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SYSTEMATIC REVIEW

Resisted Sled Sprint Training to Improve Sprint Performance: A Systematic Review

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Abstract

Background Based on recent findings regarding the mechanical determinants of sprint performance, resisted sled sprint (RSS) training may provide an effective tool for the improvement of sprint acceleration and maximal velocity. However, the volume and intensity for effective RSS training in different populations is unclear.

Objectives The primary objective was to evaluate the effectiveness of RSS training compared with unresisted sprint (URS) training, and the differential effects of sled load on RSS training outcomes.

Data Sources: Study Eligibility and Appraisal A systematic review was performed primarily using PubMed and SPORTDiscus databases. Peer-reviewed studies were accepted only if the participants used a sled towing device for a longitudinal intervention of resisted sprint training, and if RSS training was the primary difference in training intervention between groups. Effect size (ES) reported using Cohen's *d* was presented to compare the magnitude of effect between both dependent and independent groups.

Results A total of 11 studies fulfilled the eligibility criteria. Sled loads were prescribed either as a percentage of body mass (%BM), a targeted reduction in velocity compared with unresisted sprint velocity (%V_{dec}) or as an absolute load (kg). RSS training with 'light' (<10 %BM or <10 %V_{dec}) loads provide 'small' decrements in acceleration (−1.5 %, ES = 0.50) to 'moderate' improvements in maximal sprint velocity (2.4 %, ES = 0.80) in sprint-trained individuals. 'Moderate' (10–19.9 %BM or 10–14.9 %V_{dec}) to 'very heavy' (>30 %BM or >30 %V_{dec}) sled loads provide 'trivial' to 'extremely large' improvements in acceleration performance (0.5–9.1 %, ES = 0.14–4.00) in strength-trained or team sport individuals. Whether RSS training is more effective than URS training in the improvement of acceleration or maximal sprint velocity remains equivocal.

Conclusions RSS training is a novel training method with potential for the improvement of sprint performance, but its performance benefits over URS training remain to be conclusively demonstrated. Between-study comparisons are limited primarily by discrepancies in the training status and phase of the participants, and sled load prescription. Future work is required to define the optimal load and volume for RSS depending on the specific components of sprint performance to be enhanced.

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Key Points

Resisted sled sprint training with sled loads ranging from 12 to 43 % of body mass (%BM) is effective in the improvement of sprint performance for trained individuals, whilst lighter loads may not provide a sufficient stimulus above that of unresisted sprint (URS) training.

A combination of resisted sled sprint training with traditional URS or plyometric training may provide benefits to sprint acceleration above that of URS training alone.

Sprint adaptations may be velocity specific with heavy (>20 %BM) sled loads improving initial acceleration where velocity is slow and resistive forces are high, and light (<10 %BM) sled loads improving the maximal velocity phase where velocity is high and resistive forces are low. Further research is required to test these hypotheses.

1 Introduction

1.1 Determinants of Sprint Performance

The ability to improve maximal sprint performance is a central training goal for conditioning coaches from a range of sports and disciplines. Sprint acceleration is defined as the rate of change in running velocity. Positive instantaneous acceleration over time implies an increase in sprint velocity. The maximal velocity phase is defined as a period in which the top sprint velocity is reached, and thus, acceleration is close to zero. Transition velocity is measured as a split between the acceleration and maximal velocity phases. For any sprint-based performer, an improvement in overall performance can result from an improvement in acceleration and/or maximal velocity phases [1]. Additionally, abilities for acceleration and maximal velocity are commonly monitored indicators of physical performance in field sport competition and training [2–7].

Sprint and strength coaches primarily focus on two general methods to improve sprint performance. Programmes are designed to either increase an athlete's force and power output, or improve the efficiency and use of a given physical output [8]. The latter method traditionally requires sprint technique drills such as 'ankling', 'heel kicks' and 'high-knee' exercises [8]. With regard to increasing force and power output, various training methods have illustrated a positive transfer of training to sprint performance with increases in maximal strength [1, 9], maximal power [10, 11], reactive strength (plyometric training) [12] and combinations of these methods [13–17]. Whilst use of the aforementioned methods displays effective improvements in sprint acceleration or maximal velocity, the majority of training interventions and exercises focus on enhancing production of force (e.g. back squat), force velocity (e.g. Olympic lift variations) or reactive strength (e.g. drop jumps) in the vertical direction of movement. A recent meta-analysis reported a transfer of training between improvements in squat strength (vertical force production) and sprint performance [9]. However, a greater transfer of resistance training to sport performance may be achieved if the conditioning programme emphasises a similar motor pattern and contraction type (i.e. comparable mechanical properties) to the performance movement [18].

Several ground reaction force (GRF) components work in coordination to produce a positive running velocity. Horizontal (anteroposterior) force production is divided into braking (negative, posterior) and propulsive (positive, anterior) constituents [19]. The sum of horizontal and vertical force vectors is termed resultant (total) GRF [20]. Ratio of forces, which describes the effectiveness of force application onto the ground, is computed for each stance phase as the net horizontal component over the resultant GRF [20]. As ratio of force is decreasing linearly with increasing velocity over the transition from acceleration to maximal velocity phase, an index of force application technique represents the decrement in ratio of forces with increasing velocities [20–22].

Recent studies have established that acceleration and maximal velocity sprint performance are related to the technical ability to apply GRF in a more horizontal direction [19–25]. For example, the mechanical determinants of sprint performance in nine high-level male sprinters (4 elite, 5 sub-elite), using a series of interconnected force plates beneath the sprinting surface were recently investigated [22]. Sprint acceleration, measured as block clearance velocity, was neither correlated to averaged resultant ($r = -0.021$) nor averaged vertical GRF ($r = -0.241$). However, the average horizontal force ($r = 0.775$) and average ratio of forces (the ratio of horizontal to resultant force production) ($r = 0.821$) were correlated to acceleration ability [22]. Rabita et al. [22] summarised that (a) elite sprinters are able to produce greater horizontal force per unit body mass at any given velocity than sub-elite sprinters, (b) production of greater horizontal force is due to a more horizontal orientation of GRF (i.e. technical ability), and (c) sub-elite sprinters produce equal, if not more, resultant force per unit body mass than elite sprinters. Therefore, resultant and vertical force production are not key variables for differentiation of sprint acceleration ability [22].

Findings on acceleration performance and horizontal application of force are supported by a similar study using three-dimensional force plate analysis of the sprint acceleration phase [25]. Well-trained sprinters (block clearance velocity = 9.72 m/s) produced a greater horizontal GRF than trained (block clearance velocity = 8.41 m/s) and non-trained (block clearance velocity = 7.32 m/s). Although well-trained sprinters produced a greater resultant GRF than the non-trained individuals, no differences existed between the two former groups [25]. Additionally, differentiations between maximal sprint velocity have been attributed to vertical force production during the stance phase [26, 27]. Using a treadmill sprint design, Weyand et al. [26] reported on relationships between maximal velocity and the production of greater maximal GRFs. A runner with a maximal velocity of 11.1 m/s was observed to have 1.26× greater vertical production per unit body mass compared to a runner with a maximal velocity of 6.2 m/s. The relative average vertical force production and maximal velocity were correlated ($r = 0.624$), thereby predicting 39 % of the variance in maximum velocity [26]. However, this study used a wide-range of individuals from the physically active to elite sprinters and therefore the results do not identify differences between a narrow focus of high-level athletes. Using aforementioned methods applied to sprint performance, Rabita et al. [22] found horizontal force and ratio of forces at 40 m to respectively predict 82 and 81 % of the variation in maximal velocity at 40 m in well-trained sprinters. However, no significant correlation existed between vertical force ($r = -0.216$) or resultant force ($r = -0.137$) at 40 m and maximal sprint velocity.

1.2 Resisted Sled Sprint Training

A strong transfer between training and performance provides training efficiency, which is paramount to both coaches and athletes [18]. Resisted sled sprint (RSS) training is one such training method that is consistent with this philosophy [24, 28]. RSS training involves a set number of maximal straight-line sprint efforts whilst towing a sled device. The sled is attached to the athlete by a chest or waist harness and cord. An external overload, above that of unresisted sprint training (URS), is therefore a direct function of the sled mass and the coefficient of friction between the sled and the ground surface. Acute (i.e. single sprint session) studies have identified RSS efforts as a potential method for enhancement of both physical output and efficiency of physical output when compared with traditional URS alone [29–36]. Regarding the technical efficiency of physical output, towing a weighted sled load at 30 % of body mass increases horizontal impulses beyond those observed during URS [31]. This finding may be because of the increased trunk (and likely whole body) lean angle observed in RSS compared with URS efforts [30, 32, 34, 37]. An increase in trunk lean angle with RSS likely allows for a greater application of force in the horizontal direction when compared with URS efforts. However, an increase in trunk angle may be inappropriate for the maximal velocity phase of sprinting [38]. Therefore, for training-induced improvements in physical output, RSS training may provide a stimulus for increases in muscle strength or peak force [29, 35, 36], or rate of force development [29, 33]. In summary, RSS training may be an effective method of providing a horizontal resistance whilst closely replicating the motor pattern of sprinting. Consequently, RSS training may provide an effective alternative or combination exercise to traditional vertical force production methods of strength and power training [24, 39].

Whether acute RSS studies should or can be translated into training prescription is unclear as it remains to be conclusively demonstrated that training outcomes in response to RSS are consistent with kinematic changes observed during single sessions of RSS. For example, acute (within-session) changes in sprint kinematics associated with RSS training suggest a potentially negative mechanical transfer from ‘heavy’ RSS training to sprint acceleration [35, 38, 40–42]. This negative transfer may include unfavourable changes in stride length or stride frequency that lead to reductions in URS velocity. Conversely, compared with lighter loads or URS training, ‘heavy’ RSS training may aid sprint performance through aforementioned improvements in force or power output and technical application of force. Regardless of kinetic and kinematic changes, the effectiveness of transfer from longitudinal RSS training should ultimately be quantified in terms of an improvement in sprint acceleration and/or maximal velocity. Additionally, it is unclear whether reported longitudinal adaptations to RSS training are specific to the population studied (e.g. trained vs. untrained).

Therefore, a systematic review of research on longitudinal RSS training is required to assess the efficacy of RSS training and to provide contemporary recommendations for use by strength and conditioning coaches working with various training populations. Given this knowledge gap, and on the basis of recent findings on the mechanical determinants of sprint acceleration and maximal velocity, the primary objective of this review is to review training studies that compare the effectiveness of RSS training with URS training, and the differential effects of sled loads on training outcomes in response to RSS. The secondary objective is to provide sport practitioners with a critical evaluation of the current sled sprint methodologies given that caution should be exercised over generalising research findings to applied practice, especially in the context of specific athletic populations.

2 Methods

2.1 Literature Search

The systematic review process was directed under the PRISMA guidelines and checklist [43]. The search was completed separately by two authors (GP and BE). Using keywords and Boolean operators, a systematic review of the literature was performed using PubMed and SPORTDiscus (Fig. 1). The following terms were searched for in 'all fields': "resisted sprint", sled AND sprint, resisted AND sprint, tow AND sprint, resisted AND sled, sprint AND drag. The term 'dog' was excluded from all searches using NOT. Results were limited by language (English) and source (journal article, book, review). Further records were added based on previous reading, expertise among co-authors and the subsequent citations of seminal papers.

2.2 Study Selection

Study selection criteria were as follows: (1) must have used a sled device for resisted sprint training (i.e. multiple training sessions), (2) resisted sled sprints were the primary difference in training intervention between groups, (3) presence of a comparison group from the same population pool as the RSS training group, and (4) study published following a peer-review process. Sprint performance technology and methodology were not taken into account as potential inclusion/exclusion criteria.

2.3 Data Analysis and Presentation

Analyses were calculated separately and cross-checked for accuracy by two authors (GP and BE). Corresponding authors were contacted electronically if specific data were required, although not all requests were met. Percentage

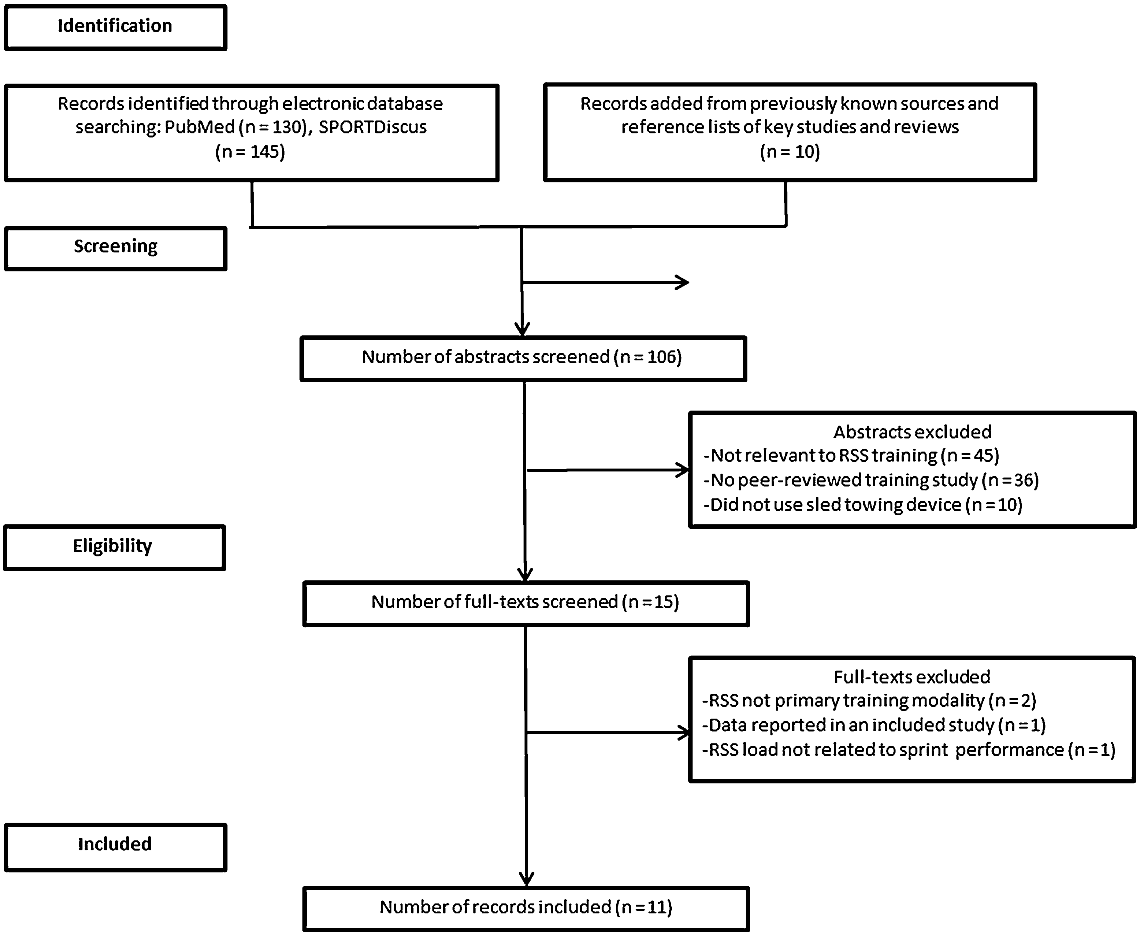

Fig. 1 Flow of information through the systematic review process. *RSS* resisted sled sprint

change from pre- to post-training in sprint testing was calculated manually from each individual study using the following formula where x_{pre} = mean pre-training sprint performance score and x_{post} = mean post-training sprint performance score:

$$\%\,\text{change} = \left(\frac{x_{\mathrm{post}} - x_{\mathrm{pre}}}{x_{\mathrm{pre}}}\right) \times 100.$$

Effect size (ES) (reported using Cohen's d [44]) was presented to compare the magnitude of effect between both dependent and independent groups. ES for dependent groups (magnitude of effect between pre- to post-training) was calculated using the following formula [44] where d is ES, x_{pre} is the mean pre-training sprint performance score, x_{post} is the mean post-training sprint performance score and SD is the standard deviation of the change in sprint performance from pre- to post-training.

$$d = \frac{\overline{x_{\mathrm{post}}} - \overline{x_{\mathrm{pre}}}}{\mathrm{SD}}$$

ES for independent groups (magnitude of effect difference between two interventions) was calculated using the following formula [45] where d is ES, x_t is the mean change in sprint performance of treatment group, x_c is the mean change in sprint performance of comparison group, and $\mathrm{SD}_{\mathrm{pooled}}$ is the pooled standard deviation of the change in sprint performance from pre- to post-training of both groups:

$$d = \frac{\overline{x_t} - \overline{x_c}}{\mathrm{SD}_{\mathrm{pooled}}}.$$

$\mathrm{SD}_{\mathrm{pooled}}$ was calculated using the following equation [45] where n_t is the number of participants in treatment group, n_c is the mean change in sprint performance of comparison group, and $\mathrm{SD}_{\mathrm{pooled}}$ is the the pooled standard deviation of the change in sprint performance from pre- to post-training of both groups:

$$\mathrm{SD}_{\mathrm{pooled}} = \frac{(n_t - 1)\mathrm{SD}_t^2 + (n_c - 1)\mathrm{SD}_c^2}{n_t + n_c}.$$

In the case where 90 % confidence intervals (CI) were used as an alternative to SD [46], the following formula was used to convert CI to SD where n is the number of participants:

$$\mathrm{SD} = \frac{(\mathrm{CI} \times \sqrt{n})}{1.644854}.$$

Interpretation of ES magnitude were considered with the following thresholds: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99) and extremely large (≥4.00) [47]. Calculations were performed using Microsoft Excel (Microsoft, Redmond, WA, USA). Kinetic and kinematic data were not the focus of this review and are only presented for discussion purposes. Therefore, % change and ES calculations are not presented for these data.

3 Results

Eleven papers met the inclusion criteria for this review [28, 46, 48–56] (Fig. 1). Because of significant variations in velocity phase durations between subjects of differing sprint abilities [1, 3, 57], this review defines the initial acceleration phase as 0–20 m and the maximal velocity (or near-maximal velocity) phase as distances greater than 20 m.

Three different methods of RSS load prescription were used within the studies eligible for review. Six studies prescribed sled load to produce a target percentage reduction in sprint velocity ($n\ \%V_{\mathrm{dec}}$) compared with URS velocity [28, 49, 51–53, 55]. For example, a sled load prescribed to reduce 0–10 m average velocity by 10 % is written as 10 $\%V_{\mathrm{dec}}$. Four studies prescribed a load based on a percentage of body mass (%BM) [46, 50, 54, 56], whilst one study prescribed an absolute sled load of 5 kg [48].

Some studies reported both $n\ \%V_{\mathrm{dec}}$ and %BM sled load values [28, 51, 53, 55, 56]. For example, sled loads of 10 $\%V_{\mathrm{dec}}$ are equivalent to between 10 and 13 %BM [28, 51, 53, 56]. We propose a general categorisation of sled loads (Table 1) and have used these consistently in this review, whilst study details are presented in Table 2. RSS loads ranged between 5 and 43 %BM or between 6 and 30 $\%V_{\mathrm{dec}}$ (Table 2). Changes in sprint performance following RSS training, comparisons of sprint training modalities and both kinetic and kinematic sprint details are also presented in Tables 3, 4, and 5, respectively.

In sprint- and strength-trained athletes, RSS training at a load of 7.5 $\%V_{\mathrm{dec}}$ provided a significant and 'moderate' effect for an improvement in 15–30 m velocity. However, no sprint improvement above a 'small' effect was observed at any other distance over 0–50 m or on maximal velocity [55]. RSS training with heavier loads of ~13.0 %BM

Table 1 Proposed categorisation of resisted sled sprint sled loads

Category	%BM	$\%V_{\mathrm{dec}}$
Light (L)	<10.0	<10.0
Moderate (M)	10.0–19.9	10.0–14.9
Heavy (H)	20.0–29.9	15.0–29.9
Very heavy (VH)	>30.0	>30.0

%BM sled load as a percentage of body mass, $\%V_{dec}$ decrement in sprint velocity elicited by sled load compared with unresisted sprint velocity

Table 2 Study details

Study	Participants (*n*)	Age, mean (years)	Study duration (weeks)	Total sessions (*n*)	Sprint distance			RSS training intensity			Sprint surface	CON details	Other training?
					Per repetition, range (m)	Per session, range (m)	Training total (m)	%BM	$\%V_{\mathrm{dec}}$	Load category			
Alcaraz et al. [55]	M (14) and F (8), sprint-trained	21.2	4	8	30	90–180	1080	~8–9	7.5	L	Synthetic track	URS	Flying sprints, plyometrics
Bachero-Mena, Gonzalez-Badillo [56]	M (19), physically active	20.8	7	14	20–35	100–210	2115	(G1) 5 (G2) 12.5 (G3) 20	(G1) 5.6 (G2) 10 (G3) 15.5	(1) L (2) M (3) H	Synthetic track		NT
Clark et al. [51]	M (14), NCAA D3 Lacrosse	19.8	7	13	18–55	240–400	4060	10	<10	L		URS	Norm
Harrison, Bourke [50]	M (15), semi/professional rugby	20.5	6	12	20	120	1440	13		M	Synthetic track	Rugby only	Rugby, RT, speed drills
Kawamori et al. [28]	M (21), competitive and recreational team sports	22.6	8	16	5–15	90–140	1740	(G1) ~13 (G2) ~43	(G1) 10 (G2) 30	(1) M (2) VH	Hardwood floor		Norm
Lockie et al. [52]	M (18), team sport, strength-trained	23.1	6	12	5–20	195–320	3100	12.6		M	Outdoor grass field	URS	Norm
Luteberget et al. [46]	F (18), semi-professional handball	21.8	10	20	10–20	240–280	5200	12.4		M	Hardwood floor	URS	Norm
Makaruk et al. [53]	F (36), physically active	22.1	9	24	20–35	180–360	6210	7.5–10	10	L	Synthetic tartan track	URS and NT	NT
Spinks et al. [49]	M (30), strength-trained, field sports	21.8	8	16	5–25	215–340	4090		10	M		URS and NT	Norm
West et al. [54]	M (20), strength- and sprint-trained professional rugby	26.0	6	12	20	60 (RSS) and 60 (URS)	720 (RSS) and 720 (URS)	12.6		M	Rubber-crumb field	URS	Norm
Zafeiridis et al. [48]	M and F (22), recreationally active	20.1	8	24	20–50	280	6720	5 kg (~7 %)		L		URS	NT

%BM sled load as a percentage of body mass, *CON* control group, *D3* Division 3, *F* female, *(G1)* group 1, *(G2)* group 2, *(G3)* group 3, *H* heavy, *L* light, *M* male, *M* moderate, *NCAA* National Collegiate Athletic Association, *Norm* maintained normal training pattern specific to participant sport, *NT* no training, *Pro* professional, *rep* repetition, *RSS* resisted sled sprint, *RT* resistance training, $\%V_{dec}$ decrement in sprint velocity elicited by sled load, *URS* unresisted sprint, *VH* very heavy, blank data indicates not reported

Table 3 Changes in sprint performance following RSS training

Study	RSS group by sled load (load category)	Sprint performance variable (m)	Δ Sprint performance (%)	$p < 0.05$	ES (Cohen's d)	ES rating
Alcaraz et al. [55]	7.5 %V_{dec} (L)	V 0–15	−1.54	n	−0.50	Small
		V 0–30	0.90	n	0.50	Small
		V 0–50	0.69	n	0.31	Small
		V 15–30	2.36	y	0.80	Moderate
		V 30–50	1.25	n	0.38	Small
		V Max	−0.11	n	−0.04	Trivial
Bachero-Mena, Gonzalez-Badillo [56]	5 %BM (L)	T 0–10	1.70	n	0.66	Moderate
		T 0–20	1.32	n	0.53	Small
		T 0–30	1.18	n	0.91	Moderate
		T 0–40	1.29	y	1.22	Large
		T 10–40	1.10	y	1.25	Large
		T 20–30	0.00	n	0.00	No change
		T 20–40	1.27	y	1.10	Moderate
	12.5 %BM (M)	T 0–10	0.58	n	0.29	Small
		T 0–20	0.66	n	0.50	Small
		T 0–30	0.71	n	0.66	Moderate
		T 0–40	0.74	y	1.01	Moderate
		T 10–40	0.92	n	1.40	Large
		T 20–30	1.89	y	1.89	Large
		T 20–40	0.94	y	1.33	Large
	20 %BM (H)	T 0–10	0.56	n	0.24	Small
		T 0–20	0.97	y	1.30	Large
		T 0–30	0.70	y	1.59	Large
		T 0–40	0.73	y	1.09	Moderate
		T 10–40	0.63	n	0.35	Small
		T 20–30	0.96	n	0.59	Small
		T 20–40	0.00	n	0.00	No change
Clark et al. [51]	<10 %V_{dec} (L)	T 18.3–54.9	0.13	n	0.13	Trivial
		V 18.3–54.9	0.09	n	0.07	Trivial
Harrison, Bourke [50]	13 %BM (M)	T 0–5	8.42	y		
		T 0–10	5.81	n		
		T 0–30	4.33	n		
		V Max	3.05	n		
Kawamori et al. [28]	10 %V_{dec} (M)	T 0–5	3.13	n	0.65	Moderate
		T 0–10	2.91	y	0.83	Moderate
	30 %V_{dec} (VH)	T 0–5	5.47	y	0.96	Moderate
		T 0–10	5.37	y	1.55	Large
Lockie et al. [52]	12.6 %BM (M)	V 0–5	7.09	y	1.58	Large
		V 0–10	5.64	y	1.08	Moderate
		V 5–10	0.15	n	0.06	Trivial
Luteberget et al. [46]	12.4 %BM (M)	T 0–10	0.50		0.14	Trivial
		T 0–30	3.33		0.64	Moderate
Makaruk et al. [53]	<10 %V_{dec} (L)	V 0–20	2.46	y		
Spinks et al. [49]	10 %V_{dec} (M)	V 0–5	9.12	y		
		V 0–15	7.81	y		
		V 5–10	6.08	y		
		V 10–15	7.37	y		

Table 3 continued

Study	RSS group by sled load (load category)	Sprint performance variable (m)	Δ Sprint performance (%)	$p < 0.05$	ES (Cohen's *d*)	ES rating
West et al. [54]	12.6 %BM (M)	*T* 0–10	2.30	y	4.00	Extremely large
		T 0–30	2.58	y	3.33	Very large
Zafeiridis et al. [48]	5 kg (L)	*V* 0–10	4.08	y		
		V 10–20	−1.13	n		
		V 0–20	1.97	y		
		V 20–40	0.94	n		
		V 40–50	1.05	n		
		V 20–50	−0.23	n		

%BM sled load as a percentage of body mass, *ES* effect size, *H* heavy, *L* light, *M* moderate, *n* no, *RSS* resisted sled sprint, *T* sprint time, *V* sprint velocity, *VH* very heavy, *V Max* maximum sprint velocity, $\%V_{dec}$ decrement in unresisted sprint velocity elicited by sled load, *y* yes, blank data indicates not reported

resulted in significant improvements in 0–5 m (8.4 %) [50], 0–10 m (2.3 %), and 0–30 m (2.6 %) time [54] in strength-trained and high-level rugby players. Further improvements in 0–10 m (5.8 %), 0–30 m time (4.3 %), and maximal sprint velocity (3.1 %) were also observed, but although meaningful in applied practice, did not reach statistical significance [50]. In team sport athletes, similar sled loads of ~13 %BM or 10 $\%V_{\text{dec}}$ provided a significant training improvement of 7.1–9.1 % (0–5 m) [49, 52], 2.9–5.6 % (0–10 m) [28, 52], 7.8 % (0–15 m) [49], and 3.3 % (0–30 m) [46]. A sled load of <10 $\%V_{\text{dec}}$ did not provide training improvements in maximal velocity phase sprinting for collegiate lacrosse players [51]. However, when physically active cohorts trained with 'light' RSS loads, improvements were observed in both acceleration [48, 53] and maximal velocity [56].

Compared with URS groups, no additional benefit to acceleration or maximal velocity was observed following light RSS (L-RSS) training in sprint and strength-trained male individuals [55] and moderate RSS (M-RSS) in semi-professional female handball players and male field sport players [46, 49]. Two studies found improvements in a RSS training group to be greater than those seen in a URS group [48, 54]. One study recording a 'very large' (ES = 2.1) and 'large' (ES = 1.8) effect difference in favour of RSS training for 0–10 and 0–30 m time, respectively [54]. Conversely, one study found URS training to have a 'moderate' (ES = 1.1) benefit to maximal velocity beyond RSS training with a load of <10 $\%V_{\text{dec}}$ [51].

When a direct comparison of RSS loads was performed in field sport athletes, very heavy RSS (VH-RSS) training was 'moderately' more beneficial to 0–10 m time than M-RSS training (ES = 0.73), although this difference did not reach statistical significance [28]. In physically active male and female individuals, 'small' to 'large' differences between L-, M- and heavy RSS (H-RSS) groups were observed over a range of sprint measures (Table 4) [56]. One study found a significant decrease in the URS resultant and vertical impulse at 8 m from the start line following 16 sessions of VH-RSS training [28]. This difference was significantly greater ($p = 0.023$ and 0.020, respectively) than that following 16 sessions of M-RSS training in a matched-cohort [28].

4 Discussion

4.1 Methodological Considerations for RSS Training

4.1.1 *Prescription of Sled Load and Sprint Surface*

Sled load compromises the total mass of the sled device and the amount of external mass placed on the sled. Three methods of sled load prescription were used within the 11 reviewed training studies. Prescribing a %BM sled load is a simple and easily reproducible method from research to practice. However, the %BM loading method does not consider individual variation in strength, power or sprint velocity characteristics [35, 46]. For example, moderate to strong correlations exist between RSS velocity with URS performance ($r = 0.640$–0.876), countermovement jump (CMJ) height ($r = -0.650$ to -0.730), normalised CMJ peak power ($r = -0.700$ to -0.810) and loaded squat jump peak power ($r = -0.660$ to -0.800) [58, 59]. These data suggest two athletes towing the same load relative to BM may experience two different training stimuli, (e.g. high force-low velocity vs. low force-high velocity). Therefore, RSS loads prescribed as %BM hold less validity to loads prescribed relative to velocity characteristics (i.e. sprint performance level) of the athletes.

Different sprint surfaces and/or sled models will elicit varying degrees of coefficient of friction [60]. Such variations in coefficient of friction between surfaces imply that

Table 4 Comparisons of sprint training interventions

Study	First and second training group for comparison	Sprint performance variable (m)	$p < 0.05$ between groups	ES (Cohen's *d*)[a]	ES rating
Alcaraz et al. [55]	L-RSS vs. URS	*V* 0–15	n	0.05	Trivial
		V 0–30	n	0.29	Small
		V 0–50	n	0.23	Small
		V 15–30	n	0.36	Small
		V 30–50	n	−0.24	Small
		V Max	n	−0.25	Small
Bachero-Mena, Gonzalez-Badillo [56]	L-RSS vs. M-RSS	*T* 0–10		0.52	Small
		T 0–20		0.21	Small
		T 0–30		0.43	Small
		T 0–40		0.63	Moderate
		T 10–40		0.39	Small
		T 20–30		−1.23	Large
		T 20–40		0.48	Small
	L-RSS vs. H-RSS	*T* 0–10		0.50	Small
		T 0–20		0.00	No difference
		T 0–30		0.50	Small
		T 0–40		0.06	Trivial
		T 10–40		0.50	Small
		T 20–30		−0.60	Moderate
		T 20–40		1.10	Moderate
	M-RSS vs. H-RSS	*T* 0–10		0.00	No difference
		T 0–20		−0.33	Small
		T 0–30		0.00	No difference
		T 0–40		0.00	No difference
		T 10–40		0.25	Small
		T 20–30		0.77	Moderate
		T 20–40		0.88	Moderate
Clark et al. [51]	L-RSS vs. URS	*T* 18.3–54.9	n	−1.08	Moderate
		V 18.3–54.9	n	−1.11	Moderate
Harrison, Bourke [50]	M-RSS vs. CON				
Kawamori et al. [28]	VH-RSS vs. M-RSS	*T* 0–5	n	0.47	Small
		T 0–10	n	0.73	Moderate
Lockie et al. [52]	M-RSS vs. URS	*V* 0–5		0.06	Trivial
		V 0–10		0.22	Small
		V 5–10		−0.92	Moderate
Luteberget et al. [46]	M-RSS vs. URS	*T* 0–10		−0.58	Small
		T 0–30		−0.55	Small
Makaruk et al. [53]		*V* 0–20	n		
Spinks et al. [49]	M-RSS vs. URS	*V* 0–5	n		
		V 0–15	n		
		V 5–10	n		
		V 10–15	n		
West et al. [54]	M-RSS vs. URS	*T* 0–10	y	2.11	Very large
		T 0–30	y	1.76	Large
Zafeiridis et al. [48]	L-RSS vs. URS	*V* 0–10	y		
		V 10–20	n		
		V 0–20	y		
		V 20–40	y		

Table 4 continued

Study	First and second training group for comparison	Sprint performance variable (m)	$p < 0.05$ between groups	ES (Cohen's d)[a]	ES rating
		V 40–50	y		
		V 20–50	y		

CON non-sprint- control, *ES* effect size, *H* heavy, *L* light, *M* moderate, *n* no, *RSS* resisted sled sprint, *T* sprint time, *URS* unresisted sprint, *V* sprint velocity, *VH* very heavy, *V Max* maximum sprint velocity, *y* yes, blank data indicates not reported

[a] Positive effect in direction (favour) of first training group, negative effect in direction (favour) of second training group

towing the same absolute load on grass vs. synthetic or wooden flooring, for example, will provide a disparity in training stimulus. Additionally, there are substantial inter-athlete differences in the strength of the relationship between 30-m sprint time and sled load, variations between the rate of increase in sprint time (with increases in sled load) and the coefficient of friction of the running surface [60, 61]. We advise caution when generalising a %BM load prescription method to a different surface than that used by a published study. Just one of the four studies that prescribed sled load as a %BM did not identify the training surface used [51]. An RSS load prescribed as n %V_{dec} is easily transferable to practice, divergent populations, and surface types. Practical equations are available to calculate percentage reductions in velocity without the need for rigorous testing [32, 40, 49].

For inter-study comparisons, a problem arises when there are differences in the distance over which maximal velocity is measured. For example, from the five studies that prescribe load based on n %V_{dec}, one study uses 0–10 m average velocity [28], one study uses 0–20 m average velocity [53], two studies use maximal instantaneous sprint velocity (0–50 m) [51, 55], and one study uses a regression equation based on 15-m RSS performance [49]. Each study differs in %V_{dec} distance to specifically match their sprint performance variables. For example, Kawamori et al. [28] uses a 0–10 m sprint as the main performance variable from pre- to post-training and therefore determines %V_{dec} from a 0–10 m sprint. However, the variation between methodologies distorts the effectiveness of inter-study comparison as an acceleration %V_{dec} (e.g. 0–10 or 0–20 m) does not necessarily equal the same %V_{dec} to maximal velocity sprinting (e.g. 0–50 m).

The prescription of training loads based on a given exercise one-repetition maximum (1RM) is a common method of strength and power training prescription within strength and conditioning practice. A recent cross-sectional study innovatively attempted to determine the equivalent of 1RM in an RSS model, terming it 'maximal resisted sled load' (MRSL) [59]. MRSL was determined as the heaviest sled load that did not reduce one's average 15–20 m sprint velocity to be less than 10–15 m velocity. In other words, a sled load greater than MRSL does not permit constant 'acceleration' throughout a 20-m sprint. Using 21 male participants (competitive sprinters or soccer players), MRSL was correlated to 20 m URS ($r = 0.706$) and 20-m sprint time undertaken with RSS loads ranging from 5 to 30 %BM ($r = 0.440$–0.734) [59]. However, the MRSL protocol has not been tested for reliability. If validated, the MRSL may be a feasible method for prescribing RSS training load on an individual basis, while also allowing practitioners to periodise RSS training based on a sled repetition-maximum.

In summary, unless using the identical sled device and sprint surface of a given published study, RSS training protocols that prescribe sled load from %BM may not hold sufficient external validity for practical use. The replication of studies that prescribe loads based on n %V_{dec} are likely to be valid for direct application by practitioners. Caution is advised for direct comparison between results from RSS training studies with differing protocols owing to a variation in the approach to sled load prescription and running surface.

4.1.2 Harness Attachment and Cord Length

The angle of tow cord does not significantly affect 30-m RSS time with a sled load of up to 20 %BM [61]. To the authors' knowledge, despite some authors using considerably long cords (e.g. greater than 20 m [31]), there is no research documenting the effect of harness length or attachment position on acute or long-term sprint performance, kinematics or kinetics. One study has investigated the effect of towing cord attachment position on sled walking kinematics [62]. A VH-RSS load of 50 %BM and belt attachment produced 58 % more hip extension moment impulse compared with a vest attachment. The vest attachment created 57 % greater knee moment impulse compared with the belt [62]. Therefore, it is recommended to use a belt attachment to challenge hip extension and a vest harness to overload knee extension, although these data are based on heavy sled walking and may have limited application for sprint training [62].

Table 5 Changes in kinetic and kinematic parameters following resisted sled sprint training

Study	Location of kinetic and/or kinematic measurement (from start line)	Variables	Δ Sprint kinematics	Δ Sprint kinetics
Alcaraz et al. [55]	3 and 45 m	SL, SF, CT, LD, TA, thigh, shank, foot	RSS = p-p and b-g ↑ TA (3 m) b-g ↑ SL, LD, shank (45 m) URS = b-g ↑ thigh, p-p ↓ CT (45 m)	
Clark et al. [51]	37.5–44 m	SL, SF, CT, FT	ns	
Kawamori et al. [28]	1st GC and 8 m	SL, SF, RI, VI, NHI, BI, PI	10 $\%V_{\mathrm{dec}}$ = p-p ↑ SL (8 m) 30 $\%V_{\mathrm{dec}}$ = p-p ↑ SL (1st GC), ↑ SF (8 m)	30 $\%V_{\mathrm{dec}}$ = p-p and b-g ↓ RI, VI (8 m)
Lockie et al. [52]	0–5 m and 5–10 m	SL, SF, CT, FT	RSS = p-p ↑ SL (0–5, 0–10 and 5–10 m) URS = p-p ↑ SL, ↓ SF (0–5, 0–10 and 5–10 m), ↑ CT (0–5 and 0–10 m), ↓ FT (0–5 m)	
Makaruk et al. [53]	1 m, third to fourth GC, 0–20 m	SL, SF, CT, FT, knee-T, knee-fs	RSS = p-p ↑ SL, knee-T, CT, ↓ SF, (0–20 m) URS = p-p ↑ SF (0–20 m)	
Spinks et al. [49]	First to second GC	SL, SF, CT, TA, ShF, ShE, ShR, ShAV, ElF, ElE, ElR, ElAV, HipF, HipE, HipR, HipAV, KR, KAV	RSS = b-g ↑ ShE (first GC) p-p ↑ TA (first and second GC), ShAV (first GC), ↓ CT (second GC) URS = b-g ↑ ElF (first GC) p-p ↑ TA (first and second GC), ↓ CT, ↑ ShE (second GC)	
Zafeiridis et al. [48]	Third GC and 42–47 m	SL, SF, TA	RSS = b-g and p-p ↑ TA (third GC) p-p ↑ SF (third GC) URS = b-g and p-p ↑ SL (42–47 m)	

b-g between group, *BI* braking impulse, *CT* ground contact time, *ElE* elbow extension, *ElF* elbow flexion, *ElR* elbow range of movement, *ElAV* elbow angular velocity, *foot* foot angle, *FT* flight time, *GC* ground contact, *HipF* hip flexion, *HipE* hip extension, *HipR* hip range of movement, *HipAV* hip angular velocity, *KAV* knee angular velocity, *knee-T* knee angle at toe-off, *knee-fs* knee angle at foot strike, *KR* knee range of movement, *LD* landing distance, *NHI* net horizontal impulse, *ns* no significant changes ($p > 0.05$), *PI* propulsive impulse, *p-p* pre- to post-training, *RI* relative resultant impulse, *RSS* resisted sled sprint group, *SF* stride frequency, *shank* shank angle, *ShF* shoulder flexion, *ShE* shoulder extension, *ShR* shoulder range of movement, *ShAV* shoulder angular velocity, *SL* stride length, *TA* trunk angle, *thigh* thigh angle, *URS* unresisted sprint group, $\%V_{dec}$ decrement in unresisted sprint velocity elicited by sled load, ↑ indicates significant ($p > 0.05$) increase, ↓ indicates significant ($p > 0.05$) decrease, *VI* relative vertical impulse, blank data indicates not reported

4.1.3 Kinetic and Kinematic Data Collection

Although the analysis of kinetic and kinematic changes with acute RSS is not central to this review, variation in measurement protocol is an important discussion point. Of the 11 studies reviewed, seven performed pre-and post-training kinematic analysis [28, 48, 49, 51–53, 55] whilst only one study measured sprint kinetic data [28] (Table 5). A large variation between kinematic data collection protocols is present between studies. Whilst some studies measured stride kinematics over a given distance [48, 51–53, 55], others recorded data from a specific single step at a given distance from the start line [28, 48, 49, 53]. Interpretation of kinematic changes in performance may be misleading if data are collected from such short ranges, especially a single ground contact. Therefore, individual study conclusions regarding the relationship between changes in sprint performance and the associated changes in kinematics and/or kinetics should be inferred with caution. However, the primary focus of this review is the effect of RSS training on sprint acceleration or maximal velocity. While the authors are aware changes in sprint kinematics may be related to changes in sprint performance, the relationship between stride length and stride frequency is variable between individuals [57, 63].

4.2 The Effectiveness of RSS Training Protocols

4.2.1 Sampling Considerations

The main focus of this review is evaluate RSS vs. URS training, and the potential differential effects of RSS training at different sled loads as an effective tool for improving in acceleration and/or maximal sprint velocity. The review will not consider comparisons against a non-training control group. Comparisons to a non-training control are not applicable to coaches working in applied sporting environments. However, the effectiveness, or otherwise, of RSS training must be considered as a function of sampling or publication biases, and the training population or training phase in which the research was undertaken. A systematic review may be affected by (1) an expectancy or coaching bias within the individual studies, and (2) publication bias, in that studies with positive or significant findings are more likely to be published than studies with negative or non-significant results [64]. In relation to training phase, a study on semi-professional soccer players observed significantly decreased sprint acceleration performance, decreased lower body power and higher body fat values at the start of preseason training when compared with the final week of the previous competitive season [65]. Therefore, a high rate of sprint improvement in a preseason training intervention may be linked to the lower relative level of sprint velocity, power and body composition. As players reach peak physical ability following preseason training [65], the rate of improvement in sprint velocity may not be as high as that observed within a preseason intervention.

Another important factor is the sample from the study population is drawn particularly in the context of the individuals' training age, history and fitness characteristics. For example, the rate of physical adaptation to training is linked to an individual's initial level in a given parameter of fitness [66]. This initial level of fitness can be affected by the age and training experience of the athlete. Furthermore, the training phase of the season can influence what level of trainedness the athlete is at [65]. Therefore, interpretation of RSS training outcomes is dependent on the study population and the training phase within which the intervention took place. For example, individuals defined as strength trained are not necessarily familiar with sprint training, and unlikely to have experienced greater than 12 months of periodised sprint training wherein sessions would prioritise maximal efforts and technical guidance. Conversely, sprint-trained individuals are likely to have developed a more advanced technical sprint model than non-sprint-trained participants. Additionally, a higher level of sprint-specific muscle power is likely more common in sprint-trained individuals than their untrained counterparts [67]. Therefore, interventions to address the sprint-specific muscle output or technical efficiency of sprint-trained individuals will likely have a lower rate of improvement compared with non-sprint-trained populations. The authors of this review assumed that participants defined as strength-trained individuals were not specifically sprint trained unless reported to in the methods section of the reviewed studies.

4.2.2 Effects of RSS Training on Sprint Performance

Two studies have investigated the effectiveness of RSS training per se as training methodology for improving sprint performance i.e. without comparison to a control or URS training group. In one study, L-RSS training provided no improvement in acceleration in strength- and sprint-trained athletes; in fact, a 'small', yet non-significant, 1.5 % reduction (ES = 0.50) in 0–15 m sprint velocity following eight sessions of L-RSS training was observed [55]. Although L-RSS training provided a moderate improvement in 15–30 m velocity [55], the effect on transition velocity may have been amplified by the relative reduction in 0–15 m performance. The L-RSS training group also completed concurrent resistance and plyometric training, including 150–200 m of URS training per week. Respective improvements of 2.9 and 4.3 % in 20 m velocity were observed in elite junior male sprinters following either a 7-week high-force or high-velocity resistance training programme [68]. The resistance training programmes were performed concurrently with individual sprint training programmes [68]. One interpretation is that a certain volume of URS training is required alongside L-RSS exercise to stimulate an improvement in sprint performance in sprint-trained athletes. Another study performed with team sport athletes found no improvement (ES = 0.07–0.13) in maximal velocity during sprint performance following L-RSS training [51]. Notably, the training group performed 4 × 150 m of concurrent URS distance per week [51]. It is possible that, alongside L-RSS training, higher volumes of URS are required to stimulate improvements in sprint performance in team sport athletes. Conversely, both of these RSS training studies took place when the respective athletes were considered to be in a trained state [51, 55]. As the respective L-RSS training programmes were not effective during the in-season, further research may wish to explore if a training effect exists when programmed during the pre-season.

A lack of improvement in the sprint performance of trained individuals following L-RSS training may be explained by several reasons. First, neither study observed changes in stride length, stride rate nor ground contact time from pre- to post-training [51, 55]. However, Alcaraz et al. [55] did observe increases in trunk angle at the second stride (acceleration phase) but not at 45 m (maximal velocity phase). As kinematic measurements were restricted to just two distances, the interpretation of results is limited. The lack of substantial change in sprint kinematics suggests that these instances of L-RSS training were unlikely to provide the necessary resistive overload required for positive kinematic transfer to sprint performance [51, 55]. A recent study in court sport athletes suggested that a sled load of greater than 20 %BM is required to improve explosiveness from the sprint start [29]. To improve sprint acceleration, the existing superior force production capabilities of a strength- and sprint-trained athlete may necessitate a sled load greater than that of a non-strength-trained individual. Therefore, the RSS load required for improving acceleration through increases in sprint-specific lower limb muscle power in strength- and sprint-trained athletes may be greater than 20 %BM. Further research on H- and VH-RSS training with strength- and sprint-trained individuals is required to test this hypothesis. Alternatively, this RSS training programme of only eight sessions, totalling a 4-week training volume of 1080 m [55], may not provide the required overload to elicit improvements in sprint performance. Although further training may have allowed for adaptation, Clark et al. [51] found no sprint improvement following more than 7.5 times the total L-RSS training volume performed in the aforementioned study [55]. Therefore, the performance of and the neuromuscular, kinetic and kinematic adaptations to L-RSS require further investigation.

Six studies investigated M-RSS training in participants with a training background in various sports. Five of six studies found significant improvements in acceleration (2.3–9.1 %; ES = 0.83–4.00) or maximal velocity (2.6–7.4 %; ES = 0.64–3.33) following M-RSS training [28, 49, 50, 52, 54]. The participants ranged from strength-trained semi- and professional rugby players [50, 54], strength-trained field sport athletes [49, 52] and recreational to competitive field sport athletes [28]. Corresponding longitudinal changes in kinematic parameters in these studies included an increase in step length [28, 52], stride frequency [28], trunk angle [49] and a decrease in ground contact time [49]. Unfortunately, not all studies measured kinematic changes [46, 50, 54]. Only one study observed a lack of improvement in acceleration following M-RSS training, which was performed with female handball players who were 'accustomed to strength training' (ES = 0.14) [46]. On the opposite end of the spectrum, West et al. [54] observed respective 'extremely large' and 'very large' effects for 0–10 m and 0–30 m sprint performance following RSS training with a 12.6 %BM load during a preseason period with professional rugby players. This study used a combination of 3 × 20 m RSS and 3 × 20 m URS efforts, which represents the lowest training volume from the studies in this review, with just 720 m of RSS and 720 m of URS over 12 training sessions. Strength and conditioning coaches in rugby may be interested in the sprint performance improvements provided by this relatively low volume RSS training plan. The study provides evidence that strength-trained rugby players with some experience of structured sprint training can improve acceleration and maximal velocity performance by ~2.5 % if M-RSS training is performed in a preseason period [54]. Improvements in acceleration performance of 1–3 % are consistent with that previously observed in strength-trained male individuals following 30 %1RM jump squat training [11]. Similarly, improvements in 30 m sprint time of 3.5 % have been observed following 9 weeks of heavy resistance training and combined with speed training in soccer players not previously strength-trained [15]. In practical terms, a 1–3 % differential in sprint performance may be the difference between first and last place in an elite sprint race [57, 69]. Small improvements in acceleration performance may also differentiate between successful and unsuccessful actions in team sports. For example, a 1 % improvement in acceleration may improve a rugby or soccer player's chances of reaching the ball before an opponent.

A second study reported improvements of 5.8 % from 0 to 10 m and 4.3 % from 0 to 20 m in academy rugby players after 12 sessions of RSS training at 13 %BM [50]. The academy rugby players were younger (20.5 vs. 26.0 years) and slower (30 m time: 5.1 vs. 4.3 s) than the players trained by West et al. [54]. Although strength trained, the academy players were likely weaker (due to age) and, based on sprint performance times, unaccustomed to specific sprint training in comparison to professional players. Therefore, the greater performance improvements observed in this study [50] may be owing to the novel speed training stimulus per se and cannot be wholly attributed to RSS training.

Other studies have observed improvements in acceleration of between 5.6 and 9.1 % using a 12.6 %BM or 10 $\%V_{\mathrm{dec}}$ sled load [49, 52]. Participants in one study were either in offseason or preseason and therefore have likely entered the study in a less trained state [52], whereas the phase of the season was not reported in the second study [49]. Luteberget et al. [46] observed a 'moderate' effect of RSS training at 12.4 %BM on 30 m sprint performance (3.3 %, ES = 0.64) in semi-professional female handball players following 20 sessions, totalling 5200 m of RSS distance. Interestingly, no improvement was found over 0–10 m (0.5 %, ES = 0.14). These results imply that a sled load of 12.4 %BM in female handball players improved performance in the maximum velocity phase, but not acceleration. In summary, for training with M-RSS, the benefits to both sprint acceleration and maximal velocity are not consistent, but all six studies reported benefits of M-RSS training to either one of sprint acceleration or maximal velocity.

H-RSS training has hitherto not been performed on trained individuals and highlights an area of research required to bridge the gap in knowledge between the effects of M- and VH-RSS loads. A paucity of training studies using H- or VH-RSS loads may be owing to negative speculation from previous studies. To this end, it is commonly advised to use the heaviest possible RSS load without an alteration of sprint technique i.e. a prescription based on kinematic considerations [38, 40–42]. This prescription often results in a load close to 10–13 %BM or 10 %V_{dec}. Conversely, various investigations have proposed that a sled load of >20 %BM is required to provide an overload stimulus for improvements in force production and application characteristics during the sprint acceleration phase [29, 31, 33–35]. A RSS load of 10 %BM is likely to preserve sprint kinematics, but may not provide the necessary overload to enhance first-step explosiveness in trained athletes. Moreover, RSS training with a load of 20 %BM has elicited 'large' increases in 0–20 m and 0–30 m sprint time in individuals not previously trained for sprinting or strength (ES = 1.30–1.59) [56]. The conflicting opinion on the efficacy of H- or VH-RSS loads within the published literature should instigate a greater depth of research on the longitudinal effects of RSS training with heavy loads.

Only one study eligible for this review evaluated VH-RSS training [28]. VH-RSS training elicited a 'moderate' to 'large' positive effect on acceleration performance (5.4–5.5 %, ES = 0.96–1.55) [28]. The participants in this study were neither sprint nor strength trained and completed the training either during off- or preseason. The improvements in acceleration performance following VH-RSS training were related to mechanical changes in force application [28]. The study observed a concurrent decrease in resultant and vertical force during the URS support phase following VH-RSS training. No changes in force application were observed following M-RSS training in a matched cohort. These results imply that VH-RSS, but not M-RSS training teaches non-sprint-trained individuals to direct GRF impulse in a more horizontal direction [28]. Other RSS training studies monitoring changes in kinetic determinants of sprint performance are presently lacking.

As described earlier, improvements in sprint performance following RSS training may be explained by an increase in trunk angle or lean [48, 49, 55], greater stride length [28, 52, 53, 55], greater stride frequency [28, 48] or a decreased ground contact time [49]. Owing to inconsistencies with the measurements of kinematic variables, the exact mechanical transfer from RSS training to sprint performance remains unclear.

Improvements in sprint performance are coupled with changes in sprint kinetics and performance variables associated with power. Improvements in sprint performance following M-RSS training have been observed concurrently with increases in vertical jump peak power output [55], vertical jump height [46, 49, 50, 56], vertical jump starting strength [50], drop jump reactive strength index [52] and horizontal bound distance [49]. Starting strength is a measure of very fast force production capabilities previously correlated to initial sprint acceleration [70, 71]. Reactive strength is measured by dividing jump height divided by contact time from a drop jump. Positive changes in sprint kinetic and performance variables associated with power may be general outcomes of increased ankle, knee or hip concentric power and stiffness characteristics, which are related to improved acceleration ability [36, 72, 73].

In summary, L- to VH-RSS training is not detrimental to sprint performance in sprint- and strength-trained or untrained individuals. Contrary to previous concerns, H- and VH-RSS training has elicited improvements in sprint acceleration. RSS training, using loads of 12–43 %BM (or 10–30 %V_{dec}), is an effective tool for improving sprint performance. However, the relationship between performance improvements in acceleration or maximal velocity and the required RSS load, volume, concurrent training methods and training experience of the individual remains to be fully elucidated. Future research is required to (1) evaluate the effectiveness of L-, H- and VH-RSS training in various training groups, (2) further explore the effect of H- and VH-RSS training in sprint- and strength-trained groups, and (3) evaluate the specific kinetic and kinematic transfer pathways of RSS training to sprint performance.

4.2.3 *RSS vs. URS Training*

As described above, in certain populations or training phases, it may be that RSS training is simply a general training stimulus to improve sprint performance that would also be achieved by URS. However, six studies were eligible for this review that have specifically compared the training effects of L- or M-RSS to URS training (Table 4), and were performed in either team sport or strength-trained participants [46, 49, 51, 52, 54, 55]. No study exists at present that has compared URS training with H- to VH-RSS training.

One study observed URS training to be 'moderately' more effective (ES = 1.08–1.11) than L-RSS training in the improvement of maximal velocity in non-sprint- or strength-trained lacrosse players [51]. This result is similar to that observed in physical education students, where URS training was more effective in improving maximal velocity when compared with 5 kg RSS training [48]. Although

Clark et al. [51] did not measure initial acceleration, Zafeiridis et al. [48] observed that 5 kg RSS training is more effective for improving acceleration compared with URS training. Therefore, L-RSS training was effective in improving acceleration whilst URS was more beneficial to maximal velocity. This result pertains to a velocity-specific adaptation to sprint training as discussed further in Sect. 4.2.4. An equal benefit of 4 weeks of L-RSS or URS training was observed in sprint- and strength-trained athletes for both acceleration and maximal velocity [55]. As previously discussed, this study did not include a high volume of URS training in conjunction with the L-RSS intervention. Given the currently available evidence, L-RSS training alone is no more effective for the improvement of acceleration and maximal sprint velocity than URS training when programmed for strength-trained or active sportspeople.

In a study on M-RSS training in professional rugby players, RSS and URS training groups observed marked improvements in 0–10 m (RSS = 2.3 %, ES = 4.00; URS = 1.2 %, ES = 0.50) and 0–30 m sprint time (RSS = 2.6 %, ES = 3.33; URS = 1.2 %, ES = 1.67). The magnitude of effect between-groups were ‘very large’ for 0–10 m (ES = 2.11) and ‘large’ for 0–30 m (ES = 1.76) in favour of M-RSS training [54]. A combination of RSS and URS training was likely a key factor in the improvement of sprint velocity more so than traditional sprint training alone, with the authors citing the potential for a post-activation potentiation (PAP) stimulus from the sled sprints [54]. Although an effective PAP stimulus improves sprint performance [74–76], it is unclear whether RSS efforts provide an acute PAP benefit to sprint performance. Two studies using non-sprint- or strength-trained participants have provided conflicting results [77, 78]. However, the performance effect of a PAP stimulus is heightened with training experience [79], and therefore the results of previous RSS and PAP studies cannot be generalised to findings in sprint- and strength-trained rugby players. A PAP effect may have positively affected long-term sprint performance in the study by West et al. [54], but further work on the acute and longitudinal effects of RSS and PAP in well-trained individuals is warranted. If a PAP stimulus did provide a key difference to benefits on acceleration between RSS and URS training, it is unclear whether M-RSS training alone would have provided the same improvement to sprint performance.

Improvements in sprint acceleration and maximal velocity of 1.1–11.4 % have been observed following heavy resistance training and plyometric [16], or heavy resistance training alone [80] in team sports players who were not specifically sprint trained. Sprint performance improvements of 5.6–9.1 % have been observed using similar sled loads (~12 %BM), but with greater total sprint distances of 3100–4090 m [49, 52] than the study by West et al. [54]. Although a greater total RSS volume may enhance the training effect on sprint performance, the participants in the two studies used non-sprint-trained participants [49, 52]. The effect of a general sprint stimulus on non-sprint-trained individuals is illustrated when the performance effects of M-RSS and URS are compared, whereby neither study found RSS training to be more effective than URS training [49, 52]. As discussed above, in populations without a history of sprint training, the opportunity to consistently practice sprinting through either M-RSS or URS training will likely result in an improvement in sprint acceleration. Neither training programme combined M-RSS with URS efforts, contradicting the possible reasons for a lack of improvement in sprint performance in the two aforementioned studies using L-RSS in sprint-trained athletes [55] and lacrosse players [51].

In semi-professional female handball players, URS training is ‘likely’ more beneficial to 0–10 m sprint performance in comparison to M-RSS training, although the magnitude of effect between training modalities was considered as ‘small’ (ES = 0.58). The authors [46] cite possible sex differences (muscle mass, maximal muscle strength) as reasons for varying results between their own and similar studies [50, 51, 54]. As discussed in Sect. 4.1.1, sled load prescription relative to body mass is not optimal because it does not take into account muscle strength, muscle mass or other variables related to power [46].

Kinetic, kinematic and neuromuscular adaptations may differ between URS and RSS training. Improvements in sprint performance have been associated with longitudinal changes in sprint kinetics and kinematics (Table 5). Spinks et al. [49] identified a greater increase in pre- to post-training trunk lean and improved musculotendon stiffness after RSS as key factors in the improvement of acceleration when compared with the URS group. Increases in trunk lean support the theory that RSS training may improve the angle of horizontal force application [30, 32, 34, 38], which may provide a positive technical adaptation to sprint performance [19–25, 81]. However, an increase in body lean may not be specific to just RSS training, with evidence of similar adaptations following URS training [49]. In that study, both RSS and URS groups experienced changes in stride length, stride frequency and contact time, which were sufficient to stimulate improvements in acceleration [49]. Results for changes in stride length following RSS training are equivocal [49], but underscore the aforementioned issues with kinematic analysis. For instance, a 9 % decrease in stride length over the first two steps observed in one study [49] is in contrast to an observed 7.8 % increase in stride length from 0 to 5 m in another [52].

A limitation to the kinematic data is the measurement of variables at only the first two steps as load-specific training adaptations may be present at distances beyond this mark. The study by Spinks et al. [49] is unable to provide a rigorous explanation regarding the kinematic adaptations between RSS and URS training for the full 15-m acceleration. Both RSS and URS groups improved in the 5 Bound Test (5BT) [49], a repeated horizontal test of reactive strength. Concurrent improvements in the 5BT and sprint performance corroborate findings regarding the relationship between faster athletes and their ability to apply force more effectively in the horizontal plane [20–22]. Alcaraz et al. [55] observed no significant improvement in sprint acceleration following eight sessions of RSS, but did observe small improvements in 15–30 m (2.4 % in RSS) and 30–50 m velocity (1.9 % in URS). Therefore, instead of adaptations to the sprint acceleration phase, the study observed improvements in the maximal velocity phase following both RSS and URS training [55]. Kinematic variables in this study were measured at both the second step and the step at 45 m from the start line [55]. These measurements distances provide a useful idea of sprint kinematic in the acceleration and maximal velocity phase. However, further measurement distances would improve our understanding of the relationship between changes in sprint performance and sprint kinematics following RSS changes. Given the sled load used by Alcaraz et al. [55] was lighter than that used by Spinks et al. [49], and the different sprint adaptations observed, RSS training of differing sled loads can provide performance changes to different phases of sprint performance. The exact details of the phase-specific changes remain to be investigated.

Finally, two studies comparing RSS and URS training in untrained populations [48, 53] used light sled loads and similar total training volumes, finding comparable improvements of 2.5 % [53] and 2.0 % [48] in 0–20 m sprint performance for the RSS groups. These findings indicate that L-RSS training will improve sprint acceleration performance in untrained individuals. Because of the untrained nature of the individuals, it is possible that any form of structured lower body strength or power training, including RSS training, will have a positive effect on sprint performance. From a performance task perspective, no between-group (RSS vs. URS) differences were observed for measures of maximal strength, maximal power, agility or aerobic conditioning, concluding that both training modalities allow for the maintenance or improvement of these characteristics when part of an overall training programme [46, 55].

In summary, RSS training is no more effective in eliciting positive changes to acceleration or maximal velocity when compared with traditional URS training. However, it remains unclear as to the differences in specific kinematic or kinetic adaptations between RSS and URS training in athletes of different sprint and strength training backgrounds. Moreover, the combination of L- or M-RSS training with URS or plyometric training may induce sprint performance adaptations above that of traditional sprint or RSS training alone. Specifically, a RSS PAP stimulus may be used for improved acceleration in sprint- and strength-trained male individuals, but this contention requires further research investigation. Unfortunately, no data are currently available comparing the effects of H- or VH-RSS and URS training.

4.2.4 RSS Training: Comparison of Sled Loads

Of the 11 studies in the review, two studies directly used H- or VH-RSS training, finding significant improvements in acceleration performance and providing no decrement to performance in acceleration or maximal velocity phase [28, 56] (Table 3). Kawamori et al. [28] performed 16 training sessions of 5–15 m sprints with two groups using either a very heavy (30 $\%V_{\mathrm{dec}}$ of 10 m sprint time) or moderate (10 $\%V_{\mathrm{dec}}$ of 10 m sprint time) sled load. The VH-RSS group observed improvements of 5.5 % in 0–5 m acceleration (ES = 0.96), whereas the M-RSS group observed a non-significant 3.2 % improvement (ES = 0.65) over this distance [28]. Both VH- and M-RSS groups improved 0–10 m time by 5.4 % (ES = 1.55) and 2.9 % (ES = 0.83), respectively [28]. The improvements in 0–5 m time were limited to the VH sled group, indicating that a sled load sufficient to reduce 10 m sprint velocity by 30 % was superior in improving early acceleration compared to a sled that reduces 10 m sprint velocity by 10 % [28]. These findings should diminish previous concerns [38, 40–42] regarding H- or VH-RSS training and the possible negative effects on sprint performance, at least when considering acceleration as the performance parameter.

Further comparisons to M-RSS training show that VH-RSS training provided a greater training effect on 0–5 m (ES = 0.47) and 0–10 m (ES = 0.73) acceleration [28]. Given the earlier discussion of training history, a notable aspect of these data is the lower number of ‘recreational’ participants in the M-RSS ($n = 3$) vs. VH-RSS group ($n = 5$). Although the groups were randomised and matched for 10 m sprint time [28], recreational participants are likely to experience a greater adaptive response to training in comparison to trained participants. Even if the general improvements observed after VH-RSS compared with M-RSS may not be entirely due to the difference in sled load, this study is suggestive of training adaptations being velocity specific, i.e. heavier loads enhance the force domain of power output, whilst lighter loads enhance the velocity domain of power output [10, 11, 82]. Therefore, with regard to RSS training, VH loads may improve performance at low velocities where horizontal force output is high (i.e. acceleration phase), whilst lighter sled loads or URS training may improve performance at higher velocities, where horizontal force output is low (i.e. close to, or at maximal velocity phase). Further research is required to test these contentions, and higher level participants, longer study durations and comparisons to traditional sprint training will allow an improved external validity of results for elite athlete training programmes.

A recent study investigated the rate of force development in the early acceleration phase in strength- and sprint-trained adolescent male and female individuals [33]. The results suggest that a load of 10 %BM is too light to stimulate positive changes in peak 20 ms the rate of force development in the early acceleration phase, whilst a two-fold higher load (20 %BM) does provide the necessary overload. In comparison to 10 %BM sled loads, heavier loads increase ground contact time during RSS efforts [30, 31, 34]. This increased ground contact time may provide a longer duration for increased ground force production and therefore may help stimulate longitudinal improvements in sprint-specific force and power output [34]. Similarly, the kinetic and kinematic data collected by Kawamori et al. [28] provide an insight to the potential mechanisms of the enhanced sprint performance following VH and M-RSS training. At first ground contact, no significant changes were observed for GRF impulse variables [28]. However, increases in stride length (8.1 %) were observed in the VH-RSS group at first ground contact from pre- to post-intervention. There were no changes in stride length for the M-RSS group, or stride frequency for either RSS intervention. The GRF data do not describe the possible adaptation that the VH-RSS training provided for improvements in 0–5 m acceleration over the M-RSS group, and the data are only reported at the first ground contact and 8 m from the start. Kinetic and kinematic changes may have occurred at any point between these two markers and therefore further research is required to monitor the biomechanical changes following M- or VH-RSS training. That said, the difficulty of measuring GRF at every step of a sprint is underscored by a necessity for six relatively expensive force plates connected in series to measure the kinetics of just five foot contacts in a 0–10 m sprint [22]. Notably, the VH-RSS group decreased resultant and vertical impulses at 8 m from pre- to post training compared with the M-RSS group [28]. This finding supports observations from cross-sectional studies where superior sprint performances are associated with a mechanically more efficient application of force in the horizontal plane, rather than increases in the magnitude of resultant (i.e. total) GRF produced [20–22, 24, 25]. In this case, a decrease in vertical impulse may be evidence of an increased ratio of forces as a greater contribution of force is now directed horizontally. However, ratio of forces has yet to be determined as an accompanying marker of improved sprint performance and therefore more research is required before this concept can be confirmed.

In a second investigation of different RSS training loads, L-, M- and H-RSS training benefited at least one phase of sprint performance in recreationally active populations [56]. Notwithstanding earlier discussions of the importance of training history to training outcomes, the results support the suggested velocity-specificity outcomes from RSS training. Improvements in sprint acceleration were found in the H-RSS training group, but not L- or M-RSS cohorts. Although H-RSS training did provide significant improvements to 0–30 and 0–40 m sprint time, the transition times (10–40 m, 20–30 m and 20–40 m) would suggest that these improvements were only made in the acceleration phase of the sprint [56]. This finding implies that H-RSS loads may stimulate improvements in acceleration velocity, but not maximal velocity. L-RSS training provided a ‘large’ (ES = 1.22) improvement to 0–40 m sprint time. The study also observed a ‘moderate’ improvement in 0–10 (ES = 0.66) and 0–30 m (ES = 0.91) time following L-RSS training, but these changes did not reach significance. M-RSS provided a ‘moderate’ improvement to both 0–30 m and 0–40 m time, although only 0–40 m time was significant [56]. Recreationally active individuals are not experienced in structured sprint training programmes and therefore do not regularly practice maximal sprint efforts, so the equivocal outcomes require further investigation. Regardless of sled load, 200–410 m per week of maximal effort sprint training [56] may have provided adequate practice for technical improvements in sprint performance.

In summary, a thorough review of between-load RSS comparison is limited by a lack of studies, with no investigations using sprint- or strength-trained participants. Conclusions from field sport players would suggest that improvements in acceleration are greater following VH-RSS training in comparison to M-RSS training. However, further evidence is required before this theory can be generalised to practice. Again, this section suggests that H- and VH-RSS training is not detrimental to longitudinal sprint performance.

5 Conclusions

When considering the available research evaluating RSS training, careful consideration of the training population and training phase within which each study was completed is required. Results from individuals who are neither sprint nor strength trained should not be generalised to their well-trained counterparts without caution. Untrained individuals are more likely to experience improvements to any general sprint training stimulus, whereas the rate of improvement in sprint performance in preseason is unlikely to be recapitulated during the competitive season.

While several gaps exist in the knowledge around RSS training, several general observations can be made. There is no evidence that RSS training with loads up to 43 %BM or 30 %V_{dec} is detrimental to sprint acceleration or maximal velocity. RSS training with 'light' (L-RSS) (<10 %BM or <10 %V_{dec}) to 'very heavy' (VH-RSS) (43 %BM or 30 %V_{dec}) loads is likely to be effective in improving acceleration for individuals without prior sprint or strength training experience. However, unresisted sprint (URS) training appears to be equally effective in the improvement of acceleration and has likely greater benefits for maximal sprint velocity in this specific population. The majority of studies suggest that RSS training with M-RSS (10–20 %BM or 10–14.9 %V_{dec}) to 'very heavy' (VH-RSS) (>30 %BM or >30 %V_{dec}) loads are effective in the improvement of sprint acceleration in strength-trained and team sport athletes who are not necessarily sprint trained. However, RSS training in these examples provided no more benefit than URS training.

No study to date has compared the benefits, if any, to sprint performance between H-, VH-RSS and URS training. Moreover, future studies should look at the combination of RSS training and other forms of strength/power training such as heavy strength training, Olympic lifting, jump squats and plyometric activity as part of a periodised training plan. In practical terms, competitive athletes will not perform just one exercise, or train one physical characteristic, within a training block. Optimal training volumes in an overall training programme are therefore a function of sled load, concurrent URS training and training experience. However, as a general recommendation based on current evidence, effective sled sprint training blocks will last for ≥6 weeks and include two to three sessions per week of 5–35 m sprints, totalling 60–340 m per session.

The component of sprint performance that adapts positively to training is likely to be specific to the sled load employed for training. Preliminary evidence suggests that H- to VH-RSS training will improve the initial acceleration phase (high horizontal force output, low velocity) whilst M-RSS training will improve the maximal velocity phase (low horizontal force output, higher velocity). Therefore, strength and conditioning coaches should determine sled training load based on the training goal (acceleration or maximal velocity), and/or the individual sprint force–velocity profile of the athlete, and/or the strength/power phase of their programme. Although kinetic and kinematic adaptations differ between training studies, improvements in sprint performance should be paramount to the sports coach. Further research into the specific adaptations from sled sprint training will inform discussion about the annual periodisation of RSS training for competitive athletes.

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References

1. Delecluse C. Influence of strength training on sprint running performance: current findings and implications for training. Sports Med. 1997;24(3):147–56.
2. Spencer M, Lawrence S, Rechichi C, et al. Time–motion analysis of elite field hockey, with special reference to repeated-sprint activity. J Sports Sci. 2004;22(9):843–50.
3. Little T, Williams AG. Specificity of acceleration, maximum speed, and agility in professional soccer players. J Strength Cond Res. 2005;19(1):76–8.
4. Brechue WF, Mayhew JL, Piper FC. Characteristics of sprint performance in college football players. J Strength Cond Res. 2010;24(5):1169–78.
5. Gabbett TJ. GPS analysis of elite women's field hockey training and competition. J Strength Cond Res. 2010;24(5):1321–4.
6. Wisbey B, Montgomery PG, Pyne DB, et al. Quantifying movement demands of AFL football using GPS tracking. J Sci Med Sport. 2010;13(5):531–6.
7. Gabbett TJ, Jenkins DG, Abernethy B. Physical demands of professional rugby league training and competition using microtechnology. J Sci Med Sport. 2012;15(1):80–6.
8. Cissik JM. Means and methods of speed training, part I. Strength Cond J. 2004;26(4):24–9.
9. Seitz LB, Reyes A, Tran TT, et al. Increases in lower-body strength transfer positively to sprint performance: a systematic review with meta-analysis. Sports Med. 2014;44(12):1693–702.
10. Delecluse C, Van Coppenolle H, Willems E, et al. Influence of high-resistance and high-velocity training on sprint performance. Med Sci Sports Exerc. 1995;27(8):1203–9.
11. McBride JM, Triplett-McBride T, Davie A, et al. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. J Strength Cond Res. 2002;16(1):75–82.
12. de Villarreal ES, Requena B, Cronin JB. The effects of plyometric training on sprint performance: a meta-analysis. J Strength Cond Res. 2012;26(2):575–84.
13. Lyttle AD, Wilson GJ, Ostrowski KJ. Enhancing performance: maximal power versus combined weights and plyometrics training. J Strength Cond Res. 1996;10(3):173–9.
14. Harris GR, Stone MH, O'Bryant HS, et al. Short-term performance effects of high power, high force, or combined weight-training methods. J Strength Cond Res. 2000;14(1):14–20.
15. Kotzamanidis C, Chatzopoulos D, Michailidis C, et al. The effect of a combined high-intensity strength and speed training program

on the running and jumping ability of soccer players. J Strength Cond Res. 2005;19(2):369–75.

16. Ronnestad BR, Kvamme NH, Sunde A, et al. Short-term effects of strength and plyometric training on sprint and jump performance in professional soccer players. J Strength Cond Res. 2008;22(3):773–80.
17. Jacobson BH, Conchola EG, Glass R, et al. Longitudinal morphological and profiles for American, NCAA Division I football players. J Strength Cond Res. 2013;27(9):2347–54.
18. Young WB. Transfer of strength and power training to sports performance. Int J Sports Physiol Perform. 2006;1(2):74–83.
19. Hunter JP, Marshall RN, McNair P. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomech. 2005;21(1):31–43.
20. Morin JB, Edouard P, Samozino P. Technical ability of force application as a determinant factor of sprint performance. Med Sci Sports Exerc. 2011;43(9):1680–8.
21. Morin JB, Bourdin M, Edouard P, et al. Mechanical determinants of 100-m sprint running performance. Eur J Appl Physiol. 2012;112(11):3921–30.
22. Rabita G, Dorel S, Slawinski J, et al. Sprint mechanics in world-class athletes: a new insight into the limits of human locomotion. Scand J Med Sci Sports. 2015;. doi:10.1111/sms.12389.
23. Kugler F, Janshen L. Body position determines propulsive forces in accelerated running. J Biomech. 2010;43(2):343–8.
24. Buchheit M, Samozino P, Glynn JA, et al. Mechanical determinants of acceleration and maximal sprinting speed in highly trained young soccer players. J Sports Sci. 2014;32(20):1906–13.
25. Otsuka M, Shim JK, Kurihara T, et al. Effect of expertise on 3D force application during the starting block phase and subsequent steps in sprint running. J Appl Biomech. 2014;30(3):390–400.
26. Weyand PG, Sternlight DB, Bellizzi MJ, et al. Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J Appl Physiol. 2000;89(5):1991–9.
27. Weyand PG, Bundle MW, McGowan CP, et al. The fastest runner on artificial legs: different limbs, similar function? J Appl Physiol. 2009;107(3):903–11.
28. Kawamori N, Newton RU, Hori N, et al. Effects of weighted sled towing with heavy versus light load on sprint acceleration ability. J Strength Cond Res. 2014;28(10):2738–45.
29. Cottle CA, Carlson LA, Lawrence MA. Effects of sled towing on sprint starts. J Strength Cond Res. 2014;28(5):1241–5.
30. Cronin J, Hansen K, Kawamori N, et al. Effects of weighted vests and sled towing on sprint kinematics. Sport Biomech. 2008;7(2):160–72.
31. Kawamori N, Newton R, Nosaka K. Effects of weighted sled towing on ground reaction force during the acceleration phase of sprint running. J Sports Sci. 2014;32(12):1139–45.
32. Lockie RG, Murphy AJ, Spinks CD. Effects of resisted sled towing on sprint kinematics in field-sport athletes. J Strength Cond Res. 2003;17(4):760–7.
33. Martínez-Valencia MA, Romero-Arenas S, Elvira JL, et al. Effects of sled towing on peak force, the rate of force development and sprint performance during the acceleration phase. J Hum Kinet. 2015;46(1):139–48.
34. Maulder PS, Bradshaw EJ, Keogh JW. Kinematic alterations due to different loading schemes in early acceleration sprint performance from starting blocks. J Strength Cond Res. 2008;22(6):1992–2002.
35. Murray A, Aitchison TC, Ross G, et al. The effect of towing a range of relative resistances on sprint performance. J Sports Sci. 2005;23(9):927–35.
36. Okkonen O, Hakkinen K. Biomechanical comparison between sprint start, sled pulling, and selected squat-type exercises. J Strength Cond Res. 2013;27(10):2662–73.
37. Agar-Newman DJ, Klimstra MD. Efficacy of horizontal jumping tasks as a method for talent identification of female rugby players. J Strength Cond Res. 2015;29(3):737–43.
38. Alcaraz PE, Palao JM, Elvira JL, et al. Effects of three types of resisted sprint training devices on the kinematics of sprinting at maximum velocity. J Strength Cond Res. 2008;22(3):890–7.
39. Los Arcos A, Yanci J, Mendiguchia J, et al. Short-term training effects of vertically and horizontally oriented exercises on neuromuscular performance in professional soccer players. Int J Sports Physiol Perform. 2013;9(3):480–8.
40. Alcaraz PE, Palao JM, Elvira JL. Determining the optimal load for resisted sprint training with sled towing. J Strength Cond Res. 2009;23(2):480–5.
41. Cissik JM. Means and methods of speed training: part II. Strength Cond J. 2005;27(1):18–25.
42. Behrens MJ, Simonson SR. A comparison of the various methods used to enhance sprint speed. Strength Cond J. 2011;33(2):64–71.
43. Moher D, Liberati A, Tetzlaff J, et al. Research methods and reporting-preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Br Med J. 2009;338(7716):332.
44. Cohen J. Statistical analysis for the behavioral sciences. 2nd ed. Hillsdale: Lawrence Erlbaum Associates; 1988.
45. Thalheimer W, Cook S. How to calculate effect sizes from published research: a simplified methodology. http://work-learning.com/effect_sizes.htm. Retrieved 2 Jan 2015.
46. Luteberget LS, Raastad T, Seynnes O, Seynnes M. Effect of traditional and resisted sprint training in highly-trained, female team handball players. Int J Sports Physiol Perf. 2015;10(5):642–7. doi:10.1123/ijspp.2014-0276.
47. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. Sportscience. 2010;14:49–58.
48. Zafeiridis A, Saraslanidis P, Manou V, et al. The effects of resisted sled-pulling sprint training on acceleration and maximum speed performance. J Sports Med Phys Fitness. 2005;45(3):284–90.
49. Spinks CD, Murphy AJ, Spinks WL, et al. The effects of resisted sprint training on acceleration performance and kinematics in soccer, rugby union, and Australian football players. J Strength Cond Res. 2007;21(1):77–85.
50. Harrison AJ, Bourke G. The effect of resisted sprint training on speed and strength performance in male rugby players. J Strength Cond Res. 2009;23(1):275–83.
51. Clark KP, Stearne DJ, Walts CT, et al. The longitudinal effects of resisted sprint training using weighted sleds vs. weighted vests. J Strength Cond Res. 2010;24(12):3287–95.
52. Lockie RG, Murphy AJ, Schultz AB, et al. The effects of different speed training protocols on sprint acceleration kinematics and muscle strength and power in field sport athletes. J Strength Cond Res. 2012;26(6):1539–50.
53. Makaruk B, Sozanski H, Makaruk H, et al. The effects of resisted sprint training on speed performance in women. Hum Mov. 2013;14(2):116–22.
54. West DJ, Cunningham DJ, Bracken RM, et al. Effects of resisted sprint training on acceleration in professional rugby union players. J Strength Cond Res. 2013;27(4):1014–8.
55. Alcaraz PE, Elvira JLL, Palao JM. Kinematic, strength, and stiffness adaptations after a short- term sled towing training in athletes. Scand J Med Sci Sports. 2014;24(2):279–90.
56. Bachero-Mena B, Gonzalez-Badillo JJ. Effects of resisted sprint training on acceleration with three different loads accounting for 5, 12.5 and 20% of body mass. J Strength Cond Res. 2014;28(10):2954–60.
57. Mackala K. Optimisation of performance through kinematic analysis of the different phases of the 100 metres. New Stud Athl. 2007;22(2):7.

58. Martinez-Valencia M, Linthorne N, Alcaraz P. Effect of lower body explosive power on sprint time in a sled-towing exercise. Sci Sports. 2013;28(6):e175–8.
59. Martinez-Valencia MA, Gonzalez-Rave JM, Santos-Garcia DJ, et al. Interrelationships between different loads in resisted sprints, half-squat 1 RM and kinematic variables in trained athletes. Eur J Sport Sci. 2014;14(Suppl 1):S18–24.
60. Linthorne NP, Cooper JE. Effect of the coefficient of friction of a running surface on sprint time in a sled-towing exercise. Sports Biomech. 2013;12(2):175–85.
61. Linthorne NP. A mathematical modelling study of an athlete's sprint time when towing a weighted sled. Sports Eng. 2013;16(2): 61–70.
62. Lawrence M, Hartigan E, Tu CH. Lower limb moments differ when towing a weighted sled with different attachment points. Sports Biomech. 2013;12(2):186–94.
63. Hunter JP, Marshall RN, McNair PJ. Interaction of step length and step rate during sprint running. Med Sci Sports Exerc. 2004;36(2):261–71.
64. Hopewell S, Loudon K, Clarke MJ, et al. Publication bias in clinical trials due to statistical significance or direction of trial results. Cochrane Database Syst Rev. 2009;1(1). doi:10.1002/14651858.MR000006.pub3.
65. Caldwell BP, Peters DM. Seasonal variation in physiological fitness of a semiprofessional soccer team. J Strength Cond Res. 2009;23(5):1370–7.
66. Duthie GM. A framework for the physical development of elite rugby union players. Int J Sports Physiol Perform. 2006;1(1):2–13.
67. Cormie P, McBride JM, McCaulley GO. Power-time, force-time, and velocity-time curve analysis of the countermovement jump: impact of training. J Strength Cond Res. 2009;23(1):177–86.
68. Blazevich AJ, Jenkins DG. Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. J Sports Sci. 2002;20(12):981–90.
69. Mann R, Herman J. Kinematic analysis of Olympic sprint performance: men's 200 meters. Int J Sports Biomech. 1985;1(15):151–62.
70. Young W, McLean B, Ardagna J. Relationship between strength qualities and sprinting performance. J Sports Med Phys Fitness. 1995;35:13–9.
71. Young W. Laboratory strength assessment of athletes. New Stud Athl. 1995;10:89–96.
72. Murphy AJ, Lockie RG, Coutts AJ. Kinematic determinants of early acceleration in field sport athletes. J Sports Sci Med. 2003;2(4):144–50.
73. Debaere S, Delecluse C, Aerenhouts D, et al. From block clearance to sprint running: characteristics underlying an effective transition. J Sports Sci. 2013;31(2):137–49.
74. McBride JM, Nimphius S, Erickson TM. The acute effects of heavy-load squats and loaded countermovement jumps on sprint performance. J Strength Cond Res. 2005;19(4):893–7.
75. Yetter M, Moir GL. The acute effects of heavy back and front squats on speed during forty-meter sprint trials. J Strength Cond Res. 2008;22(1):159–65.
76. Byrne PJ, Kenny J, O'Rourke B. Acute potentiating effect of depth jumps on sprint performance. J Strength Cond Res. 2014;28(3):610–5.
77. Smith CE, Hannon JC, McGladrey B, et al. The effects of a postactivation potentiation warm-up on subsequent sprint performance. Hum Mov. 2014;15(1):36–44.
78. Whelan N, O'Regan C, Harrison AJ. Resisted sprints do not acutely enhance sprinting performance. J Strength Cond Res. 2014;28(7):1858–66.
79. Wilson JM, Duncan NM, Marin PJ, et al. Meta-analysis of postactivation potentiation and power: effects of conditioning activity, volume, gender, rest periods, and training status. J Strength Cond Res. 2013;27(3):854–9.
80. Hermassi S, Chelly MS, Tabka Z, et al. Effects of 8-week in-season upper and lower limb heavy resistance training on the peak power, throwing velocity, and sprint performance of elite male handball players. J Strength Cond Res. 2011;25(9):2424–33.
81. Kawamori N, Nosaka K, Newton RU. Relationships between ground reaction impulse and sprint acceleration performance in team sport athletes. J Strength Cond Res. 2013;27(3):568–73.
82. Jones K, Bishop P, Hunter G, et al. The effects of varying resistance-training loads on intermediate- and high-velocity-specific adaptations. J Strength Cond Res. 2001;15(3):349–56.