Variation in responses to sprint training in male youth athletes: a meta-analysis

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Abstract

The trainability of youths and the existence of periods of accelerated adaptation to training have become key subjects of debate in exercise science. The purpose of this meta-analysis was to characterise youth athletes' adaptability to sprint training across PRE-, MID-, and POST-peak height velocity (PHV) groups. Effect sizes were calculated as a measure of straight-line sprinting performance with studies qualifying based on the following criteria: (a) healthy male athletes who were engaged in organised sports; (b) groups of participants with a mean age between 10 and 18 years; (c) sprint training intervention duration between 4 and 16 weeks. Standardised mean differences showed sprint training to be moderately effective (ES = 1.01 95% confidence interval: 0.43-1.59) with adaptive responses being of large and moderate magnitude in the POST- (ES = 1.39; 0.32-2.46) and MID- (ES = 1.15; 0.40-1.9) PHV groups respectively. A negative effect size was found in the PRE group (ES = -0.18; -1.35-0.99). Youth training practitioners should prescribe sprint training modalities based on biological maturation status. Twice weekly training sessions should comprise of up to 16 sprints of around 20 m with a work to rest ratio of 1:25, or greater than 90 seconds.

Keywords: Velocity; speed; adolescent; children; sport, trainability.

INTRODUCTION

Sprinting velocity is an important factor in high performance in a variety of sports with acceleration requiring a high level of force production in order to propel the body forward [31]. This quality may be a particularly influential factor in age grade sport where youths' sprint performance increases with age [57] which, in turn, exerts a progressive impact on motor performance [33,42]. Sprinting over a short distance is a common and important event in youth sport [57] and Mendez-Villanueva *et al* [43] observed youth soccer players to reach speeds of up to 29.5 ± 1.4 ($km \cdot h^{-1}$) in matches. Additionally, straight sprints have been shown to be the most common type of movement prior to goal-scoring [3,16].

Improvements in sprinting velocity during youth occur due to growth and maturation [49]; however, training that specifically targets the physical, metabolic and neurological elements that facilitate short, impulsive movements can also be effective [18]. Sprint training programmes commonly include sprinting itself, without external resistance, typically over short distances (30 m) and combined with longer rest periods (3 mins) [27]. These programmes have been shown to enhance sprinting velocity over a commensurate distance in youth athletes [27] as they do in adults [20].

To our knowledge, there are no studies which subject male youth athletes to a sprint training stimulus whilst also controlling for biological maturity status. This means that many of the principles that determine conventional programming of youth sprint training remain unfounded. To our knowledge, just one meta-analysis [59] has specifically quantified the effect of sprint training on sprinting velocity in youth, however, just two studies were part of that review. The authors of that analysis found a favourable small averaged effect size (-0.57 ± 0.31) on sprint velocity. Recent intervention studies have shown variable results for sprint training at different stages of maturation with limited evidence suggesting that this training modality could be less effective prior to the attainment of peak height velocity (PHV) [56,71]. This could indicate the presence of a maturational threshold [40] that mediates responses to training and longitudinal research suggests this could be concurrent with the onset of PHV [52]. The current meta-analysis aims to clarify this observation by undertaking a comprehensive analysis of the effect of sprint training on sprinting velocity in young male athletes. A secondary aim is to determine whether the current literature supports the idea of specific periods of enhanced adaptation to this type of training.

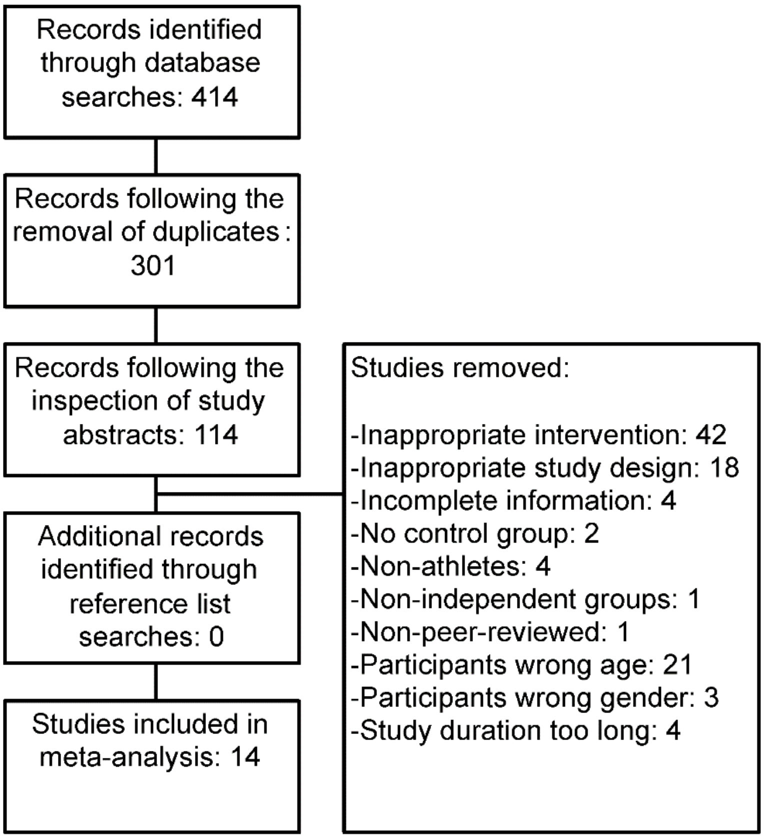
MATERIALS AND METHODS

Protocol

This review used the same methodology as a recent meta-analysis on plyometric training in male youth athletes [47] and was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [28]. The study was approved by the university's institutional review board.

Literature search

With no date restrictions, searches of the PubMed, Google Scholar, Sport Discus, Medline, CINAHL and Science Direct databases were undertaken. Words that were used as either individual search terms, or in conjunction with each other, included 'speed', 'velocity', 'agility', 'sprint', 'sprinting', 'alactic' 'acceleration', 'running', 'training', 'exercise', 'change of direction', 'paediatric', 'youth', 'children', 'adolescents', 'athletes' and 'sport'. In selecting studies for inclusion, a review of all relevant article titles within each database was conducted before an examination of article abstracts and, then, full published articles. Following the further elimination of inappropriate studies for a variety of reasons (Figure 1), a search of article reference lists was carried out. Only peer-reviewed articles were selected.



Selection of studies

The following criteria determined the eligibility of studies for inclusion in the review: healthy males, between the mean age of 10 and 18 years, who were engaged in organised sport: the male adolescent growth spurt occurs around the age of 11 years in boys [32] but can be preceded by a number of markers of sexual maturation, such as pubic hair and genitalia development around the age of 10 years [67]. By age 18 years, full adult height is usually attained [12,63]. Interventions must have been between 4 and 16 weeks in duration and must have included a control group. The protocols of included studies must have comprised sprinting movements with recovery after each effort [59] and must have focused on improving sprint performance. Studies that utilised resisted sprinting (which we considered a form of resistance training), or repeated sprint training as a mechanism to improve sprint endurance, were not considered.

It should be noted that in some studies, specific sprint training was carried out alongside other training modalities as part of a wider fitness programme. Means and standard deviations for a measure of post-intervention sprinting performance were used to calculate an effect size.

Maturity Status

The participants of included studies were subdivided into three sections based on the maturity status classifications of a recently published meta-analysis [47] on youth plyometric training which was based on that of a previous review [59]: 10-12.99 years = pre-PHV (PRE), 13-15.99 years = mid-PHV (MID) and 16-18 years = post-PHV (POST). The period we categorised as MID coincides with the 'interval of maximal growth' in males of North American/European extraction [33,36,59] and a number of longitudinal studies have estimated the PHV of this population to occur around this time [4,17,52,65]. In and around the age of 14 years is a critical period for training-related physiological development in youth [15]. The onset of the growth spurt occurs approximately one year prior to this [68] and up to 94% of full adult height is attained by age 15 [34,35]. At this time, the highest degree of diversity in biological maturity amongst boys is apparent, with these differences typically levelling off after the age of 16 years [38], a period we define as POST. The characteristics of the participants of the studies are reported in Table 1.

	All		PRE		MID		Post	
	Experimental (*n*= 166)	**Control (*n*=141)**	**Experimental (*n*=21)**	**Control (*n*=20)**	**Experimental (*n*=68)**	**Control (*n*=58)**	**Experimental (*n*=77)**	**Control (*n*=63)**
Mean age (y)	15.1 ± 2.1	15.1 ± 2.2	11.2 ± 0.3	11.2 ± 0.3	14.1 ± 0.7	13.9 ± 0.6	16.8 ± 0.7	16.9 ± 0.7
Mean height (cm)	170.4 ± 10.5	170.0 ± 10.8	151.8 ± 4.0	151.1 ± 3.0	164.8 ± 2.6	164.2 ± 2.4	179.2 ± 3.8	179.0 ± 4.8
Mean body mass (kg)	62.8 ± 11.8	63.2 ± 11.7	40.5 ± 5.0	40.5 ± 5.0	53.8 ± 3.1	54.3 ± 2.6	72.4 ± 4.8	72.7 ± 5.0

Table 1 Descriptive data for male youth athletes from sprint training studies included in meta-analysis.

Data extraction

For studies in which data were not clearly or completely reported, article authors were contacted for clarification. Where possible, 30 m sprint distance times were used to measure sprinting velocity. This was rationalised on the basis that sprinting over this distance is representative of sport specific maximal velocity [11]. Where a 30 m sprint was not carried out, sprint times for the closest measured distance were utilised instead. Table 2 shows all of the included studies.

Study Name	Age (yrs) (SD)	Maturation	Height (cm) (SD)	Weight (kg) (SD)	Sport	Group	Group Identifier in study	Number of Participants	Training frequency (per week)	Number of Weeks	Mean Total sessions	Test
Pettersen and Mathisen [51]	11.5 (0.3)	Pre	154.7 (4.6)		Soccer	Training	TG	14	1	6	6	20 m sprint (s)
Venturelli, Bishop and Pettene [71]	11 (0.5)	Pre	149 (6)	40.5 (5)	Soccer	Sprint-training	STG	7	2	12	24	20 m sprint (s)
Chaouachi et al. [7]	14.2 (0.9)	Mid	167.2 (5.7)	54.1 (6.3)	Soccer	Change of direction	CODG	12	3	6	18	30 m sprint (s)
Christou et al. [8]	13.8 (0.4)	Mid	162 (3.8)	52 (3.3)	Soccer	Strength-soccer	STR	9	2	16	32	30 m sprint (s)
Christou et al. [8]	13.5 (0.9)	Mid	163 (2.5)	54.1 (2)	Soccer	Soccer	SOC	9	2	16	32	30 m sprint (s)
de Villarreal et al. [13]	15.33 (0.34)	Mid	168.04 (7.78)	57.13 (8.34)	Soccer	Combined	CombG	13	2	9	18	10 m sprint (s)
Mathisen [39]	13.5 (0.24)	Mid	162.5 (8.1)	48.8 (10.1)	Soccer	Training	TG	14	1	8	8	20 m sprint (s)

Meckel et al. [41]	14.3 (0.5)	Mid	166.1 (8.1)	56.5 (10.9)	Soccer	Short-sprint repetition	SST	11	3	7	21	30 m sprint (s)
Alves et al. [1]	17.33 (0.71)	Post	177.67 (5.57)	70.54 (9.09)	Soccer	G1	G1	9	1	6	6	15 m sprint (s)
Alves et al. [1]	17.22 (0.44)	Post	173.5 (6.86)	69.76 (6.93)	Soccer	G2	G2	8	2	6	12	15 m sprint (s)
Buchheit et al. [5]	16 (0.8)	Post	181 (6)	71.2 (10.3)	Handball	Speed/agility	S/A	7	2	4	8	10 m sprint (s)
Gottlieb et al. [19]	16.3 (0.5)	Post	185.3 (4)	78.2 (5.9)	Basketball	Specific Sprint Training	SST	10	2	6	12	20 m sprint (s)
Kotzamanidis et al. [27]	17 (1.1)	Post	178 (35)	73.5 (1.2)	Soccer	Combined	COM	12	2	9	18	30 m sprint (s)
Shalfawi et al. [61]	16.3 (0.5)	Post	178.5 (7.3)	68.1 (9.4)	Soccer	Training	Training	8	2	8	16	40 m sprint (s)
Tonnessen et al. [69]	16.4 (0.9)	Post	176.3 (7.4)	67.2 (9.1)	Soccer	Training	TG	10	1	10	10	40 m sprint (s)
Tsimahidis et al. [70]	18 (1.2)	Post	183 (1.3)	80.9 (10.2)	Basketball	Combined training programme	CTP	13	2	10	20	30 m sprint (s)

Analysis and interpretation of results

The meta-analysis was carried out using RevMan [53] with study participants divided into PRE, MID and POST-PHV maturation groups in order to isolate a training effect with respect to an estimate of likely maturity status. The inverse-variance random effects model for meta-analyses was used because it allocates a proportionate weight to trials based on the size of their individual standard errors [14] and facilitates analysis whilst controlling for heterogeneity across studies [25]. Effect sizes are represented by the standardised mean difference and are presented alongside 95% confidence intervals. The calculated effect sizes were interpreted using the conventions outlined for standardised mean difference by Hopkins et al [24]. (<0.2 = trivial; 0.2-0.6 = small, 0.6-1.2 = moderate, 1.2-2.0 = large, 2.0-4.0 = very large, >4.0 = extremely large).

In order to assess heterogeneity amongst the included studies, the I^2 statistic was evaluated. Low, moderate and high levels of heterogeneity correspond to I^2 values of 25%, 50% and 75%, however, these thresholds are considered tentative [23].

Study quality

Funnel plots were subjectively analysed to assess publication bias which was apparent however, a risk of bias quality scale was not utilised. The Cochrane Collaboration has discouraged the use of such scales, saying that the practice is not supported by empirical evidence and assessment criteria may result in inaccurate study weights [22]. Moreover, it has also been suggested that controls such as blinding are difficult to implement in training intervention studies [47]. Previous reviews on training studies in youths have reported low study quality and a medium to high risk of bias [47] and we adopted that assumption in this review.

Subgroup analysis

In order to identify potential sources of heterogeneity, moderator variables were determined *a priori* and assessed, a summary of which can be seen in Table 3. The moderator variables were analysed with a random effects model and were selected based on differences in sport, training programme characteristics and performance testing methods. A division was made between soccer and other sports on the basis that youth athletes may be more likely to partake in activities in which they excel, meaning faster athletes may express a preference for sports that place a premium on sprinting velocity [37]. The variables of programme duration and mean total sessions were divided at their medians as it was hypothesised that longer training programmes may lead to greater performance improvements. Training frequency was subdivided into 1, 2 and 3 sessions per week as this variable may have an impact on the magnitude of adaptation to short sprint training [55]. Subgroups were also formed based on the total number of sprints per session, sprint distance and rest interval between sprints. Lastly, the distance used for performance testing was categorised as '0-20 m' (inclusive of 20 m) and '20-40 m' as shorter distances may be more sensitive to detecting accelerative potential, whilst longer distances are more effective for measuring maximal velocity [29].

Moderator	**Group**	***n***	***ES* (95%CI)**	***P***	**I^2**
Sport	Soccer	*13*	0.76 (0.43-1.59)	*0.001*	69%
	Other	*3*	4.34 (0.46-8.22)	*0.03*	
Programme duration (weeks)	>8	*7*	2.06 (0.58-3.53)	*0.006*	73.6%
	≤8	*9*	0.55 (0.24-0.87)	*<0.001*	
Total training sessions (*n*)	>17	*8*	1.69 (0.48-2.90)	*0.006*	65.5%
	<17	*8*	0.59 (0.24-0.95)	*<0.001*	
Training frequency (per week)	1	*4*	0.64 (0.07-1.21)	*0.03*	53.1%
	2	*10*	1.53 (0.51-2.54)	*0.003*	
	3	*2*	0.29 (-0.29-0.88)	*0.33*	
Total sprints per session (*n*)	>16	*5*	0.20 (-0.30-0.71)	*0.44*	67.0%
	<16	*6*	1.41 (0.15-2.68)	*0.03*	
Sprint distance (m)	≥20	*7*	0.94 (-0.07-1.95)	*0.07*	0%
	<20	*6*	0.80 (0.02-1.59)	*0.05*	
Rest interval (s)	≥90	*6*	1.13 (-0.07-2.34)	*0.07*	0%
	<90	*6*	0.58 (-0.02-1.19)	*0.06*	
Testing distance (m)	0-20	*8*	0.70 (0.14-1.26)	*0.01*	49.8%
	20-40	*8*	1.60 (0.48-2.72)	*0.005*	

Table 3 Effects of moderator variables on effect sizes

RESULTS

Following the search process, 414 studies were identified. When duplicates were removed, this was reduced to 301 with this being further reduced to 114 following the inspection of abstracts. After full studies were individually inspected for eligibility, 14 remained. These were included in the meta-analysis, being allocated to one of the three maturity classifications (PRE, MID, POST). Eleven of the studies included soccer players with the remainder being basketball (n = 2) and handball (n = 1). In terms of biological maturity, there were two studies carried out in prepubertal children, five in midpubertal and seven in postpubertal athletes.

Main effect

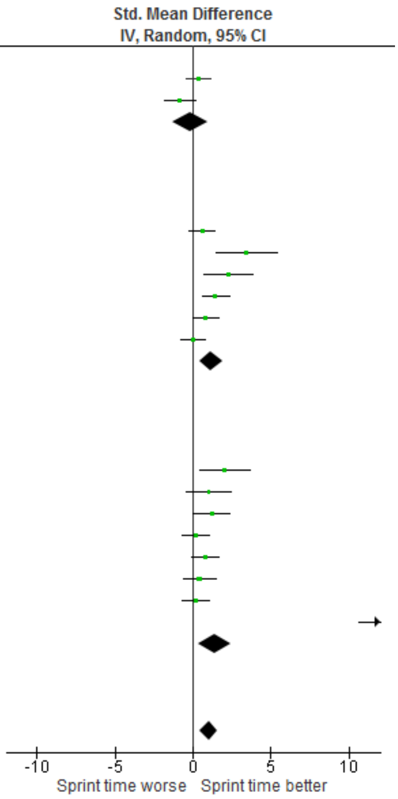
Across all groups included in the meta-analysis there was a significant improvement in sprinting velocity (ES = 1.01 [0.43-1.59], Z = 3.40 [p = 0.0007]). The overall estimate was of moderate magnitude but showed a high level of between-study heterogeneity (I^2 = 79% [p < 0.00001]).

Effects between and within maturity groups

Heterogeneity between maturity groups was moderate (I^2 = 55.5% [p = 0.11]).

In the PRE group, the effect size for change in sprinting velocity was small and non-significant (ES = -0.18 [-1.35-0.99], Z = 0.30 [p = 0.77]). The POST group showed the greatest effects for sprinting velocity. The mean estimate for POST was of large magnitude (ES = 1.39 [0.32-2.46], Z = 2.54 [p = 0.01]) but was highly heterogeneous (I^2 = 85% [p < 0.00001]). The MID group estimate was moderate (ES = 1.15 [0.40-1.90], Z = 3.01 [p = 0.003]) and was also highly heterogeneous (I^2 = 69% [p = 0.006]). Figure 2 shows forest plots with associated effect sizes.

Study or Subgroup	Control Mean	Control SD	Control Total	Experimental Mean	Experimental SD	Experimental Total	Weight	Std. Mean Difference IV, Random, 95% CI
1.1.1 PRE								
Pettersen and Mathisen	3.97	0.24	11	3.89	0.18	14	7.4%	0.37 [-0.43, 1.17]
Venturelli, Bishop and Pettene	3.56	0.13	9	3.66	0.09	7	6.8%	-0.83 [-1.87, 0.22]
Subtotal (95% CI)			**20**			**21**	**14.2%**	**-0.18 [-1.35, 0.99]**
Heterogeneity: Tau² = 0.49; Chi² = 3.20, df = 1 (P = 0.07); I² = 69%								
Test for overall effect: Z = 0.30 (P = 0.77)								
1.1.2 MID								
Chaouachi et al.	4.43	0.18	12	4.33	0.14	12	7.3%	0.60 [-0.22, 1.42]
Christou et al. (SOC)	5.22	0.1	4	4.85	0.1	9	4.3%	3.44 [1.47, 5.42]
Christou et al. (STR)	5.22	0.1	4	4.94	0.12	9	5.3%	2.27 [0.69, 3.84]
de Villarreal et al.	1.93	0.1	13	1.78	0.1	13	7.2%	1.45 [0.57, 2.33]
Mathisen	3.58	0.2	12	3.42	0.18	14	7.4%	0.82 [0.01, 1.63]
Meckel et al.	4.74	0.22	13	4.74	0.2	11	7.4%	0.00 [-0.80, 0.80]
Subtotal (95% CI)			**58**			**68**	**38.9%**	**1.15 [0.40, 1.90]**
Heterogeneity: Tau² = 0.56; Chi² = 16.16, df = 5 (P = 0.006); I² = 69%								
Test for overall effect: Z = 3.01 (P = 0.003)								
1.1.3 POST								
Alves et al. (G1)	2.56	0.02	3	2.38	0.09	9	5.1%	2.05 [0.41, 3.70]
Alves et al. (G2)	2.56	0.02	3	2.49	0.07	8	5.7%	1.02 [-0.41, 2.46]
Buchheit et al.	1.94	0.11	7	1.83	0.05	7	6.4%	1.21 [0.03, 2.38]
Gottlieb et al.	3.01	0.13	9	2.99	0.07	10	7.1%	0.19 [-0.72, 1.09]
Kotzamanidis et al.	4.31	0.16	11	4.19	0.14	12	7.3%	0.77 [-0.08, 1.63]
Shalfawi et al.	5.58	0.23	7	5.49	0.18	8	6.8%	0.41 [-0.61, 1.44]
Tonnessen et al.	5.19	0.18	10	5.15	0.2	10	7.2%	0.20 [-0.68, 1.08]
Tsimahidis et al.	5.32	0.03	13	4.97	0.01	13	1.4%	15.16 [10.62, 19.70]
Subtotal (95% CI)			**63**			**77**	**46.9%**	**1.39 [0.32, 2.46]**
Heterogeneity: Tau² = 1.84; Chi² = 45.25, df = 7 (P < 0.00001); I² = 85%								
Test for overall effect: Z = 2.54 (P = 0.01)								
Total (95% CI)			**141**			**166**	**100.0%**	**1.01 [0.43, 1.59]**
Heterogeneity: Tau² = 1.03; Chi² = 71.23, df = 15 (P < 0.00001); I² = 79%								
Test for overall effect: Z = 3.40 (P = 0.0007)								
Test for subgroup differences: Chi² = 4.49, df = 2 (P = 0.11), I² = 55.5%								



Effect of moderator variables

Subgroup analysis suggested programme duration accounted for a significant proportion of the between-group heterogeneity (I^2 = 73.6%) with longer (>8 weeks) programmes producing greatest gains in sprinting velocity (ES = 2.06 [0.58-3.53], Z = 3.40 [p = 0.006]). Sport (I^2 = 69%), total training sessions (I^2 = 65.5%), training frequency (I^2 = 53.1%), total sprints per session (I^2 = 67.0%) and sprint test distance (I^2 = 49.8%) all accounted for large proportions of between-group heterogeneity. Mean estimates remained heterogeneous in most subgroups and the level of heterogeneity was lower in subgroups with smaller effect sizes, shorter programmes, less training sessions, a greater number of sprints, shorter sprint distances, shorter rest intervals and shorter sprint test distances.

DISCUSSION

Our main moderator of interest in youth trainability was maturity status. The results of this meta-analysis showed that sprint training improves sprint performance in youths, but results were heterogeneous. Sprint training became progressively more effective with increasing maturity.

During growth and maturation, the natural development of sprint performance occurs due to greater muscular size, increased limb length, changes to musculotendinous tissue, enhanced neural and motor development and better movement quality and coordination [50]. The timing and tempo of these factors is highly variable across individuals [33] and manipulation or changing of any of the variables, through training or natural development, could result in improvements in sprinting velocity. However, given that there are so many variables that contribute to this quality, it has thus far been difficult to determine how best to structure training in youth [59].

Sprint training was found to be moderately effective in the MID phase and largely effective in the POST phase. We found no evidence for the effectiveness of sprint training in the PRE group; however with only two studies included in this part of the analysis, any conclusions drawn from these data are limited. As highlighted by McNarry *et al.* [40] in a statement by the British Association of Sport and Exercise Sciences, a review [59] found that the trainability of sprinting velocity in youths was approximately 50% lower in MID than it was in PRE and POST groups. That investigation by Rumpf *et al*. [59] examined the effects of multiple different training modalities, such as plyometric and resistance exercise, on sprinting and is opposed by the results of the current meta-analysis. This is possibly due to the multi-dimensional nature of the training methods examined, contrasting with the current study.

The pattern of trainability of sprinting velocity in this review is in line with that described in a previous investigation: Meyers *et al*. [45] found that maximal sprinting velocity seemed to develop at quicker rates during and after the growth spurt. These authors identified maturation-related increases in stride length, accentuated by improved stabilisation of stride frequency and ground contact times, as potential mediators of sprinting velocity development around PHV. Greater leg length has previously been associated with higher sprinting velocity in youth

[42] and it seems that sprinting performance during and after the growth spurt may be further enhanced by increases in strength and power [45]. Also, Philipaerts *et al*. [52], conducting a longitudinal evaluation of a number of different physical abilities in male youth soccer players, found that 30 m sprint time reached its fastest rate of development ($-0.4\ s \cdot yr^{-1}$) around PHV, before levelling off after the growth spurt. The lack of improvement in younger athletes found in the current study and the large magnitude of response of the oldest athletes support the findings of Meyers *et al*. [45] and could indicate the presence of a maturational threshold for the development of sprinting velocity around the time of PHV.

Greater levels of strength are related to faster sprinting performance in youth [10] which may explain why training was more effective with increasing age. During the growth spurt, elevated testosterone, growth hormone and IGF-1 contribute to the accumulation of fat free mass and relative reduction of body fat such that, by the age of 18 most males have obtained 90% of their total skeletal mass [54]. This results in enhanced levels of strength [44,54] and ultimately, given their dependent relationship, greater sprinting velocity [2]. This may explain why the development of sprinting velocity could be further expedited when specific sprint training is combined with strength training as has been shown previously [27]. The progressively increasing rate of muscle mass accumulation beyond the onset of the growth spurt [64] could play a role in the higher rate of sprinting velocity development in the POST phase when both training and natural development are considered. Increases in muscle cross-sectional area can enhance force output capability, which in turn can have positive effects on sprinting performance [66]. Given that both the current analysis, and the study by Meyers *et al*. [45], showed a similar trajectory of development in the POST period, this may be one of the most influential elements of sprint performance as it can also interact with factors such as fascicle length, pennation angle and tendon stiffness [45]. However, it should be noted that as youths grow, relative strength can decrease as height and bodyweight increase [73]. If this process outpaces that of maturation, a decrease in performance is possible, thus underlining the importance of continuous strength training to uphold sprint performance throughout youth [73].

A result of the current meta-analysis is that sprint training seemed to be ineffective in the PRE group and recent evidence seems to support this finding. Rumpf *et al*. [56] showed that resisted sprint training was not effective in pre-pubertal athletes in contrast to a mid/post-PHV group. The latter group adapted to training to a similar extent to that observed in adult investigations [31,72]. In maximal sprinting, Rumpf *et al*. [58] showed that stretch-shortening cycle activity showed variability across the developmental continuum with leg stiffness being 44.5% and 18.4% higher in the POST-PHV period than it was in the PRE- and MID- periods respectively. The authors highlight that the musculotendinous tissue of younger boys is more compliant than that of older boys, meaning that as a youth physically matures, he is better able to utilise the stretch-shortening cycle whilst sprinting. Also, concentric and eccentric power was greater in older participants than it was in younger participants and these factors, individually or combined, could have resulted in a lower response in younger athletes. Reinforcing the above evidence, Meylan *et al*. [46] recently demonstrated that a group of PRE athletes showed smaller improvements in sprint times than MID and POST athletes following an eight week training programme.

In youth, short-distance acceleration is achieved through a combination of increased stride length and frequency [26]. However, Meyers *et al*. [45] showed that running stride frequency decreases in the PRE stage and this could potentially reduce the effectiveness of sprint training at this stage. Accordingly, those researchers recommended that training in the pre-pubertal period should incorporate exercises to improve stride frequency, likely because younger athletes may be more dependent on that quality to generate sprinting velocity. Indeed the results of this meta-analysis could inform a long-term training strategy for sprinting performance in youth: boys who are undergoing the growth spurt, or who have already experienced it, could preferentially focus on improving strength and rate of force development in an effort to take advantage of a hormonal profile that is conducive to improving those particular qualities [45]. Similarly, younger athletes could have a preferential focus on addressing their own unique limiting factors in sprinting performance, such as stride frequency.

It is important to note that many of the above observations relate to the natural development of sprinting velocity in youth, rather than the magnitude of adaptations due to training. Nevertheless, these underlying processes of growth and maturation seem to have mediating effects on trainability levels as it is possible that biological maturation can either enhance or undermine the effectiveness of the training stimulus [47]. This means that practitioners must consider these factors when constructing developmentally-appropriate sprint training programmes.

A further factor to consider is the mean training loads of the maturity groups. As displayed in Table 4, the PRE and POST groups had largely similar training loads when measured by total distances sprinted and total sessions per programme; yet they adapted at different magnitudes. However, the POST group underwent a substantially lower volume of sprints per session at almost double the distance of the PRE group, indicating that a lower volume of sprints over a longer distance may be a more effective training protocol in youth athletes. The MID group had a substantially higher volume of training than the PRE or POST groups and this could mean that MID athletes may require a sprint training stimulus of greater duration or magnitude in order to realise the benefits of training.

	ALL	**PRE**	**MID**	**POST**
Number of sprints	16.7 ± 8.6	25.0 ± 7.1	21.9 ± 7.3	11.4 ± 6.1
Sprint distance (m)	22.7 ± 15.0	13.5 ± 2.1	30.3 ± 20.0	22.2 ± 15.0

Total load (m [sprints x distance])	418.8 ± 301.7	330.0 ± 42.4	742.6 ± 364.1	340.4 ± 290.8
Work interval (s)	4.5 ± 0.7	5.0	4.0	-
Rest interval (s)	116.2 ± 52.5	100.0 ± 35.4	88.0 ± 39.6	140.3 ± 58.6
Training frequency (per week)	1.9 ± 0.6	1.5 ± 0.7	2.2 ± 0.8	1.8 ± 0.5
Number of weeks	8.7 ± 3.5	9.0 ± 4.2	10.3 ± 4.5	7.4 ± 2.2
Total sessions	16.3 ± 8.3	15.0 ± 12.7	21.5 ± 9.2	12.8 ± 4.9

Table 4 Mean training programme characteristics in reviewed studies

Another factor to consider is the potential impact of moderators of the training effect. In meta-analysis, moderator analysis can be utilised to evaluate the impact of effect size modifiers, such as training intensity and duration, on the main effect [60]. However, difficulty in comparing the intensity of various programmes across studies, in addition to incomplete information, necessitated the examination of alternative factors. In the current analysis, the moderator variables of sport, programme duration, total training sessions, training frequency, total sprints per session and testing distance were all shown to be potential sources of moderate to high heterogeneity. As expected, larger effects were seen in programmes that lasted longer and had more training sessions per programme. Effect sizes were of greater magnitude in programmes with less than 16 sprints performed over distances greater than 20 m and with rest intervals higher than 90 seconds. Also, 2 sessions per week seemed more effective than 1 whilst distances of between 20 m and 40 m were more sensitive to measuring changes in sprinting performance following an intervention when compared to 0 m to 20 m. Three sessions per week had a lower effect size than 2 sessions per week and this could be explained by an imbalance of studies in the respective subgroups or a suboptimal response to progressively higher training volumes: higher volumes of training are not necessarily more beneficial [6]. The presence of high heterogeneity after subgroup analysis suggests that moderators of the main effect may not have been found, meaning other factors could account for training adaptations. This would seem to imply a potential synergy between programming variables and other factors, such as biological maturity, in determining the magnitude of response to sprint training in youth athletes. Predominantly lower variation between maturity groups when compared to moderator variables was an expected outcome as a result of the highly variable nature of training programmes across studies. Heterogeneity within maturity groups could also be evidence of differing mechanisms of physiological adaptation to training. This may be particularly applicable in cases in which the effect size of maturity groups was similar despite a large degree of heterogeneity, as can be observed in the MID and POST groups.

This study does have some limitations. The categories used to account for biological maturity [47] are based on chronological age and can account for only some of the developmental diversity that is seen across groups. Examination of the I^2 statistics revealed high levels of heterogeneity between studies, indicating a level of inconsistency amongst results which can negatively impact the confidence of study recommendations [23]. However, heterogeneity is likely always present in meta-analyses [14]. The relatively small body of data relating to sprint training in youth means that more research is required to make more definitive conclusions based on maturation status. However, this is potentially offset by the finding that, based on current literature, sprint training does generally increase performance in youth athletes. Researchers should therefore use this review as a basis for formulating future training interventions.

Based on the available literature, it seems that training sessions to improve sprinting velocity should comprise of up to 16 sprints of around 20 m with a work to rest ratio of 1:25, or greater than 90 seconds. Two sessions per week would seem to be adequate in enhancing sprinting performance over an 8 week period. However, these parameters may need to be varied based on the maturity status of the athlete, with sprint training across all ages occurring alongside exercises that address the effects of performance limiters or leverage the positive changes associated with maturation.

As sprint trainability may vary as youth athletes grow, a concentrated approach to offsetting negative confounding factors during times of lower trainability, prior to PHV, could be used. Following this, practitioners could directly target key times of heightened response to increase the efficiency of training, focusing efforts on improving strength and sprinting performance during and after PHV. During the PRE stage of development, coaches should directly address the factors that could result in reduced adaptive responses, focusing training on activities that improve fundamental movements such as running, skipping, jumping and balancing [30]. This can be combined with training that enhances stride frequency [45] such as assisted or downhill sprinting. However, the suitability of this training method for athletes who are not advanced has been questioned [62]. Additionally, fast leg drills (at intervals or on command) to facilitate faster limb motion than would be typically possible during standard sprinting could be combined with bounding movements [9]. This can form the basis to advance onto more complex tasks as the youth develops skill and dexterity [30]. Training that targets concentric strength may underpin sprint performance over shorter distances, whilst stretch-shortening activities may have more influence as distance increases [21]. As the athlete advances, such work could be transitioned into more specialised squat and weightlifting variations, higher intensity plyometric exercises [48] and resisted sprint training [56]. In this way, a multi-modal approach across all youths seems best with sprint training occurring alongside complimentary exercises in order to support the development of sprinting velocity throughout growth and maturation.

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