maximal-strength [26, 27], reactive-strength [28], and resisted sprinting [29, 30] have been shown to elicit a positive effect on sprint performance in team-sport athletes, sprinters, and recreational participants. However, despite these positive findings of strength training on sprint performance, the studies were conducted only on male participants, had limited female participants, or there was no indication as to the sex of the participants. Researchers have previously stated that men yield greater absolute strength compared with women [31]. However, Nimphius et al. [32] have suggested that when the confounding factor of strength is removed (i.e., normalised for lean body mass), there are no significant differences in relative lower-body maximal strength between the sexes. Furthermore, men and women demonstrated similar neural adaptations (i.e., increased motor unit recruitment and synchronisation, and neural activation) [32, 33] and improvements in maximal strength following a maximal-strength training intervention. Nevertheless, given the biological differences (i.e., hormonal profile, menstrual cycle), it may be erroneous therefore to apply research conducted on male athletes to female athletes. There has been an exponential rise in the participation, professionalism, and profile of female sports in recent years; however, there is currently a lack of research on elite female athletes [34]. Accordingly, there is no agreement as to whether various strength training methods improve sprint performance in female team-sport athletes.

The aims of this systematic review were to investigate (1) the overall effect of lower-body strength training on sprint performance, and (2) the effect of specific strength training modalities (i.e., reactive-; maximal-; combined-;

special-strength) on sprint performance in female team-sport athletes.

2 Methods

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [35].

2.1 Search Strategy

An electronic database search was performed using PubMed, MEDLINE, SPORTDiscus, CINAHL, the Cochrane Library, and SCOPUS to identify relevant articles that investigated the effect of different strength training modalities on sprint performance in female team-sport athletes. The strength training modalities were categorised and defined as (1) maximal strength: the ability to generate maximal external force through high-load, low-velocity movements (i.e., squats, deadlifts) [15]; (2) explosive strength: the ability to exert maximal force in minimal time through high load, high-velocity movements (i.e., squat jumps, Olympic lifts) [16, 17]; (3) reactive strength: the ability to effectively utilise the stretch–shortening cycle (SSC) and explosively transition from an eccentric to concentric muscle action [18, 19] and may be developed through plyometric exercises (i.e., drop jumps, hurdle jumps); (4) special strength: the intensification in the work of the muscular system in a manner that is predominantly inherent within the sport (i.e., resisted sprint training) [20]. In agreement with the PICO (Population, Intervention, Comparison, Outcome) framework [36], search phrases were determined through pilot screening of previously known literature to identify terms relevant to the population, the training intervention, and the performance outcome. Search terms and Boolean operators used in the database search are presented in Table 1. Further records were identified from the bibliographies of eligible studies. Attempts were made to contact authors where full-text articles of selected studies were not available and to request any missing relevant information within the articles (i.e., post-test data). The database search was limited to original peer-reviewed journal articles published in English from the earliest available records up to and including December 2021.

2.2 Study Criteria

All records were screened against the predefined inclusion/exclusion criteria. Studies were included if they met the following inclusion criteria: (1) studies included a comparative group (e.g., control group, traditional sprint training); (2) training interventions $\geq$ 1 session per week for $\geq$ 4 weeks that used strength training modalities (e.g., maximal; explosive; reactive; [i.e., plyometric training] and special strength [i.e., resisted sprinting]), for the lower body and measured sprint performance as an outcome; (3) studies included pre- and post-test data; (4) participants were female with a mean age $\geq$ 16 years; (5) participants competed in regional-, national-, or elite-level team sport (i.e., field- or court-based sport). Studies were excluded if any of the following criteria applied: (1) participants were untrained or recreationally trained; (2) interventions included assisted sprinting; (3) data from male and female participants were pooled; (4) participants were recruited from individual sports; (5) participants included special populations (e.g., athletes with disabilities, people with health conditions, pregnant women, older adults, children); (6) study designs only measured the relationship between strength and sprint performance, or the effect of post-activation potentiation on sprint performance; (7) acute interventions lasting < 4 weeks; and (8) studies that only measured the outcome of upper-body strength training interventions.

2.3 Study Selection

Reference management software (Zotero, USA) was used to import all records from each database. Duplicate records were removed prior to screening the remaining records against the inclusion/exclusion criteria. Studies were screened using a two-step process by the principal assessor (WH). Studies were initially screened by title and abstract. The second stage involved screening the full-text articles. Study selection was confirmed by a second reviewer (KB).

Table 1 Database literature search strategy

Search terms	Keywords
1. Population	'Female team sports' OR 'female invasion sports' OR 'female athletes' OR 'women's team sports' OR 'women's invasion sports' OR 'women athletes'
2. Intervention	'Strength' OR 'reactive-strength' OR 'explosive strength' OR 'special strength' OR 'resistance training' OR 'power training' OR 'plyometric' OR 'weightlifting' OR 'resisted sprinting' OR 'sled sprinting' OR 'circuit training' OR 'jump training'
3. Outcome	'Sprint*' OR 'sprint performance' OR 'acceleration' OR 'velocity' OR 'speed performance'
Search phrase	1 AND 2 AND 3

In the event of a disagreement, reviewers engaged in discussion to agree a decision with any disparities resolved by a third reviewer (RH).

2.4 Data Extraction

Data from the relevant records were extracted by the principal assessor (WH) to an Excel spreadsheet. The following information was extracted from each of the selected studies: general study information (i.e., author(s), year); descriptive information of participants (i.e., height, mass, age, sample size, sport, performance level, training background); training invention details (i.e., control group instruction, time of season, strength training addition or replacement, strength training modality, programme information, performance measures, training programme frequency and duration); and performance outcome following the training intervention (i.e., pre- and post-test data, % change, effect size, *p*-value). A second reviewer (KB) cross-checked the relevant data.

Sprint outcome data were categorised into subgroups to reflect the different stages of a sprint. Categorisation of sprint outcome data was informed by previous literature [9, 37–39]. Data from initial start position (0 m) to between 0 m and ≤ 10 m, 0 m to > 10 m and ≤ 20 m, and 0 m to > 20 m and ≤ 40 m were categorised into the following subgroups: 0–10 m, 0–20 m, 0–40 m, respectively. Split times (e.g., 10–20 m) were not included for analysis. Analysis of these subgroups aimed to identify the effectiveness of strength training on sprint performance changes.

2.5 Study Quality Assessment

The current review evaluated study quality using a scoring system adopted by previous researchers [37, 40–42]. This scoring system expands on the current scales used to evaluate the methodological quality in healthcare research and interventions (i.e., PEDro, Delphi, Cochrane). Brughelli et al. [43] developed this scoring system to rate the quality and scientific rigour in athletic-based training environments using a combination of items from the PEDro, Delphi, and Cochrane scales. The authors also state that sports science research typically scores very low on these methodological scales. Many of the criteria on these scales are not relevant in athletic-based research interventions such as blinding of participants and, thus, the quality of studies may be classified as poor [43].

The current methodological scale assesses study quality using a 10-item checklist (Table 2). A score of 0 (clearly no), 1 (maybe), or 2 (clearly yes) is given for each item. This results in a total scoring range of between zero and 20. McMaster et al. [40] observed that items 2, 3, and 4 prove the most decisive in separating high-quality and low-quality studies.

2.6 Meta-Analysis

Review Manager (RevMan 5.4; Cochrane Collaboration, Oxford, United Kingdom) was used to carry out the meta-analysis. A random-effects meta-analysis was used to determine the summary effect of strength training on sprint performance. Effect estimates were presented as standardised mean difference (SMD) with 95% confidence intervals (CI). The SMD is used as a summary statistic and represents the size of the effect in each study relative to the between-participant variability in outcome measurements observed in that study [44]. Improvements in sprint performance are typically measured as a decrease in time (s) or an increase in peak velocity (m/s) [39, 45]. To standardise the direction of the results, studies that reported velocity as a sprint performance metric had their pre- and post-test velocity changes reversed before computation of the SMD to ensure that both time and velocity changes represented the same direction on the forest plot [37]. The SMD was calculated using RevMan 5.4 by subtracting the delta value (i.e., change in time from pre- to post-test) of the experimental group from the delta value of the control group, and dividing by the pooled standard deviation of each condition.

Within-group effect size (ES) was calculated manually to determine the magnitude of effect between pre- and post-test results in the experimental groups. The SMD used in the current meta-analysis is the ES known as Hedges' g [44]. To ensure consistency in the calculation of data, Hedges' g was used to calculate the within-group pre- to post-test ES. Hedges' g is considered a corrected ES because it corrects for bias in small samples ($n < 20$) [46]. Hedges' g is calculated as the difference in means divided by the pooled standard deviation (SD) and multiplied by the correction factor to yield an unbiased effect estimate [47, 48]:

Table 2 Study quality scoring system

No	Item	Score
1	Inclusion criteria stated	0–2
2	Subjects assigned appropriately (random/equal baseline)	0–2
3	Intervention described	0–2
4	Control group	0–2
5	Dependent variable defined	0–2
6	Assessments practical	0–2
7	Training duration practical (acute vs long term)	0–2
8	Statistics appropriate (variability, repeated measures)	0–2
9	Results detailed (mean, SD, percent change, effect size)	0–2
10	Conclusions insightful (clear concise, future directions)	0–2
	Total	0–20

$$g = \frac{M_{\mathrm{post}} - M_{\mathrm{Pre}}}{\mathrm{SD}_{\mathrm{pooled}}} \times \left(1 - \frac{3}{4(n_1 + n_2) - 9}\right)$$

where M_{post} is the mean of the post-test sprint data and M_{pre} is the mean of the pre-test sprint data. The SD_{pooled} is the pooled standard deviation of the measurements:

$$\mathrm{SD}_{\mathrm{pooled}}\sqrt{\frac{(n_1 - 1)SD_1^2 + (n_2 - 1)SD_2^2}{n_1 + n_2 - 2}}$$

where $SD^2{}_1$ is the standard deviation of the pre-test sprint data, $SD^2{}_2$ is the standard deviation of the post-test sprint data, and n is the number of observations.

The calculated effect magnitudes were interpreted using the following thresholds: trivial (<0.20), small (0.20–0.49), moderate (0.5–0.79), large (>0.80) [49]. A positive SMD indicated a decrease in sprint performance for the experimental group (i.e., decreased sprint velocity or increased sprint time; favours control group) whereas a negative SMD indicated an improvement in sprint performance for the experiment group (i.e., increased sprint velocity or decreased sprint time; favours experimental).

Percentage change from pre- to post-intervention in sprint performance was computed from each individual study using the following formula:

$$\%\mathrm{Change} = \left(\frac{M_{\mathrm{post}} - M_{\mathrm{pre}}}{M_{\mathrm{pre}}}\right) \times 100$$

Heterogeneity was assessed using the I^2 statistic and between-study variance was assessed using tau-squared (Tau^2) [44]. The I^2 statistic can be interpreted as the proportion of the total variability of the effect estimates due to the between-study variance (Tau^2) rather than sampling error (i.e., chance) [50]. A value of 0% indicates no observable heterogeneity with values of 25%, 50%, and 75%, considered low, moderate, and high, respectively [51]. This was supported by the Chi^2 statistic which assesses whether observed differences in results are compatible with chance alone. A low p-value, or a large Chi^2 statistic relative to its degree of freedom, provides evidence of heterogeneity. The alpha level for identifying heterogeneity was set a $p<0.10$ [44].

2.7 Publication Bias

The potential of publication bias relating to small study sample size was assessed through visual inspection of the funnel plot and through Egger's linear regression test [52]. An asymmetrical funnel plot and a statistically significant Egger's test ($p \leq 0.05$) indicate the presence of a small study effect. Lin et al. [53] observed that Egger's regression test detected publication bias more frequently than other tests.

2.8 Sensitivity Analysis

Sensitivity analysis was performed on each individual study comparison to identify whether the overall result and conclusions were affected by the different decisions that could be made during the review process [44]. The analysis was repeated with the removal of each individual study comparison in turn. If there was not a substantial impact (e.g., change from a large to small effect) on the overall summary effect, this suggested the results and conclusions were not dependent on a single study and can be treated with a higher degree of certainty.

2.9 Moderator Variables

Additional subgroup analyses were undertaken to assess the potential effects of moderator variables (i.e., potential variables that are likely to influence the effects of the training intervention). These variables were determined based on a priori identification of factors which could affect the overall summary effect. Using a random-effects model, the following potential moderators likely to influence the overall summary effect were selected: programme duration (weeks), the total number of training sessions, and age category. Subgroups for programme duration and number of total training sessions were determined using a median split. Participant's age was categorised by adult (mean age ≥ 18 years) versus youth (mean age <18 years).

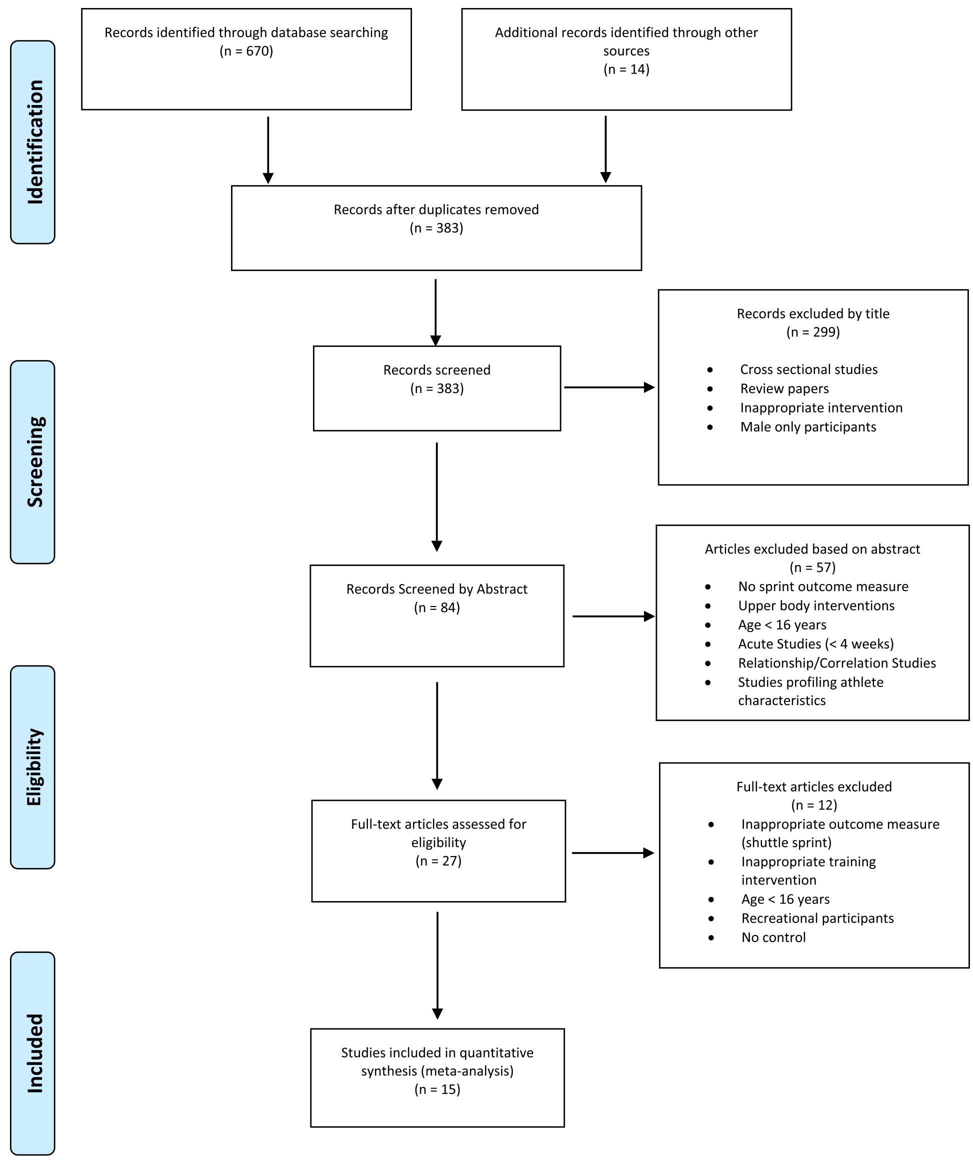
3 Results

The PRISMA flow diagram illustrating the selection process is presented in Fig. 1. A total of 15 studies met all of the predetermined inclusion criteria and were included in the final analysis. Four different strength modalities were utilised in the included studies: maximal strength $n=2$ [54, 55], reactive strength $n=8$ [56–63], combined strength $n=3$ [64–66] and special strength $n=2$ [67, 68]. All studies were graded according to the 10-item quality scoring scale outlined in Table 2. Results ranged from 16 to 20 with a mean score of 18.7 ± 1.23 and are presented in Table 3. All of the studies that were included for the final analysis were deemed high quality.

3.1 Study Characteristics

Tables 3, 4 and 5 present the individual study descriptive characteristics, training intervention information, and sprint outcomes for all the included studies. The 15 studies represent a total sample size of 362 participants (intervention $n=190$; control $n=172$) and 17 intervention groups. The participants in the included studies ranged from 16.1 to

Fig. 1 PRISMA flow diagram



23.7 years. Collectively, the study interventions ranged from 4 to 12 weeks in duration with a frequency of 1–3 sessions per week. Sprint distances ranged from 4.6 to 40 m and were categorised into the following subgroups: 0–10 m ($n=8$), 0–20 m ($n=12$), and 0–40 m ($n=8$).

Two studies [58, 61] included both a placebo intervention group and a nutritional or drug supplementation group. In this incidence, only the placebo intervention group was included for analysis. Furthermore, studies that included an additional intervention group not satisfying the inclusion criteria were not included for analysis (i.e., assisted sprinting [68], skill-based training [59], and a male intervention group [62]). For all of the included studies, both the intervention and control groups were instructed to continue with technical and tactical training with their respective teams. Six studies [58, 60–62, 66, 68] completed the intervention as a replacement to a portion of their technical and tactical training. Three studies [57, 63, 66] included a sprint(s) as part of the intervention, while two studies [67, 68] used resisted sprint training as the primary intervention. Three control groups were reported to perform sprint training in addition to their technical training (i.e., repeated sprint training [64] and traditional sprint training [67, 68]).

3.2 Sprint Performance

For the 0–10-m subgroup, 11 experimental groups were analysed from eight original studies [54–57, 65–68] examining the effect of strength training on sprint performance. Compared with the control, the overall summary effect demonstrated a small improvement in sprint performance in favour of the experimental group, however this effect was

Table 3 Summary of subject and study descriptive characteristics, and study quality score

Study	Subject details							Study details					
	n	Age (years)	Mass (kg)	Height (m)	Sport	ST experience	Technical training	RCT?	Control group instruction?	Sprint training	ST addition or replacement?	Time of season	Quality score
González-García et al. [54]	24	16.82 ± 1.56	58.35 ± 6.28	1.64 ± 0.06	Soccer	No	3 × week	Yes	Technical training	NR	Addition	Off-season	17
Pedersen et al. [55]	34	18.5 ± 2.5	62.5 ± 8	1.68 ± 0.06	Soccer	Mixed	4–5 × week; 6.5 h	Yes	Technical training	NR	Addition	Pre-season	20
Shalfawi et al. [64]	20	19.4 ± 4.4	59.1 ± 5.6	1.68 ± 0.05	Soccer	NR	4–7 × week; 10 h	No	Technical training Resisted agility Repeated speed	Yes	Addition	In-season	18
Pardos-Mainer et al. [65]	37	16.1 ± 1.1	55 ± 7.1	1.59 ± 0.07	Soccer	No	3 × week; 1 × match	No	Technical training	NR	Addition	In-season	19
Hammami et al. [66]	28	16.6 ± 0.3	60.6 ± 4.5	1.64 ± 0.04	Hand-ball	Yes	6–7 × week; 90–100 min per session	Yes	Technical training	Yes	Replacement	In-season	19
Ramírez-Campillo et al. [62]	38	21.45 ± 2.45	60.45 ± 9.3	1.60 ± 0.06	Soccer	No experience in previous 6 months	*Training load (AU):* 411 ± 280	Yes	Technical training	NR	Replacement	In-season	18
Ramírez-Campillo et al. [60]	23	21.43 ± 2.87	56.6 ± 5.17	1.59 ± 0.04	Soccer	No experience in previous 5 months	3 × week; 1 × game; 120 min per session	Yes	Technical training	NR	Replacement	In-season	20
Ramírez-Campillo et al. [61]	20	22.8 ± 2.4	59.1 ± 7	1.62 ± 0.06	Soccer	No experience in previous 3 months	*Training load (AU):* 429 ± 265 *Other sport:* 1.3 ± 1.1 h	Yes	Technical training	NR	Replacement	In-season	19
Idrizovic et al. [59]	30	16.6 ± 0.6	59.4 ± 8.1	1.73 ± 0.04	Volleyball	Yes	10 h per week	Yes	Technical training	NR	Addition	In-season	20
Rosas et al. [58]	17	23.7 ± 2.4	59.2 ± 7.3	1.63 ± 0.06	Soccer	No experience in previous 3 months	*Training load (AU):* ~ 709 *Other sport:* 1.3 ± 1.1 h	Yes	Technical training	NR	Replacement	In-season	19
Ozbar et al. [63]	18	18.2 ± 2.3	56.6 ± 7.2	1.61 ± 0.05	Soccer	Yes	4 × week; 1 × game	No	Technical training	Yes	Addition	In-season	19
Ozbar [57]	20	19.3 ± 1.6	56.6 ± 6.1	1.63 ± 0.05	Soccer	Yes	4 × week; 2 × game	No	Technical training	Yes	Addition	NR	19

Table 3 (continued)

Study	Subject details							Study details					
	n	Age (years)	Mass (kg)	Height (m)	Sport	ST experience	Technical training	RCT?	Control group instruction?	Sprint training	ST addition or replacement?	Time of season	Quality score
Nonnato et al. [56]	16	23 ± 4	60.3 ± 4.9	1.67 ± 3.7	Soccer	NR	4 × week; 1 × game	Yes	Technical training	NR	Addition	In-season	20
Luteberget et al. [67]	18	21.6 ± 3.5	72.3 ± 5.6	1.71 ± 0.06	Hand-ball	Yes	3 × week; 1 × game	No	Technical training Traditional sprint training	Yes	Addition	In-season	16
Upton [68]	19	19.6 ± 0.9	63.4 ± 6.9	1.67 ± 0.06	Soccer	Yes	6 × week	No	Technical training Traditional sprint training	Yes	Unclear*	Pre-season	17

Data presented as mean ± Standard Deviation

*Participants completed intervention during first 30 min of soccer practice, however, it is unclear if this is an addition or replacement

AU arbitrary units, *NR* not reported, *RCT* randomised controlled trial, *ST* strength training

not statistically significant (SMD = − 0.36 [95% CI − 0.80 to 0.09], Z = 1.57, p = 0.12). The degree of overall heterogeneity was considered moderate and significant (I^2 = 66%, Tau^2 = 0.36, Chi^2 = 29.02, p = 0.001) for all outcome measures between studies. Meta-analysis for the 0–10-m subgroup is presented in Fig. 2.

Within the 0–20-m subgroup, 14 experimental groups were analysed from 12 original studies [54, 55, 57–61, 63–66, 68] examining the effect of strength training on sprint performance. When compared with the control, the overall summary effects demonstrated a moderate and significant improvement in sprint performance in favour of the experimental group (SMD = − 0.69 [95% CI − 1.06 to − 0.33], Z = 3.74, p = 0.0002). The degree of overall heterogeneity was considered moderate and significant (I^2 = 54%, Tau^2 = 0.26, Chi^2 = 28.50, p = 0.008) for all outcome measures between studies. Meta-analysis for the 0–20-m subgroup is presented in Fig. 3.

For the 0–40-m subgroup, ten experimental groups were analysed from eight original studies [56, 57, 62, 64–68] examining the effect of strength training on sprint performance. When compared with a control, the overall summary effect demonstrated a moderate and significant improvement in sprint performance in favour of the experimental group (SMD = − 0.74 [95% CI − 1.24 to − 0.24], Z = 2.89, p = 0.004). The degree of overall heterogeneity was considered moderate and significant (I^2 = 71%, Tau^2 = 0.46, Chi^2 = 30.95, p = 0.0003) for all outcome measures between studies. Meta-analysis for the 0–40-m subgroup is presented in Fig. 4.

3.3 Publication Bias

Egger's regression test and visual inspection of the funnel plot symmetry revealed no small-study effect for the 0–10-m, 0–20-m, and 0–40-m sprint subgroups (all $p > 0.05$).

3.4 Sensitivity Analysis

Sensitivity analysis revealed minor changes in the overall summary effect for the 0–10-m subgroup. Removal of one individual study comparison [66] resulted in changes to the summary effect from small to trivial. No single comparison was enough to moderate a change from non-significant to significant. The removal of individual study comparisons from the analysis for the 0–20-m subgroup had no impact with the summary effect remaining moderate. Removal of three individual study comparisons (i.e., removed individually) [64, 67, 68] from the 0–40-m subgroup yielded a change in the summary effect from moderate to large. No single comparison was enough to moderate a statistically significance change in either the 0–20-m or 0–40-m subgroups.

Table 4 Summary of intervention details

Study	*n*	Groups	Strength quality	Duration (weeks)	Frequency	Between session	Sprint testing (distance & outcome measure)	Intervention
González-García et al. [54]	8	Intervention 1 (HTG)	Maximal	7	2 × wk	48 h	10, 20 m Time	HTG: hip thrusts 4 × 4–12 60–90% 1RM
	8	Intervention 2 (SQG)						SQG: back squat 4 × 4–12 60–90% 1RM
	8	Control						Load was gradually increased from 60% up to 90% of 1RM
Pedersen et al. [55]	19	Intervention	Maximal	5	2 × wk	NR	5, 10, 15 m Time	90° Back squat @85% + 1RM 3 sessions @ 3 × 6 7 sessions @ 4 × 4 Nordic hamstring 3 × 6 Participants increased load with 2.5–10 kg as appropriate
	15	Control						
Shalfawi et al. [64]	10	Intervention	Combined (maximal; explosive)	10	2 × wk	NR	0–20, 20–40, 0–40 m Time	2–3 × 4–10 RM (leg press, leg extension, cable hip flexion, cable hip extension) 2–3 × 4–10 (Nordic hamstring) 2–3 × 4–6 (squat jump)
	10	Control						
Pardos-Mainer et al. [65]	19	Intervention	Combined (maximal; explosive)	8	2 × wk	48–72 h	10, 20, 30, 40 m Time	2 Sets × 6–10 repetitions; 0–10% BM; 3-min rest 5–6 exercises per session Diver; SL pelvic tilt; SL step up; forward/backward lunge; SL hip thrust; eccentric box drops; Russian belt posterior/anterior chain; plank; lateral plank; lumbar bridge
	18	Control						
Hammami et al. [66]	14	Intervention	Combined (maximal; reactive)	10	2 × wk	48 h	5, 10, 20, 30 m Time	1. Half-squat × 6 @ 85% of 1RM, 6 × hurdle jumps @40 cm, 10-m sprints 2. Thigh press × 6 @ 85% of 1RM, 6 × horizontal jumps, 10-m sprints 3. 8 s isometric half-squat @ 75% of 1RM, 6 × hopping on 1 foot [3 right/3 left], 10-m sprints 4. Calf extension × 6 @ 90% of 1RM, 6 × hurdle jumps [30 cm height], 10-m sprints Each set repeated × 4 for each session
	14	Control						
Ramírez-Campillo et al. [62]	19	Intervention	Reactive	6	2 × wk	72 h	30 m Time	2 × 5–10 repetitions per exercise (80–160 total jumps per leg per session) 1 repetition per set was added each week 12 jump exercises per session (i.e., cyclic and acyclic horizontal and vertical jumps, with left, right and both legs)
	19	Control						
Ramírez-Campillo et al. [60]	8	Intervention 1 (1-day)	Reactive	8	1 × wk	7 d	15 m Time	Intervention 1: 1 × week: 1 set of 14–28 repetitions Intervention 2: 2 × week: 1 set of 7–14 repetitions Drop jump, standing long jump, unilateral countermovement jump, 180° jump, repeated countermovement jump
	8	Intervention 2 (2-day)			2 × wk	NR		
	7	Control						

Table 4 (continued)

Study	*n*	Groups	Strength quality	Duration (weeks)	Frequency	Between session	Sprint testing (distance & outcome measure)	Intervention
Ramírez-Campillo et al. [61]	10 10	Intervention Control	Reactive	6	2 × wk	48 h	20 m Time	2 × 5–10 repetitions per exercise; 20% increase in volume per week, 13 jump exercises per session (i.e., cyclic and acyclic horizontal and vertical jumps, with left, right and both legs, bounce drop jumps from 20-cm box)
Idrizovic et al. [59]	13 17	Intervention Control	Reactive	12	1 × wk	7 d	20 m Time	10–27 sets × 1–5 repetitions per week; 2–5 min recovery Stiff knee leg hops; vertical jump; tuck jump; lateral/diagonal jump; broad jump; obstacle jumps; box jumps; box shuffles; drop jumps (40–60 cm); drop jump + vertical jump; SL lateral/ diagonal jump; SL broad jump; SL obstacle jump; SL box jump
Rosas et al. [58]	8 9	Intervention Control	Reactive	6	2 × wk	48 h	20 m Time	No. of jumps per week: 140 to 260 Unilateral and bilateral horizontal and vertical jumps with both cyclic and acyclic arm swings, in addition to bounce drop jumps from 40-cm boxes
Ozbar et al. [63]	9 9	Intervention Control	Reactive	8	1 × wk	7 d	20 m Time	4–5 sets, 5–15 repetitions of 4–5 exercises. 90- to 220-foot contacts Vertical, horizontal, lateral jumps, cone hops, split squat jumps, hurdle jumps, standing long jumps, jumps to sprint, jumps to change of direction sprint, single/double leg jumps, skipping
Ozbar [57]	10 10	Intervention Control	Reactive	10	2 × wk	48 h	10, 20, 30 m Time	3–5 sets, 5–8 repetitions of 6–8 exercises. 120 to 250 foot contacts Vertical, horizontal, lateral jumps, cone hops, split squat jumps, hurdle jumps, standing long jumps, jumps to sprint, jumps to change of direction sprint, single/double leg jumps, skipping
Nonnato et al. [56]	8 8	Intervention Control	Reactive	12	1 × wk	7 d	10, 30 m Time	Hurdle jumps, lateral and horizontal jumps, 30-cm box jumps, 30-cm drop jumps Wk 1–6 · 4 sets × 6 jumps · 108 jumps per session · 2-min recovery Wk 7–12 · 5 sets × 6 jumps · 140 jumps per session · 2-min recovery
Luteberget et al. [67]	10 8	Intervention Control	Special	10	2 × wk; 1 × wk on wk 6 & 10	72 h	10, 30 m Time	Wk 1–4 · 4 × 3 × 20 m · 240 m Wk 5–9 · 3 × 3 × 20 m · 280 m 2 × 5 × 10 m · 280 m Wk 10 · 4 × 3 × 20 m · 240 m Intervention completed resisted sprint training @ 12.4% ± 0.2% BM Control completed traditional sprint training
Upton [68]	9 10	Intervention Control	Special	4	3 × wk	48 h	4.6, 13.7, 22.9, 36.6 m Velocity	Intervention: Resisted sprint training 12.6% BM 10 × 13.7 m Control: Traditional sprint training 10 × 13.7 m

1RM 1 repetition max, *BM* body mass, *HTG* hip thrust group, *n* number of participants, *NR* not reported, *SL* single leg, *SQG* squat group

Table 5 Summary of sprint performance results

Study	Strength quality	Group	Distance (m)	% Change	ES (95% CI)	Findings
González-García et al. [54]	Maximal	Intervention 1	10	1.53	0.36 (−0.70, 1.42)	Small ↓ in performance
		(SQG)	20	0.21	0.04 (−0.94, 1.02)	Trivial ↓ in performance
		Intervention 2	10	−3.60	−0.46 (−1.61, 0.69)	Moderate ↑ in performance
		(HTG)	20	−2.60	−0.39 (−1.54, 0.75)	Small ↑ in performance
		Control	10	−2.56	−0.35 (−1.49, 0.79)	Small ↑ in performance
			20	−1.71	−0.26 (−1.31, 0.79)	Small ↑ in performance
Pedersen et al. [55]	Maximal	Intervention	5	−0.94	−0.20 (−0.83, 0.44)	Small ↑ in performance
			10	0.00	0.00 (−0.64, 0.64)	No performance change
			15	−0.75	−0.18 (−0.81, 0.46)	Trivial ↑ in performance
		Control	5	0.94	0.16 (−0.55, 0.88)	Trivial ↓ in performance
			10	0.00	0.00 (−0.72, 0.72)	No performance change
			15	−0.37	−0.07 (−0.79, 0.64)	Trivial ↑ in performance
Shalfawi et al. [64]	Combined	Intervention	20	0.00	0.00 (−0.88, 0.88)	No performance change
			40	0.32	0.09 (−0.79, 0.96)	Trivial ↓ in performance
		Control	20	0.56	0.18 (−0.70, 1.06)	Trivial ↓ in performance
			40	−0.16	−0.04 (−0.92, 0.83)	Trivial ↑ in performance
Pardos-Mainer et al. [65]	Combined	Intervention	10	−4.33	−1.09 (−1.77, −0.41)	Large ↑ in performance
			20	−4.17	−1.17 (−1.86, −0.49)	Large ↑ in performance
			30	−3.96	−1.06 (−1.74, −0.38)	Large ↑ in performance
			40	−4.15	−1.04 (−1.71, −0.36)	Large ↑ in performance
		Control	10	−5.24	−1.02 (−1.72, −0.33)	Large ↑ in performance
			20	1.17	0.32 (−0.34, 0.98)	Small ↓ in performance
			30	0.83	0.23 (−0.43, 0.88)	Small ↓ in performance
			40	0.80	0.21 (−0.44, 0.87)	Small ↓ in performance
Hammami et al. [66]	Combined	Intervention	5	−10.5	−2.07 (−2.99, −1.16)	Large ↑ in performance
			10	−11.7	−2.02 (−2.93, −1.11)	Large ↑ in performance
			20	−10.4	−1.05 (−1.84, −0.26)	Large ↑ in performance
			30	−8.3	−2.57 (−3.57, −1.57)	Large ↑ in performance
		Control	5	−3.05	−0.05 (−1.09, 0.40)	Trivial ↑ in performance
			10	−1.85	−0.52 (−1.27, 0.24)	Moderate ↑ in performance
			20	−0.78	−0.11 (−0.85, 0.63)	Trivial ↑ in performance
			30	−0.37	−0.09 (−0.83, 0.65)	Trivial ↑ in performance
Ramírez-Campillo et al. [62]	Reactive	Intervention	30	−5.1	−0.90 (−1.57, −0.23)	Large ↑ in performance
		Control	30	1.7	0.33 (−0.31, 0.97)	Small ↓ in performance
Ramírez-Campillo et al. [60]	Reactive	Intervention 1 (1-day)	15	−8.2	−2.55 (−3.87, −1.23)	Large ↑ in performance
		Intervention 2 (2-day)	15	−9.6	−3.12 (−4.58, −1.66)	Large ↑ in performance
		Control	15	0.9	0.14 (−0.91, 1.19)	Trivial ↓ in performance
Ramírez-Campillo et al. [61]	Reactive	Intervention	20	−3.4	−0.44 (−1.33, 0.44)	Moderate ↑ in performance
		Control	20	−0.3	−0.06 (−0.93, 0.82)	Trivial ↑ in performance
Idrizovic et al. [59]	Reactive	Intervention	20	−5.3	−0.76 (−1.56, 0.04)	Moderate ↑ in performance
		Control	20	0	0.00 (−0.67, 0.67)	No performance change
Rosas et al. [58]	Reactive	Intervention	20	−3.3	−0.28 (−1.27, 0.70)	Small ↑ in performance
		Control	20	1.3	0.13 (−0.79, 1.06)	Trivial ↓ in performance

Table 5 (continued)

Study	Strength quality	Group	Distance (m)	% Change	ES (95% CI)	Findings
Ozbar et al. [63]	Reactive	Intervention	20	− 8.1	− 1.12 (− 2.11, − 0.13)	Large ↑ in performance
		Control	20	2.6	0.21 (− 0.72, 1.14)	Small ↓ in performance
Ozbar [57]	Reactive	Intervention	10	− 13.0	− 0.57 (− 1.47, 0.32)	Moderate ↑ in performance
			20	− 10.5	− 1.50 (− 2.50, − 0.51)	Large ↑ in performance
			30	− 9.4	− 1.51 (− 2.51, − 0.52)	Large ↑ in performance
		Control	10	0.0	0.00 (− 0.88, 0.88)	No change in performance
			20	0.0	0.00 (− 0.88, 0.88)	No change in performance
			30	− 1.9	− 0.24 (− 1.12, 0.64)	Small ↑ in performance
Nonnato et al. [56]	Reactive	Intervention	10	− 8.7	− 1.89 (− 3.07, − 0.71)	Large ↑ in performance
			30	− 3.4	− 0.75 (− 1.76, 0.27)	Moderate ↑ in performance
		Control	10	− 3.1	− 0.53 (− 1.53, 0.46)	Moderate ↑ in performance
			30	− 0.8	− 0.21 (− 1.19, 0.77)	Small ↑ in performance
Luteberget et al. [67]	Special	Intervention	10	− 0.50	0.00 (− 0.88, 0.88)	No change in performance
			30	− 3.33	− 0.61 (− 1.51, 0.28)	Moderate ↑ in performance
		Control	10	− 1.99	− 0.54 (− 1.54, 0.46)	Moderate ↑ in performance
			30	− 6.50	− 1.31 (− 2.39, − 0.23)	Large ↑ in performance
Upton [68]	Special	Intervention	4.6	0.0	0.00 (− 0.92, 0.92)	No change in performance
			13.7	0.6	0.15 (− 1.08, 0.77)	Trivial ↓ in performance
			22.9	− 0.5	− 0.14 (− 0.78, 1.07)	Trivial ↑ in performance
			36.6	− 1.0	− 0.26 (− 0.67, 1.19)	Small ↑ in performance
		Control	4.6	0.5	0.06 (− 0.94, 0.81)	Trivial ↓ in performance
			13.7	− 0.4	− 0.06 (− 0.81, 0.94)	Trivial ↑ in performance
			22.9	− 0.4	− 0.06 (− 0.82, 0.94)	Trivial ↑ in performance
			36.6	− 0.2	− 0.03 (− 0.85, 0.91)	Trivial ↑ in performance

SQG squat group, *HTG* hip thrust group, *ES* effect size (Hedge's g), *95% CI* 95% confidence intervals

3.5 Moderator Variables

Subgroup analyses assessing the potential moderating factors are presented in Table 6. For the 0–10-m subgroup, programme duration had a significantly ($p = 0.05$) larger effect on performance for interventions > 8 weeks (SMD = − 0.86) compared with those with programmes ≤ 8 weeks (SMD = 0.01). Training frequency yielded no significant difference ($p = 0.90$). The magnitude was similar in the interventions with more than 12 sessions (SMD = − 0.35) compared with those with 12 sessions or fewer (SMD = − 0.30). Youth athletes (< 18 years) displayed a slightly larger improvement in sprint performance than adults (≥ 18 years) (SMD = − 0.46 vs − 0.25) but this was not statistically significant ($p = 0.69$).

For the 0–20-m subgroup, there was no statistically significant effect on performance due to programme duration, training frequency, or age. The magnitude of the effect was greater for programmes of longer duration (> 8 weeks [SMD = − 0.82] vs ≤ 8 weeks [SMD = − 0.65]), and a greater number of total sessions (> 12 sessions [SMD = − 0.82] vs ≤ 12 sessions [SMD = − 0.55]). The magnitude of effect for age was similar for both youths and adults (≥ 18 years [SMD = − 0.68] vs < 18 years [SMD = − 0.72]).

For the 0–40-m subgroup, there was no significant difference depending on programme duration and training frequency. The effect was of a similar magnitude as a function of programme duration (> 8 weeks [SMD = − 0.76] vs ≤ 8 weeks [SMD = − 0.74]), though it was greater for interventions with > 12 training sessions (SMD = − 0.87

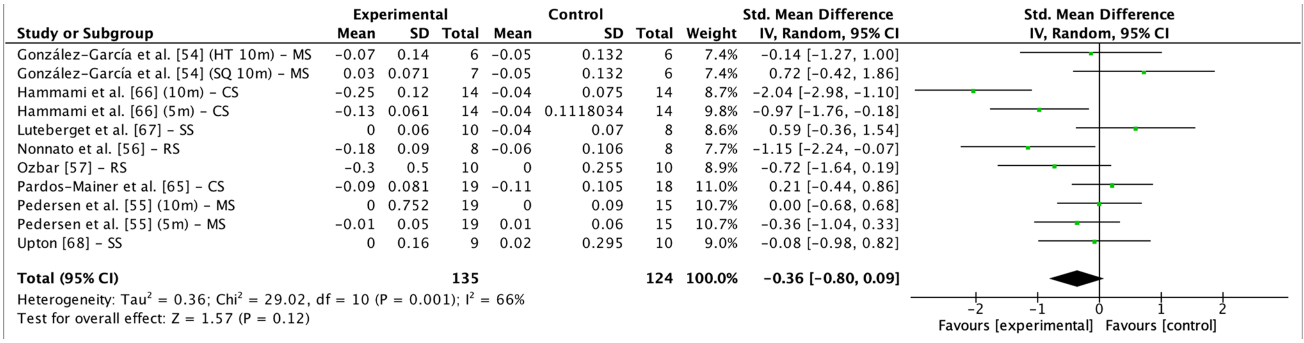


Fig. 2 Forest plot presenting the SMD ± 95% CI for between-group comparisons for 0–10 m sprint performance. *CS* combined strength, *MS* maximal strength, *RS* reactive strength, *SS* special strength

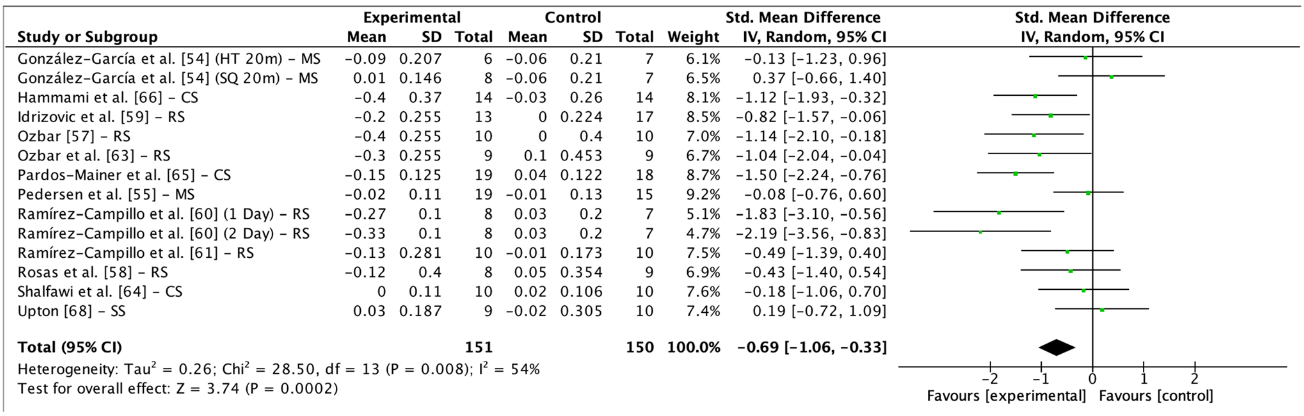


Fig. 3 Forest plot presenting the SMD ± 95% CI for between-group comparisons for 0–20 m sprint performance. *CS* combined strength, *MS* maximal strength, *RS* reactive strength, *SS* special strength

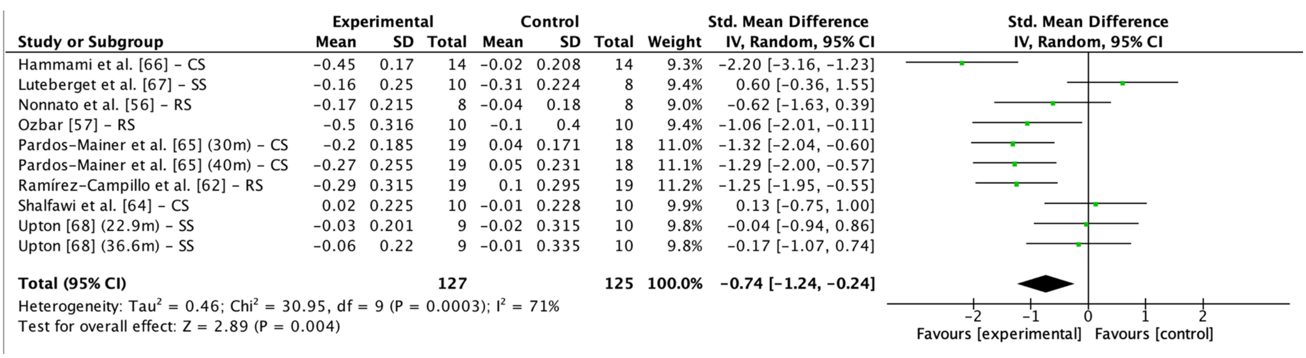


Fig. 4 Forest plot presenting the SMD ± 95% CI for between-group comparisons for 0–40 m sprint performance. *CS* combined strength, *MS* maximal strength, *RS* reactive strength, *SS* special strength

vs − 0.56). Youth athletes (< 18 years) displayed a significantly ($p = 0.01$) larger effect (SMD = − 1.35) than adults (≥ 18 years) (SMD = − 0.33).

4 Discussion

The primary aim of this meta-analysis was to investigate the overall effect of strength training on sprint performance in female team-sport athletes. This novel review is the first to

Table 6 Moderator variables

Distance	Moderator variable		SMD	95% CI		*p*-Value	
				LL	UL	Within	Between
0–10 m	Duration	> 8 weeks	− 0.86	− 1.67	− 0.05	0.04	0.05
		≤ 8 weeks	0.01	− 0.32	0.33	0.96	
	Total sessions	> 12 sessions	− 0.35	− 1.06	0.35	0.33	0.90
		≤ 12 sessions	− 0.30	− 0.72	0.13	0.17	
	Age	≥ 18 years	− 0.25	− 0.67	0.17	0.24	0.69
		< 18 years	− 0.46	− 1.38	0.46	0.33	
0–20 m	Duration	> 8 weeks	− 0.82	− 1.24	− 0.39	0.0002	0.63
		≤ 8 weeks	− 0.65	− 1.16	− 0.15	0.01	
	Total sessions	> 12 sessions	− 0.82	− 1.43	− 0.22	0.007	0.47
		≤ 12 sessions	− 0.55	− 0.98	− 0.12	0.01	
	Age	≥ 18 years	− 0.68	− 1.14	− 0.21	0.004	0.92
		< 18 years	− 0.72	− 1.35	− 0.09	0.03	
0–40 m	Duration	> 8 weeks	− 0.76	− 1.69	0.17	0.11	0.97
		≤ 8 weeks	− 0.74	− 1.29	− 0.19	0.008	
	Total sessions	> 12 sessions	− 0.87	− 1.63	− 0.10	0.03	0.54
		≤ 12 sessions	− 0.56	− 1.16	0.04	0.07	
	Age	≥ 18 years	− 0.33	− 0.92	0.27	0.29	0.01
		< 18 years	− 1.35	− 1.89	− 0.81	0.00001	

CI confidence intervals, *LL* lower limit, *SMD* standardised mean difference, *UL* upper limit

investigate the effect of differing strength training modalities on sprint performance in female team-sport athletes. Women are still under-represented within the evidence base with menstrual cycle complexities cited as a major barrier to the inclusion of female athletes in such research. As a result, evidence on male athletes is typically applied to the female population [34, 69]. This may be inappropriate because of the known physiological sex differences (i.e., hormonal profile, menstrual cycle). Furthermore, the effects of the menstrual cycle on exercise performance remain equivocal within the literature with substantial variation between individuals [70]. Consequently, female athletes may respond differently to one another following a training intervention and therefore an individualised approach should be considered based on each athlete's response to training across the menstrual cycle [70].

Sprinting is multifaceted [9] and a wide range of training methods (i.e., free sprinting, strength training, resisted sprinting) can be employed to improve performance. The principle of specificity states that training adaptations are specific to the stimulus applied [71]. Based on this principle, maximal-effort sprint training is an important component for the development of sprint performance. Maximal-effort sprinting exposes the body to large forces, high limb velocities, and short ground contact times resulting in specific neuromuscular adaptations (e.g., intermuscular coordination) that can only be gained from sprinting [10–13, 72]. Depending on time constraints within a microcycle, strength and conditioning coaches in elite team sports may programme specific speed sessions (e.g., acceleration and maximum velocity development) and use strength training as a supporting training method to optimise speed adaptations and overall performance [73]. In the context of sprint development, maximal-, explosive- and reactive-strength training may be considered 'general' training methods as they do not replicate sprinting. However, strength training can target specific neuromuscular components that may not be optimally developed through sprinting alone (e.g., increased peak force, peak power, leg stiffness, etc.) [3]. Although these methods are not considered specific for sprint development, practitioners must consider their selection in order to maximise the transfer of training effect (e.g., increasing force output through maximal strength or leg stiffness through reactive strength [74]).

The results of the analysis demonstrated that strength training results in small to moderate improvements in sprint performance. Specifically, there were small improvements found over 0–10 m and moderate improvements over both 0–20-m and 0–40-m sprint distances. However, the magnitude of improvement in sprint performance was influenced by the strength training modality utilised in the intervention (i.e., reactive; maximal; combined; and special strength). Compared with maximal- or special-strength interventions, reactive- and combined-strength training methods (i.e., combination of maximal, explosive, and/or reactive strength) can have a greater effect on sprint performance. Therefore, the results of this meta-analysis have important implications for practitioners who aim to improve sprint performance specifically among female team-sport athletes.

4.1 Reactive Strength

Reactive strength is the capacity of an athlete to bear a stretch load and subsequently switch rapidly from an eccentric to a concentric muscle action [18] and represents the ability to effectively utilise the stretch shortening cycle (SSC) [19]. Reactive strength is developed using what is commonly referred to as 'plyometrics' and can be assessed by a metric known as the reactive-strength index (RSI) [75]. RSI is calculated by dividing jump height (m) by ground contact time (s) [75], typically from jumps with an identifiable ground contact (e.g., drop jump, repeated jumps, repeated hopping). To maximise the resultant RSI score, an athlete should aim to minimise ground contact time and maximise displacement of the jump. In team sports (i.e., rugby union, soccer, volleyball, Australian rules football), reported mean RSI values have ranged from 0.89 to 2.04 [62, 76–80] in male athletes, and 0.58–1.67 [58, 61, 62, 81–84] in female athletes. Reactive strength is indicative of a fast SSC (i.e., ground contact times of < 0.250 s [85]) and the ability to rapidly generate force under high eccentric load is synonymous with the underlying components associated with sprinting [19] (e.g., the ability to rapidly produce and transmit force to the ground [10]). In a previous meta-analysis [19], RSI was found to be moderately associated with acceleration [$r = -0.426$] and top-end speed [$r = -0.326$] in male and female athletes from various sports. Moreover, RSI has been shown to differentiate between faster and slower athletes in male team sports (ES = 1.61) [86]. This highlights that plyometric training may be beneficial for improving sprint performance in female team-sport athletes.

This meta-analysis indicates that reactive-strength training improves sprint performance in female team-sport athletes. Specifically, a moderate to large improvement was observed for 0–10-m [56, 57] and 0–40-m [56, 57, 62], and a small to large improvement was observed for 0–20-m [57–61, 63] sprint performance. However, only three studies [58, 61, 62] within this meta-analysis reported RSI values. The reactive-strength interventions employed by these studies resulted in an increase of 8–21.5% in RSI while concurrently improving sprint performance by 3.2–5.2%. It should be noted that the individual components of RSI (i.e., jump height and contact time) were not presented in the included studies. Therefore, it is difficult to ascertain which component was the primary driver for change in RSI and subsequently the resultant improvement in sprint performance. Nevertheless, the findings in this meta-analysis are consistent with the previous findings of Sáez de Villarreal et al. [28], who concluded that a plyometric training intervention can enhance sprint performance in both male and female participants. Even though the studies included in this meta-analysis did not directly examine the neuromuscular adaptations of reactive-strength training, the improvements in sprint performance in female team-sport athletes may be attributed to improved neural drive to the agonist muscles, muscle activation patterns, intermuscular coordination, muscle–tendon complex stiffness, and SSC ability [87]. Previously, researchers have suggested that men and women achieve similar relative adaptations following a strength programme [88]. Equally, Ramírez-Campillo et al. [62] observed a similar rate of improvement in both RSI and sprint performance between male and female athletes following the same reactive-strength intervention. However, it is important to note that, compared with men, women have lower hysteresis (i.e., less compliant) in the tendon and aponeurosis of the medial gastrocnemius, subsequently allowing for a greater ability to use elastic energy following eccentric muscle actions (i.e., greater SSC ability) [89]. Consequently, given that both sprinting and plyometric exercises require rapid SSC muscle actions [90], the inclusion of plyometric training may assist in the development of the underlying components associated with sprinting in female team-sport athletes.

Based on the studies included in this review, it is recommended that female team-sport athletes employ a combination of unilateral and bilateral plyometric jumps, in vertical and horizontal directions, utilising fast (< 0.250 s) and slow (≥ 0.250 s) SSC actions. To target the underlying neuromuscular mechanisms of sprinting, plyometric exercises such as drop jumps, countermovement jumps (CMJ), broad jumps, bounding, pogo hops, and hurdle hops can be utilised to facilitate the transfer of training effect. To induce enhancements in sprint performance, the overall training volume and frequency can vary with 90–260-foot contacts over one to two sessions per week. Furthermore, measuring an athlete's RSI and its individual components (e.g., jump height and ground contact time) can offer valuable information and insight for practitioners as to the components driving the observed changes in RSI. This will serve as a guide for practitioners when prescribing training for their athletes.

4.2 Maximal Strength

Maximal strength is the ability to exert maximal force on an external object or resistance [15]. Lower-limb maximal strength is generally assessed through dynamic (i.e., back squat 1-repetition maximum [1 – RM]) or isometric tests (i.e., isometric mid-thigh pull) [14]. Differences in strength exist between the sexes, with female athletes typically weaker than equally trained male athletes [31, 91]. In team sports (i.e., basketball, rugby union, volleyball, handball, soccer), relative back squat 1 – RM (i.e., kilograms per kilogram of body mass [BM]) can range from 1.49 to 2.41 kg/BM [31, 92–97] in male athletes, and 1.20–1.88 kg/BM [31, 55, 66, 92] in female athletes. Further, Cormie et al. [98] reported greater increases in strength and transferability to speed in relatively weak male athletes (i.e., 1.28 kg/BM). This suggests that there may be a larger window of adaptation following maximal-strength training in female team-sport athletes, and subsequently a potentially greater transfer to sprint performance. Previously, researchers [92, 99, 100] have reported a moderate to strong relationship between maximal strength and sprint performance in female athletes. Additionally, it has been established that increases in lower body strength transfer to sprint performance in male athletes [26, 27]. However, the transfer effect of maximal-strength training to sprint performance in female athletes is unknown.

In the current meta-analysis, maximal-strength training had a trivial to small improvement on sprint performance in female team-sport athletes. Specifically, maximal strength had a trivial to small improvement on initial acceleration (i.e., 0–10 m) [54, 55]. However, there was only a trivial improvement on late-stage acceleration (i.e., 0–20 m) [54, 55]. It is important to note that even though González-García et al. [54] observed a trivial improvement in sprint performance, the authors did not report whether there were increases in maximal strength following the intervention (i.e., hip thrust 4 × 4–12 @ 60–90% 1-RM). Additionally, Pedersen et al. [55] observed a 31% increase in back squat maximal strength but only a trivial to small improvement in sprint performance. However, it is noteworthy that the back squat used throughout this intervention was performed with a partial range of motion (i.e., 90° knee angle), thus potentially limiting the transfer to sprint performance. Nevertheless, the findings in this meta-analysis are in contrast to the results of previous research on male athletes where sprint performance was improved following maximal-strength training [96, 97, 101]. The lack of substantial improvements in sprint performance from maximal-strength training in female team-sport athletes may be due to a number of reasons. Firstly, it has been suggested that improvements in sprinting performance do not necessarily occur immediately after a period of strength training [102]. Therefore, it is possible that athletes require time to adapt and transfer the gains in strength to the ‘movement’ of sprinting [102]. Furthermore, inadequate sprinting technique could potentially conceal the true effect of maximal-strength training on sprint performance [103]. It is also plausible that the results of the included studies may have been influenced by the menstrual cycle. Previously, it has been reported [104] that strength training performed by participants during the follicular phase resulted in greater strength gains compared with those who trained during the luteal phase. Additionally, female athletes can achieve similar relative adaptations in maximal strength to male athletes when the menstrual cycle is taken into consideration [88]. However, it should be noted that the small number of included studies ($n = 2$) are not sufficient to draw clear conclusions about the true effect of maximal-strength training on sprint performance for female team-sport athletes. Unlike male athlete research, no study has investigated the effect of maximal strength on longer sprint performance (> 20 m) in female team-sport athletes. Therefore, more research is required to further investigate the role of maximal-strength training on both acceleration and maximum-velocity performance in female team-sport athletes.

4.3 Combined Strength

In this review, combined-strength training methods include the use of both maximal- and reactive-strength training, or maximal- and explosive-strength training. The rationale for combined-strength training is to target differing underlying neuromuscular components in an attempt to augment improvements in the force–velocity relationship [105]. A combined-methods approach has been recommended by Haff and Nimphius [106] as the optimal approach for overall athletic performance, including enhanced sprint performance. Further, achieving an optimal balance between force and velocity capabilities can maximise lower-limb performance [107, 108], potentially transferring to sprint performance in female team-sport athletes.

The current meta-analysis demonstrated that combined-strength training can have a large improvement on sprint performance in female team-sport athletes. Specifically, a large improvement was observed for both acceleration (i.e., 0–10 m) [66] and longer sprint distances (0–20 m, and 0–40 m) [65, 66]. However, it is important to highlight that one of the included studies revealed a small reduction in acceleration performance (i.e., 0–10 m) following combined-strength training [65]. Additionally, Shalfawi et al. [64] reported no improvement in late stage acceleration (i.e., 0–20 m) or longer distances with qualities representative of maximum velocity (i.e., 0–40 m). The authors did note that the overall workload during their intervention may have been too high, subsequently impacting the athletes’ ability to adapt [64]. Nevertheless, these findings are corroborated by a previous meta-analysis [26] that reported a large improvement (ES = − 1.20) in sprint performance from combined-strength training (i.e., back squat, loaded jumps, plyometrics). Therefore, when compared with training solely for either peak force (e.g., maximal-strength training) or peak power development (e.g., explosive-strength training), a combined-strength training approach may be optimal for sprint performance [97] as it targets all of the specific neuromuscular components that are associated with sprinting (e.g., increased peak force, peak power, leg stiffness etc.) [3]. However, maximal strength is a fundamental component that underpins power [14, 105]. Consequently, it can be beneficial for 'weaker' athletes to first develop adequate levels of maximal strength in order to achieve high levels of power [105]. Further, previous work from Cormie et al. [109] demonstrated that trained males with a higher level of maximal strength (i.e., 1.97 kg/BM) displayed a greater rate of adaptation to an explosive-strength training programme (i.e., increased power output) that subsequently resulted in a significant improvement in 5- and 10-m sprint times (ES = 0.82 and 0.67). Explosive strength, which is typically measured using jump height from a CMJ assessment, has reported mean ranges of 28–60 cm [24, 62, 94, 110–112] in male, and 24–48 cm in female team-sport athletes. Therefore, given that females display lower levels of maximal- and explosive-strength compared with males [31], a mixed-methods approach to training (i.e., a combination of heavy and light loads), may be more beneficial for female athletes to improve sprint performance.

The use of combined-strength training for improving sprint performance in female athletes is supported by the findings of this meta-analysis. However, given the dearth of available studies, more research is needed to accurately determine its effect on sprint performance. Based on the studies included in this review, it is recommended that practitioners utilise a combination of maximal strength (e.g., back squat, leg press, lunge at ≥ 85% 1 − RM), explosive strength (e.g., broad jumps, CMJ, bounding), and reactive strength (e.g., drop jumps, depth jumps, hurdle jumps, pogo hops), over one to two sessions per week, to augment improvements in sprint performance for female team-sport athletes.

4.4 Special Strength

Special strength can be considered the intensification in the work of the muscular system in a manner that is predominantly inherent to the sport activity (i.e., sport-specific resistive exercise) [20]. Special-strength training applies the principle of specificity to strength training by utilising exercises that have similar motor patterns and neuromuscular characteristics to the 'competition movement' (i.e., sprinting) [74]. In the context of sprinting, special strength can be developed through resisted sprint training (RST). RST commonly employs sled sprints, uphill sprints, and motorised devices to overload the neuromuscular system while replicating the motor pattern of sprinting [3]. Further, when compared with 'general' strength training (i.e., back squat) and free sprint training, RST may improve horizontal force application and power production during sprinting [3, 29]. Consequently, based on the principle of specificity, it could be hypothesised that RST will transfer more effectively to sprint performance compared with other forms of strength training [3]. However, the benefits of RST remain equivocal within the literature.

The current meta-analysis demonstrated that, when compared with free sprint training, RST yielded no improvement in acceleration (i.e., 0–10 m) or longer sprint distances (i.e., 0–20 m, 0–40 m) in female team-sport athletes [67, 68]. It should be noted that one of the studies included in this review did observe a moderate improvement in 30-m sprint performance (ES = − 0.61) following RST, however, the magnitude of improvement was greater following free sprint training (ES = − 1.31) [67]. Nonetheless, the findings of this analysis are in contrast to the results of previous reviews indicated that RST has the potential to improve sprint performance in male and female populations [29, 30]. Previously, it has been proposed that sprint adaptations may be velocity specific [29]. For example, heavy sled loads may improve initial acceleration, where velocity is relatively low and force output is high, and light sled loads may improve the maximum velocity phase. Furthermore, very heavy loads (i.e., 80% BM) have demonstrated a substantial increase in maximal horizontal force production in male athletes when compared with free sprint training [113]. However, the studies included in this meta-analysis only investigated the effect of 'moderate' loads (i.e., 12.4% and 12.6% BM) on sprint performance in female athletes. Therefore, given that female athletes typically have lower levels of maximal-strength compared with male athletes [31], 'heavy' RST loads (> 20% BM) may be beneficial for developing the force necessary to optimise acceleration in female team-sport athletes. However, 'heavy' RST loads should be prescribed with caution so as not to adversely affect sprint mechanics. Based on the existing research on female team-sport athletes, RST may be no more effective than free sprint training for improving sprint performance [67]. Consequently, the performance benefits of RST over free sprint training remain to be conclusively demonstrated. Further research is warranted to investigate the optimal load and benefits of RST for enhancing sprint performance in female team-sport athletes.

5 Moderator Variables

A moderator analysis was undertaken to investigate variables (e.g., age, programme duration, and total number of sessions) that could potentially impact the main effects observed in this meta-analysis. The sprint performance of both adult (≥ 18 years) and youth athletes (< 18 years) was enhanced following a strength training intervention. However, youth athletes demonstrated a significantly larger improvement in performance for longer sprint distances (i.e., 0–40 m) when compared with adults. There was no significant difference in performance observed between adult and youth athletes for acceleration (i.e., 0–10 m) and late-stage acceleration (i.e., 0–20 m), although youths did demonstrate a slightly larger improvement in performance over both distances than adults. Nonetheless, these findings support the results of previous research stating that youth athletes often display a greater response to training compared with adults given their lower training age [114, 115]. Moreover, maturation of the athletes may play a role in the overall larger training effect as adaptations are considered to be greater during, and after, peak height velocity (PHV) (i.e., the time an adolescent experiences the fastest growth in their stature) [116]. Specifically, some research suggests that strength training is more effective during, and after, PHV [114]. For example, plyometric training can be more effective at improving acceleration performance (i.e., 0–10 m) in youths who are mid-PHV compared with those who are pre-PHV [117].

This moderator analysis supports the use of longer duration programmes (> 8 weeks) with a higher number of total sessions (> 12 total training sessions) to improve sprint performance. Programmes longer than 8 weeks resulted in a larger improvement in both acceleration (i.e., 0–10 m) and late-stage acceleration performance (i.e., 0–20 m). However, for distances representative of maximum velocity (i.e., 0–40 m), similar magnitudes of improvement were observed irrespective of programme duration (> 8 weeks vs ≤ 8 weeks). Further, interventions with a higher number of total sessions (> 12 sessions) demonstrated a larger improvement for longer sprint distances (i.e., 0–20 m and 0–40 m). However, during the acceleration phase (i.e., 0–10 m) there was no difference in performance regardless of the total number of sessions completed. This supports the principle that longer strength training programmes result in larger adaptations [114, 118]. For example, results from a previous review [119] reported that maximal-strength programmes exceeding 6 weeks with a frequency of 2–3 sessions per week improved strength levels to a greater degree than shorter interventions. However, contrary to this, research has suggested that plyometric training interventions longer than 8 weeks and including a higher number of total training sessions (> 12 sessions) may not provide any additional benefits for enhancing sprint performance in male and female athletes [120]. Moreover, the authors also cited an increased risk of injury with greater volumes of plyometric training, particularly in female athletes [120]. Consequently, programme duration and total number of training sessions should be considered with respect to the strength quality being trained. The evaluation of these moderating factors indicates that age, programme duration, and total number of sessions can impact the effect of strength training on sprint performance. Therefore, these findings will have important implications for practitioners in the prescription of training for female team-sport populations.

6 Limitations and Future Directions

It is important to highlight that, due to the dearth of available literature on each specific strength quality (e.g., reactive, maximal, combined, and special strength), a subgroup analysis could not be completed to conclusively demonstrate which strength training modality is most effective for improving sprint performance. Furthermore, not all control groups included in this meta-analysis were equal. For example, two control groups completed a specific speed training programme [67, 68], one included resisted agility and repeated sprint training [64], while the remaining control groups maintained technical and tactical training within their sport. Therefore, it is likely that the technical and tactical training included exposures to sprinting that could have impacted the overall findings of this meta-analysis and subsequent interpretation of the results. Additionally, it is unclear if adaptations to the interventions depend on the initial strength levels of the participants and whether this may affect the changes in sprint performance.

However, the most important limitation of this meta-analysis is the methodological considerations that are specific to the female athlete. It has been suggested that research on female participants has often not considered the menstrual cycle in their methods, further compounding the ability to draw evidence-based recommendations [69]. Only one study included in this meta-analysis acknowledged that factors such as the menstrual cycle were not considered throughout their research. Further, it is not clear whether the remaining studies applied the methodological considerations (i.e., menstrual cycle phases) required to address the known physiological difference between the sexes [69]. Additionally, variation in physiological function during the menstrual cycle exists between individuals [70, 121]. Consequently, the individual differences in hormonal concentrations (e.g., oestrogen) between participants may have contributed to the large confidence intervals observed in this meta-analysis. Hormonal disturbances may cause variation in strength and speed adaptations amongst participants, subsequently leading to heterogenic results [69]. This is supported by research indicating that physiological responses and adaptation to training will be influenced by natural hormonal fluctuations throughout the menstrual cycle [104]. For example, fluctuations in oestrogen during the menstrual cycle can potentially affect central nervous system fatigue, tendon and ligament strength, and muscle function, subsequently leading to impaired athletic performance or the ability to adapt to a strength training intervention [34]. Thus, appropriate research and training considerations should reflect this.

To overcome the androcentric research in the sport and exercise sciences, future research should employ methods that consider the effects of hormonal fluctuations, as a result of both endogenous hormonal profiles and exogenous sources (i.e., hormonal contraceptives), to mitigate the risk of heterogenic results amongst participants and provide an evidence-informed approach to training. Further investigation into the role of strength training on sprint performance in female athletes is also warranted. Future research should examine (1) the relationship between different strength qualities and sprint performance; (2) strength characteristics in stronger and weaker athletes and how they influence sprint performance; (3) the effect of maximal and explosive strength on overall sprint performance using a phased and sequential approach to training to optimise adaptation and performance (e.g., periodisation: accumulation, transmutation, and realisation) [122]; (4) the optimal load for RST that will enhance sprint performance and whether 'heavy' loads negatively affect sprint kinematics. Furthermore, there is limited evidence available on coaching practices for strength and speed training specifically in female team sports. For example, Nicholson et al. [123] investigated coaching practices for the development of sprint performance within football code athletes. However, of the 90 respondents, only seven had previously worked with female athletes. Therefore, gaining an insight into current coaching practices specifically on female athletes will further highlight gaps within the current body of evidence and direct future experimental research.

Of note, there is an over-representation of one sport throughout this meta-analysis. Specifically, soccer is the dominant sport ($n = 12$) with notable absences of other field sports such as Gaelic football, Australian rules football, and rugby. To the authors' knowledge, there is limited research available on the physical characteristics of female Gaelic football players [124, 125]. Additionally, there is no literature investigating the role of strength on speed adaptations for this cohort. Consequently, increasing the volume of research on the female athlete, specifically in Gaelic football, will result in more high-quality female-specific data and provide the practitioner with meaningful sport- and exercise-related training guidelines.

7 Conclusion

This meta-analysis demonstrates that different strength training modalities have a small to moderate effect on sprint performance in female team-sport athletes. Specifically, strength training resulted in a small improvement in acceleration (i.e., 0–10 m) and a moderate improvement over longer sprint distances (i.e., 0–20 m and 0–40 m). However, the magnitude of improvement in sprint performance was influenced by the strength modality (i.e., reactive, maximal, combined, and special strength) utilised in the intervention. The present research suggests that, compared with maximal- or special-strength interventions, reactive- and combined-strength training methods can have a greater effect on sprint performance. Further, sprint performance can be affected by age, programme duration, and total number of sessions. Sprint performance for both adult (≥ 18 years) and youth athletes (< 18 years) was enhanced. However, youth athletes demonstrated a slightly greater improvement in performance. Additionally, this analysis supports the use of a longer programme duration (> 8 weeks) and a higher number of total training sessions (> 12 sessions) to improve overall sprint performance. However, it should be noted that the strength quality being trained may dictate the total number of sessions and the duration of the programme. Practically, a competitive female athlete's training programme will be multifaceted in nature, utilising a combination of training modalities to enhance performance (e.g., technical training, free sprint training, and strength training). Therefore, these results will direct future experimental research and guide practitioners when programming to enhance sprint performance specifically in female team-sport athletes.

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Author contributions All the authors contributed to the conception and design of the study. WH drafted the manuscript and all authors contributed to editing and revising the manuscript. All authors read and approved the final manuscript prior to submission.

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