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Effects and dose–response relationships of resistance training on physical performance in youth athletes: a systematic review and meta-analysis

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ABSTRACT

Objectives To quantify age, sex, sport and training type-specific effects of resistance training on physical performance, and to characterise dose–response relationships of resistance training parameters that could maximise gains in physical performance in youth athletes.

Design Systematic review and meta-analysis of intervention studies.

Data sources Studies were identified by systematic literature search in the databases PubMed and Web of Science (1985–2015). Weighted mean standardised mean differences (SMD_{wm}) were calculated using random-effects models.

Eligibility criteria for selecting studies Only studies with an active control group were included if these investigated the effects of resistance training in youth athletes (6–18 years) and tested at least one physical performance measure.

Results 43 studies met the inclusion criteria. Our analyses revealed moderate effects of resistance training on muscle strength and vertical jump performance (SMD_{wm} 0.8–1.09), and small effects on linear sprint, agility and sport-specific performance (SMD_{wm} 0.58–0.75). Effects were moderated by sex and resistance training type. Independently computed dose–response relationships for resistance training parameters revealed that a training period of >23 weeks, 5 sets/exercise, 6–8 repetitions/set, a training intensity of 80–89% of 1 repetition maximum (RM), and 3–4 min rest between sets were most effective to improve muscle strength (SMD_{wm} 2.09–3.40).

Summary/conclusions Resistance training is an effective method to enhance muscle strength and jump performance in youth athletes, moderated by sex and resistance training type. Dose–response relationships for key training parameters indicate that youth coaches should primarily implement resistance training programmes with fewer repetitions and higher intensities to improve physical performance measures of youth athletes.

physical conditions and injury risks compared with their non-athlete peers; so the generalisability of previous research on youth athletes is uncertain.^{8–10}

To the best of our knowledge, there is only one meta-analysis available that examined the effects of RT on one specific proxy of physical performance (ie, jump performance) and in one age group (ie, youth aged 13–18 years).¹¹ It is reasonable to hypothesise that factors such as age, sex and sport may influence the effects of RT. Therefore, a systematic review with meta-analysis is needed to aggregate findings from the literature in terms of age, sex and sport-specific effects of RT on additional physical performance measures (eg, muscle strength, linear sprint performance, agility, sport-specific performance) in youth athletes.

There is also little evidence-based information available regarding how to appropriately prescribe exercise to optimise training effects and avoid over-prescription or underprescription of RT in youth athletes.¹² The available guidelines for RT prescription are primarily based on expert opinion, and usually transfer study findings from the general population (ie, healthy untrained children and adolescents) to youth athletes. This is important because the optimal dose to elicit a desired effect is likely to be different for trained and untrained youth.¹³

Therefore, the objectives of this systematic literature review and meta-analysis were (1) to analyse the effectiveness of RT on proxies of physical performance in youth athletes by considering potential moderator variables, including age, sex, sport and the type of RT, and (2) to characterise dose–response relationships of RT parameters (eg, training period, training frequency) by quantitative analyses of intervention studies in youth athletes. We hypothesised that (1) RT would have a positive effect on proxies of physical performance in youth athletes, and (2) the effects would be moderated by age, sex, sport and RT type.

METHODS

Our meta-analysis was conducted in accordance with the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).¹⁴

Literature search

We performed a computerised systematic literature search in the databases PubMed and Web of Science.

The following Boolean search syntax was used: ('strength training' OR 'resistance training' OR



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INTRODUCTION

Resistance training (RT) is a safe and effective way to improve proxies of physical performance in healthy children and adolescents when appropriately prescribed and supervised.^{1–4} Several meta-analyses have shown that RT has the potential to improve muscle strength and motor skills (eg, jump performance) in children and adolescents.^{1 5–7} However, youth athletes have different training capacities, adherence, physical demands of activities,



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'weight training' OR 'power training' OR 'plyometric training' OR 'complex training' OR 'weight-bearing exercise') AND (athlete OR elite OR trained OR sport) AND (children OR adolescent OR youth OR puberty OR kids OR teens OR girls OR boys). The search was limited to: full-text availability, publication dates: 01/01/1975 to 07/31/2015, ages: 6–13; 13–18 years, and languages: English, German. The reference list of each included study and relevant review article^{1 4–6 11 15–19} was screened for title to identify any additional suitable studies for inclusion in our review.

Selection criteria

Based on the defined inclusion and exclusion criteria (table 1), two independent reviewers (ML and OP) screened potentially relevant articles by analysing titles, abstracts and full texts of the respective articles to elucidate their eligibility. In case ML and OP did not reach an agreement concerning inclusion of an article, UG was contacted.

Coding of studies

Each study was coded for certain variables listed in table 2. Our analyses focused on different outcome categories. If studies reported multiple variables within one of these outcome categories, only one representative outcome variable was included in the analyses. The variable with the highest priority for each outcome is mentioned in table 2.

If a study solely used other tests, we included those tests in our quantitative analyses that were most similar with regard to the ones described above in terms of their temporal/ spatial structure.

Further, we coded RT according to the following training parameters: training period, training frequency, and training volume (ie, number of sets per exercise, number of repetitions per set), training intensity, temporal distribution of muscle action modes per repetition, and rest (ie, rest between sets and repetitions). Training parameters were categorised according to

Table 2 Study coding

Sex	► Male youth athletes ► Female youth athletes
Chronological age	► Children (boys: ≤13 years; girls: ≤11 years) ► Adolescence (boys:14–18 years; girls: 12–18 years) ¹⁸
Biological age	► Prepubertal (tanner stage: I–II) ► Postpubertal/pubertal (tanner stage: III–V)
Sport	► Team sports (eg, soccer) ► Martial arts (eg, judo) ► Strength-dominated sport (eg, weight-lifting) ► Technical/acrobatic sports (eg, gymnastics)
Type of resistance training	► Machine based ► Free weights ► Combined machine based and free weights ► Functional training ► Complex training ► Plyometric training
Outcome categories	► Muscle strength (preferred one repetition maximum) ► Vertical jump performance (preferred countermovement jump) ► Linear sprint performance (preferred 20 m sprint) ► Agility (preferred t-agility-test) ► Sport-specific performance (preferred throwing, hitting and/or kicking velocities)

common classifications of RT protocols.²¹ If a study reported exercise progression over the training period, the mean number of sets per exercise, repetitions per sets, rest between sets and training intensity were computed.

To obtain sufficient statistical power to calculate dose–response relationships, we summarised RT types as conventional RT (ie, machine based, free weights, combined machine based and free weights, functional training) and plyometric training (ie, jumping). As it is not possible to classify complex training as either conventional RT nor plyometric training,²² we excluded these studies^{23–27} from dose–response analyses. Our dose–response analyses were computed independent of age, sex and sport.

Assessment of risk of bias

The Physiotherapy Evidence Database (PEDro) scale was used to quantify the risk of bias in eligible studies and to provide information on the general methodological quality of studies. The PEDro scale rates internal study validity and the presence of statistical replicable information on a scale from 0 (high risk of bias) to 10 (low risk of bias) with ≥6 representing a cut-off score for studies with low risk of bias.²⁸

Statistical analyses

To determine the effectiveness of RT on proxies of physical performance and to establish dose–response relationships of RT in youth athletes, we computed between-subject standardised mean differences (SMD)=(mean postvalue intervention group–mean postvalue control group)/pooled standard deviation). We adjusted the SMD for the respective sample size by using the term $(1-(3/(4N-9)))$.²⁹ Our meta-analysis on categoric variables was computed using Review Manager V5.3.4 (Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2008). Included studies were weighted according to the magnitude of the respective SE using a random-effects model.

At least two RT intervention groups had to be included to calculate weighted mean SMDs, hereafter referred to as SMD_{wm}, for each performance category.³⁰ We used Review Manager for subgroup analyses: computing a weight for each

Table 1 Selection criteria

Category	Inclusion criteria	Exclusion criteria
Population	Healthy young athletes (mean age of 6–18 years)	Children/adolescents without an athletic background (ie, organised athletic training)
Intervention	Resistance training (RT; specific conditioning method, which involves the use of a wide range of resistive loads and a variety of training types designed to enhance proxies of health, fitness and sports performance)	Fewer than 6 RT sessions
Comparator	Active control (ie, age-matched; conducting the same regular training as the intervention group) in order to avoid bias due to growth and maturation-related performance enhancements ¹⁶	Only a passive control (ie, no regular training) and/or an alternative training group as control only (eg, stable vs unstable RT)
Outcome	At least one measure of muscle strength, vertical jump performance, linear sprint performance, agility and/or sport-specific performance	Effects of nutritional supplements; report no means and SDs/SE for the intervention and control groups post test in the results and did not reply to our inquiries sent by email
Study design	Controlled study	No controlled study

subgroup, aggregating SMD_{wm} values of specific subgroups, comparing subgroup effect sizes with respect to differences in intervention effects across subgroups.³¹ To improve readability, we reported positive SMDs if superiority of RT compared with active control was found. Heterogeneity was assessed using I^2 and χ^2 statistics.

Owing to a low number of studies in each physical performance outcome category that completely reported information on the applied RT parameters, metaregression was precluded.³⁰ According to a scale for determining the magnitude of effect sizes in strength training research for individuals who have been consistently training for 1–5 years,³² we interpreted SMD_{wm} as: trivial (<0.35); small (0.35 – 0.79); moderate (0.80 – 1.50); large (≥ 1.50). The level of significance was set at $p < 0.05$.

RESULTS

Study characteristics

A total of 576 potentially relevant studies were identified in the electronic database search (figure 1). Finally, 43 studies remained for the quantitative analyses. A total of 1558 youth athletes participated, and of these, 891 received RT in 62 RT intervention groups. The sample size of the RT intervention groups ranged from 5 to 54 participants (table 3).

There were 13 studies (21 RT intervention groups) that included children, and 29 studies (36 RT intervention groups) that included adolescents. In terms of biological maturation, only 15 studies reported Tanner stages. Three (5 RT intervention groups) of those studies examined prepubertal and 12 (15 RT intervention groups) postpubertal/pubertal youth athletes. Thirty studies (44 RT intervention groups) included boys only, whereas 4 studies (4 RT intervention groups) included girls only.

Youth athletes were recruited from team sports (soccer (20 studies; 34 RT intervention groups), basketball (9 studies; 11 RT intervention groups), baseball (3 studies; 5 RT intervention groups), handball (3 studies; 3 RT intervention groups), tennis (2 studies; 3 RT intervention groups), volleyball (1 study; 1 RT intervention group)), and strength-dominated sports (swimming (3 studies; 3 RT intervention groups), track and field (1 study; 1 RT intervention group)). No included study investigated youth athletes recruited from martial arts or technical/acrobatic sports.

Regarding the type of RT, 4 studies performed RT using machines, 4 studies using free weights, 4 studies using both machines and free weights, 5 studies performed functional RT, 5 studies performed complex training, and 19 studies applied plyometric training. Classification of studies was not always feasible due to missing information or group heterogeneity.

The RT interventions lasted between 4 and 80 weeks, with training frequencies ranging from 1 to 3 sessions per week, 1–8 sets per exercise, 4–15 repetitions per set, and 20–220 s of rest between sets. Training intensity ranged from 35% to 88% of the 1 repetition maximum (RM). Training parameters (eg, temporal distribution of muscle action modes per repetition, and rest in-between repetitions) which have gained attention in the literature⁷¹ were not quantified due to insufficient data.

A median PEDro score of 4 (95% CI 4 to 5) was detected and only 4 out of 43 studies reached the predetermined cut-off value of ≥ 6 , which can be interpreted as an overall high risk of bias of the included studies (table 3).

Effectiveness of RT

Table 4 shows the overall as well as age, sex, sport and training type-specific effects of RT on measures of muscle strength,

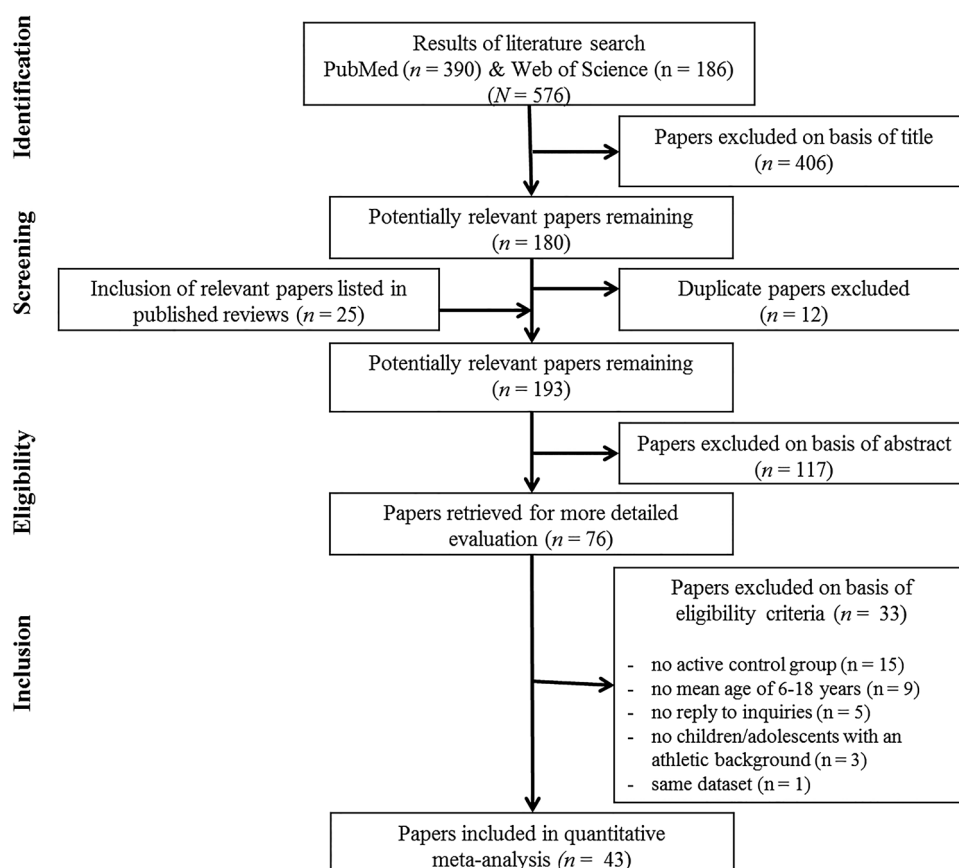


Figure 1 Flow chart illustrating the different phases of the search and study selection.

Table 3 Included studies examining the effects of resistance training in youth athletes

Author, year	N Exp	N Con	Biological age	Chronological age	Sex	Sport	RT exercise	TP	TF	TI	Sets	Reps	Rest	PEDro
Alves 2010 ^{27*}	EG I: 9 EG II: 8	6	NA	17.4±0.6	M	Soccer	EG I (1/week): CT (eg, squats and skippings; leg extension and jumps) EG II (2/week): CT (eg, squats and skippings; leg extension and jumps)	6	1	85	1	6	NA	4
Athanasίου 2004 ³³	10	10	NA	13–15	M	Basketball	MB and FW (eg, incline press, leg extension, leg curl)	8	2	NA	3	14	NA	2
Behringer 2013 ³⁴	EG I: 13 EG II: 10	10	(post-)pubertal	EG I: 15.1±1.8; EG II: 15.5±0.9; CG: 14.6±1.8	M	Tennis	EG I: MB (eg, low pulley, dead lift, leg press, lateral pull down) EG II: PT (lower and upper body: eg, skipping, lateral barrier hop, push-ups)	8	2	75	2	15	60	5
Bishop 2009 ³⁵	11	11	NA	EG: 13.1±1.4; CG: 12.6±1.9	ND	Swimming	PT (lower body: eg, hurdle jumps, DJ, jump to box)	8	2	NA	3	5	60–90	6
Brown 1986 ³⁶	13	13	NA	15.0±0.7	M	Basketball	PT (lower body: DJ (dropping height: 45 cm)	12	3	NA	3	10	30–45	4
Cavaco 2014 ^{23*}	EG I: 5 EG II: 5	6	NA	EG I: 13.8±0.5 EG II: 14.2±0.5 CG: 14.2±0.8	M	Soccer	EG I (1/ week): CT (eg, squats and linear/non-linear sprints) EG II (2/week): CT (eg, squats and linear/non-linear sprints)	6	1	85	3	6	180	5
Chelly 2009 ³⁷	11	11	NA	EG: 17±0.3; CG: 17±0.5	M	Soccer	FW (squats)	8	2	80	4	4	NA	4
Chelly 2014 ³⁸	12	11	NA	17.4±0.5	M	Handball	PT (upper and lower body: eg, hurdle jumps, DJ, push-ups)	8	2	NA	4	10	NA	6
Chelly 2015 ³⁹	14	13	Prepubertal	11.9±1.0	M	Track and field	PT (lower body: ie, hurdle jumps, DJ)	10	3	NA	5	10	NA	5
Christou 2006 ⁴⁰	9	9	(post-)pubertal	EG: 13.8±0.4; CG:13.5±0.9	M	Soccer	MB and FW (eg, leg press, bench press, leg extension, pec-dec)	16	2	68	3	12	150	4
DeRenne 1996 ⁴¹	EG I: 7 EG II: 8	6	NA	13.3±1.3	M	Baseball	EG I (1/week): MB and FW (eg, bench press, leg extension, leg curl) EG II (2/week): MB and FW (eg, bench press, leg extension, leg curl)	12	1	88	1	10	NA	3
Escamilla 2010 ⁴²	17	17	NA	12.9±1.7; CG: 12.5±1.5	M	Baseball	FT (upper body; elastic tubes)	4	2	NA	1	23	NA	4
Fernandez-Fernandez 2013 ⁴³	15	15	NA	EG: 13.2±1.6; CG: 13.2±0.5	M	Tennis	FT (core training; own body weight)	6	3	NA	2	17	58	5
Ferrete 2014 ^{24*}	11	13	NA	EG: 9.3±0.3 CG: 8.3±0.3	M	Soccer	CT (eg, squats and CMJ)	26	2	NA	3	7	NA	6
Gorostiaga 1999 ⁴⁴	9	9	(post-)pubertal	EG: 15.1±0.7; CG: 15.1±0.5	M	Handball	MB (eg, leg press, leg curl, bench press)	6	2	65	4	8	90	4
Gorostiaga 2004 ⁴⁵	8	11	NA	EG: 17.3±0.5; CG: 17.2±0.7	M	Soccer	FW (eg, squats, power clean) and PT (eg, hurdle jumps, box jumps)	11	2	NA	3	4	120	5
Granacher 2011 ⁴⁶	14	14	(post-)pubertal	EG: 16.7±0.6; CG: 16.8±0.7	M and F	eg, soccer	MB (eg, squats, leg press, calf raise)	8	2	35	5	10	150	6
Hetzler 1997 ⁴⁷	EG I: 10 EG II: 10	10	(post-)pubertal	EG I: 13.2±0.9; EG II: 13.8±0.6; CG: 13.9±1.1	M	Baseball	EG I (novice): MB and FW (eg, bench press, leg curl, leg press, biceps curls) EG II (experienced): MB and FW (eg, bench press, leg press, biceps curls)	12	3	56	3	10	180	4
Keiner 2014 ⁴⁸	EG I: 14 EG II: 30 EG III: 18	CG I: 12 CG II: 21 CG III: 17	NA	EG and CG I: U17 EG and CG II: U15 EG and CG III: U13	NA	Soccer	EG I: FW (eg, squats, bench press) (U17) EG II: FW (eg, squats, bench press) (U15) EG III: FW (eg, squats, bench press) (U13)	80 80 80	2 2 2	83 83 83	5 5 5	7 7 7	220 220 220	3

Continued

Table 3 Continued

Author, year	N Exp	N Con	Biological age	Chronological age	Sex	Sport	RT exercise	TP	TF	TI	Sets	Reps	Rest	PEDro
Klusemann 2012 ⁴⁹	EG I: 13 EG II: 11	12	NA	M: 14±1; F: 15±1	M and F	Basketball	EG I: FT (body weight RT; supervised) EG II: FT (body weight RT; video-based)	6	2	NA	NA	NA	NA	2
Kotzamanidis 2005 ⁵⁰	11	11	NA	EG: 17.1±1.1; CG: 17.8±0.3	M	Soccer	NA (conventional RT)	13	3	87	4	NA	180	3
Martel 2005 ⁵¹	10	9	NA	15±1	F	Volleyball	PT (lower body: eg, power skips, single leg bounding; aquatic)	6	2	NA	4	NA	30	5
Mataulij 2001 ⁵²	EG I: 11 EG II: 11	11	NA	15–16	M	Basketball	EG I: PT (lower body: DJ; dropping height: 50 cm) EG II: PT (lower body: DJ; dropping height: 100 cm)	6	3	NA	3	10	30	4
Meylan 2009 ⁵³	14	11	NA	EG: 13.3±0.6; CG: 13.1±0.6	M	Soccer	PT (lower body: eg, hurdle jumps, lateral bounding, skipping)	8	2	NA	3	9	90	4
Potdevin 2011 ⁵⁴	12	11	(post-) pubertal	EG: 14.3±0.2; CG: 14.1±0.2	M and F	Swimming	PT (lower body: eg, DJ, hurdle jumps)	6	2	NA	3	10	NA	5
Ramirez-Campillo 2014a ⁵⁵	EG I: 10 EG II: 10 EG III: 10	10	NA	EG I: 11.6±1.4; EG II: 11.4±1.9; EG III: 11.2±2.3; CG: 11.4±2.4	M	Soccer	EG I: PT (lower body; vertical PT) EG II: PT (lower body; horizontal PT) EG III: PT (lower body; combined vertical and horizontal PT)	6	2	NA	3	8	60	5
Ramirez-Campillo 2014b ⁵⁶	EG I: 8 EG II: 8	8	NA	13.0±2.3	M	Soccer	EG I: PT (lower body: vertical and horizontal jumps) EG II: PT (lower body: vertical and horizontal jumps; progressive PT)	6	2	NA	2	5	60	5
Ramirez-Campillo 2014c ⁵⁷	38	38	(post-) pubertal	13.2±1.8	M	Soccer	PT (lower body: DJ)	7	NA	NA	2	10	90	5
Ramirez-Campillo 2014d ⁵⁸	EG I: 13 EG II: 13 EG III: 11	14	Prepubertal	10.4±2.3	M	Soccer	EG I: PT (lower body: DJ; 30 s interest rest) EG II: PT (lower body: DJ; 60 s interest rest) EG III: PT (lower body: DJ; 90 s interest rest)	7	2	NA	2	10	30	5
Ramirez-Campillo 2015a ⁵⁹	EG I: 54 EG II: 48	55	(post-) pubertal	EG I: 14.2±2.2; EG II: 14.1±2.2; CG: 14.0±2.3	M	Soccer	EG I: PT (lower body: vertical and horizontal jumps; 24 h recovery between sessions) EG II: PT (lower body: vertical and horizontal jumps; 48 h recovery between sessions)	6	2	NA	2	8	120	5
Ramirez-Campillo 2015b ⁶⁰	EG I: 12 EG II: 16 EG III: 12	14	NA	11.4±2.2	M	Soccer	EG I: PT (lower body: bipedal jumps) EG II: PT (lower body: monopodal jumps) EG III: PT (lower body: monopodal and bipedal jumps)	6	2	NA	6	8	NA	5
Rubley 2011 ⁶¹	10	6	NA	13.4±0.5	F	Soccer	PT (lower body: eg, hurdle jumps, DJ)	14	1	NA	2	10	NA	4
Saeterbakken 2011 ⁶²	14	10	NA	EG: 16.6±0.3	F	Handball	FT (sling-training)	6	2	87	4	5	90	4
Sander 2013 ⁶³	EG I: 13 EG II: 30 EG III: 18	CG I: 15 CG II: 25 CG III: 33	NA	EG and CG I: U17 EG and CG II: U15 EG and CG III: U13	NA	Soccer	EG I: FW (eg, squats, bench press) (U17) EG II: FW (eg, squats, bench press) (U15) EG III: FW (eg, squats, bench press) (U13)	80	2	83	5	7	220	2
Santos 2008 ²⁶	15	10	(post-) pubertal	EG: 14.7±0.5 CG: 14.2±0.4	M	Basketball	CT (eg, pull over, decline press, depth jump, cone hops)	16	2	70	3	11	150	4
Santos 2011 ⁶⁴	14	10	(post-) pubertal	EG: 15.0±0.5; CG: 14.5±0.4	M	Basketball	PT (lower and upper body: eg, hurdle jumps, box jumps)	10	2	NA	3	10	120	5
Santos 2012 ⁶⁵	15	10	(post-) pubertal	EG: 14.5±0.6; CG: 14.2±0.4	M	Basketball	MB (eg, leg press, lat pull down, leg extension, pullover)	10	2	75	3	11	NA	3
Siegler 2003 ^{66†}	17	17	NA	16.5±0.9; CG: 16.3±1.4	F	Soccer	FW (eg, squat, leg extensions, calf raises, leg curls) + PT (eg, box jumps, bouncing, skipping)	10	2	NA	3	NA	NA	3
Söhnlein 2014 ⁶⁷	12	10	NA		NA	Soccer	PT (lower body: vertical, horizontal and lateral jumps)	16	2	NA	3	11	NA	2

Continued

Table 3 Continued

Author, year	N Exp	N Con	Biological age	Chronological age	Sex	Sport	RT exercise	TP	TF	TI	Sets	Reps	Rest	PEDro
Tsimachidis 2010 ^{25*}	13	13	(post-) pubertal	EG: 13.0±0.9; CG: 12.3±0.8	NA	Basketball	CT (eg, squats and sprints)	10	2	84	5	7	3	5
				EG: 18.0±1.2; CG:18.0±0.7										
Weston 2015 ⁶⁸	10	10	NA	EG: 15.7±1.2; CG: 16.7±0.9	M and F	Swimming	FT (core training: bridge, straight-leg raise; own body weight)	12	3	NA	3	NA	60	2
Wong 2010 ⁶⁹	28	23	NA	EG: 13.5±0.7; CG: 13.2±0.6	M	Soccer	FW (eg, forward lunge, back half squat, biceps curls)	12	2	NA	3	9	85	2
Zribi 2014 ⁷⁰	25	26	prepubertal	EG: 12.1±0.6; CG: 12.2±0.4	M	Basketball	PT (lower body: DJ, hurdle jumps)	9	2	NA	8	5	180	4

*Complex training study, reported training parameters referring only to strength-based exercises.

†Separate training of free weights RT and plyometric training.

CG, control group; CML, counter movement jump; CT, complex training; DJ, drop jump; EG, experimental group; F, female; FT, functional training; FW, free weights; M, male; MB, machine based; N Con, number of participants in the control group; N Exp, number of participants in the experimental group; NA, not applicable; PT, plyometric training; Reps, number of repetition per set; Rest, time of rest between sets (seconds); RT, resistance training; Sets, number of sets per exercise; TI, training frequency (times per week); TP, training intensity (% of 1 repetition maximum); TP, training periods (weeks).

vertical jump and linear sprint performance, agility and sport-specific performance.

There were moderate effects of RT on measures of muscle strength ($SMD_{wm}=1.09$; $I^2=81\%$; $\chi^2=114.24$; $df=22$; $p<0.001$; figure 2) and vertical jump performance ($SMD_{wm}=0.80$; $I^2=67\%$; $\chi^2=137.47$; $df=46$; $p<0.001$; figure 3), while there were small effects for linear sprint performance ($SMD_{wm}=0.58$; $I^2=41\%$; $\chi^2=55.74$; $df=33$; $p<0.01$; figure 4), agility ($SMD_{wm}=0.68$; $I^2=50\%$; $\chi^2=48.19$; $df=24$; $p<0.01$; figure 5) and sport-specific performance ($SMD_{wm}=0.75$; $I^2=62\%$; $\chi^2=67.81$; $df=26$; $p<0.001$; figure 6). By considering only the four studies with high quality (ie, low risk of bias), RT had moderate effects on measures of muscle strength ($SMD=1.07$; 1 study), vertical jump ($SMD_{wm}=0.89$; 3 studies) and linear sprint performance ($SMD_{wm}=1.19$; 2 studies); small effects on agility ($SMD=0.28$; 1 study); and large effects on sport-specific performance ($SMD_{wm}=1.73$; 2 studies).

There was no statistically significant effect of chronological and/or biological age on any proxy of physical performance. However, a tendency ($p=0.05$) towards larger RT effects were found for proxies of sport-specific performance in adolescents ($SMD_{wm}=1.03$) compared with children ($SMD_{wm}=0.50$; table 4). Subgroup analyses indicated that RT produced significantly larger effects ($p<0.05$) on proxies of sport-specific performance in girls ($SMD_{wm}=1.81$) compared with boys ($SMD_{wm}=0.72$; table 4). Given that most included studies ($n=38$) examined participants competing in team sports, our subgroup analyses regarding the moderator variable 'sport' is limited and did not show any significant subgroup differences (table 4). Subgroup analyses demonstrated that different training types of RT produced significantly different gains in muscle strength ($p<0.001$), agility ($p<0.05$) and sport-specific performance ($p<0.05$). Free weight RT showed the largest effects on muscle strength and agility, while for sport-specific performance, complex training produced the largest effects (table 4).

Dose-response relationships of RT

Training period

There was a significant difference for the effects of conventional RT on measures of muscle strength ($p<0.001$), vertical jump height ($p<0.05$) and agility ($p<0.001$; figure 7). The dose-response curves indicated that long lasting conventional RT (>23 training weeks) resulted in more pronounced improvements in measures of muscle strength ($SMD_{wm}=3.40$) and agility ($SMD_{wm}=1.31$), as compared with shorter training periods (<23 weeks). In terms of vertical jump height, a training period of 9–12 weeks appeared to be the most effective ($SMD_{wm}=1.20$).

Training frequency

There were no significant differences between the observed training frequencies (ie, 1, 2, 3 times per week) for RT as well as plyometric training (figure 8).

Training intensity

There was a significant difference with regard to the effects of conventional RT on measures of muscle strength ($p<0.01$; figure 9). High-intensity conventional RT (ie, 80–89% of 1 RM) resulted in more pronounced improvements in muscle strength ($SMD_{wm}=2.52$) compared with lower training intensities (ie, 30–39%, 40–49%, 50–59%, 60–69%, 70–79% of the 1 RM).

Table 4 Overall as well as age, sex, sport and training type-specific effects of resistance training in youth athletes

	Muscle strength			Vertical jump performance			Linear sprint performance			Agility			Sport-specific performance		
	SMD _{wm}	S (I)	N	SMD _{wm}	S (I)	N	SMD _{wm}	S (I)	N	SMD _{wm}	S (I)	N	SMD _{wm}	S (I)	N
All	1.09	16 (23)	278	0.80	33 (47)	702	0.58	22 (34)	527	0.68	14 (25)	410	0.75	20 (27)	345
Maturity	p=NA			p=0.60			p=0.58			p=0.99			p=0.17		
Prepubertal (Tanner Stage I and II)	oEG			0.91	3 (5)	76	0.65	3 (5)	76	0.58	1 (3)	37	0.27	1 (3)	37
(Post-) pubertal (tanner stage III–V)	0.61	6 (8)	90	1.15	11 (13)	261	0.51	4 (6)	169	0.57	3 (4)	149	0.72	8 (9)	135
Chronological age	p=0.43			p=0.74			p=0.92			p=0.39			p=0.05		
Children (boys ≤13 years, girls ≤11 years)	1.35	3 (4)	39	0.78	10 (17)	235	0.55	9 (14)	195	0.52	6 (11)	146	0.50	6 (11)	153
Adolescence (boys 14–18 years, girls 12–18 years)	0.91	13 (17)	211	0.85	22 (28)	439	0.57	13 (18)	302	0.71	7 (12)	234	1.03	13 (15)	181
Sex	p=0.92			p=0.54			p=NA			p=NA			p=0.04		
Boys	1.21	12 (18)	220	0.85	27 (40)	615	0.63	19 (30)	474	0.74	12 (22)	374	0.72	15 (22)	288
Girls	oEG			0.61	3 (3)	37	oEG			–			1.81	2 (2)	24
Sport	p=0.15			p=0.20			p=NA			p=NA			p=0.35		
Team sports	1.15	13 (20)	240	0.79	30 (44)	662	0.58	21 (33)	513	0.68	14 (25)	410	0.80	17 (24)	312
Martial arts	–			–			–			–			–		
Strength-dominant sports	0.58	2 (2)	24	1.22	2 (2)	26	oEG			–			0.34	3 (3)	33
Technical/acrobatic sports	–			–			–			–			–		
Training type	p<0.001			p=0.41			p=0.12			p=0.03			p=0.02		
Machine based	0.36	3 (3)	36	1.45	3 (3)	38	–			–			0.30	3 (3)	37
Free weights	2.97	2 (4)	72	0.90	3 (5)	80	0.61	3 (5)	80	1.31	1 (3)	62	–		
Machine based and free weights	1.16	4 (6)	54	0.77	3 (4)	39	0.18	2 (3)	29	oEG			oEG		
Functional training	0.62	2 (3)	34	0.39	2 (3)	52	0.19	2 (3)	52	0.38	2 (3)	52	0.79	5 (5)	84
Complex training	oEG			1.66	4 (5)	56	1.11	3 (5)	38	0.66	2 (3)	38	1.85	2 (3)	25
Plyometric training	0.39	4 (5)	56	0.81	16 (25)	406	0.64	10 (16)	300	0.62	7 (13)	249	0.74	10 (15)	190

N, total number of participants in the included experimental groups; NA, not applicable; oEG, only one experimental group; S (I), number of included studies (number of included experimental groups); SMD_{wm}, weighted mean standardised mean difference; y, years.

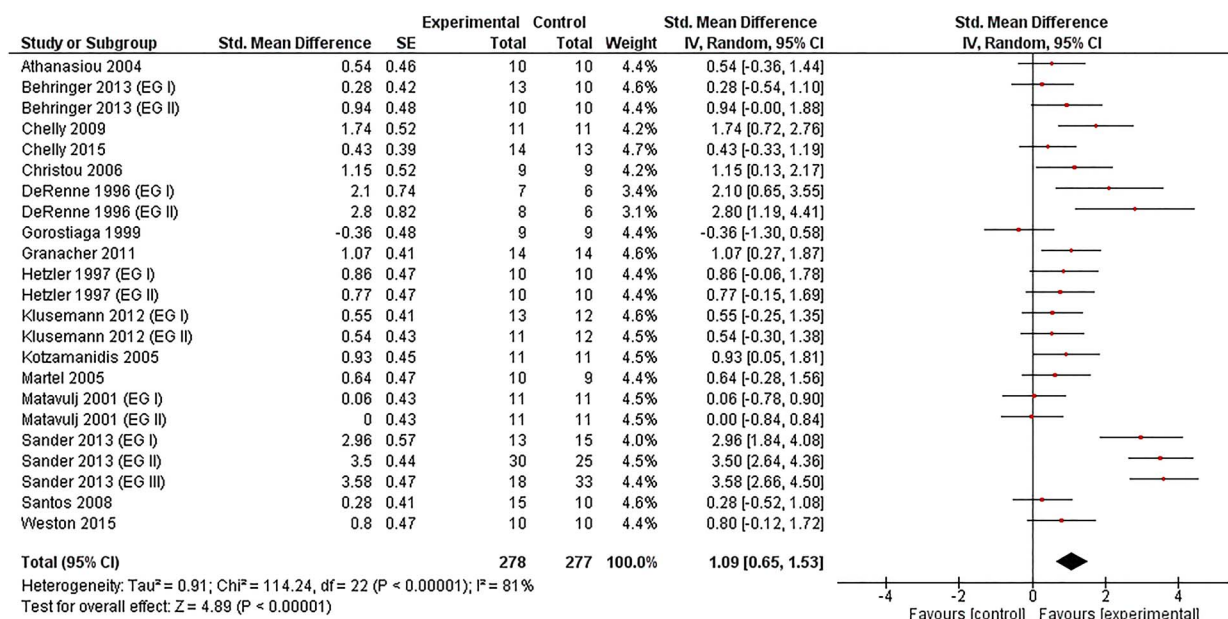


Figure 2 Effects of resistance training (experimental) versus active control on measures of muscle strength (IV, inverse variance).

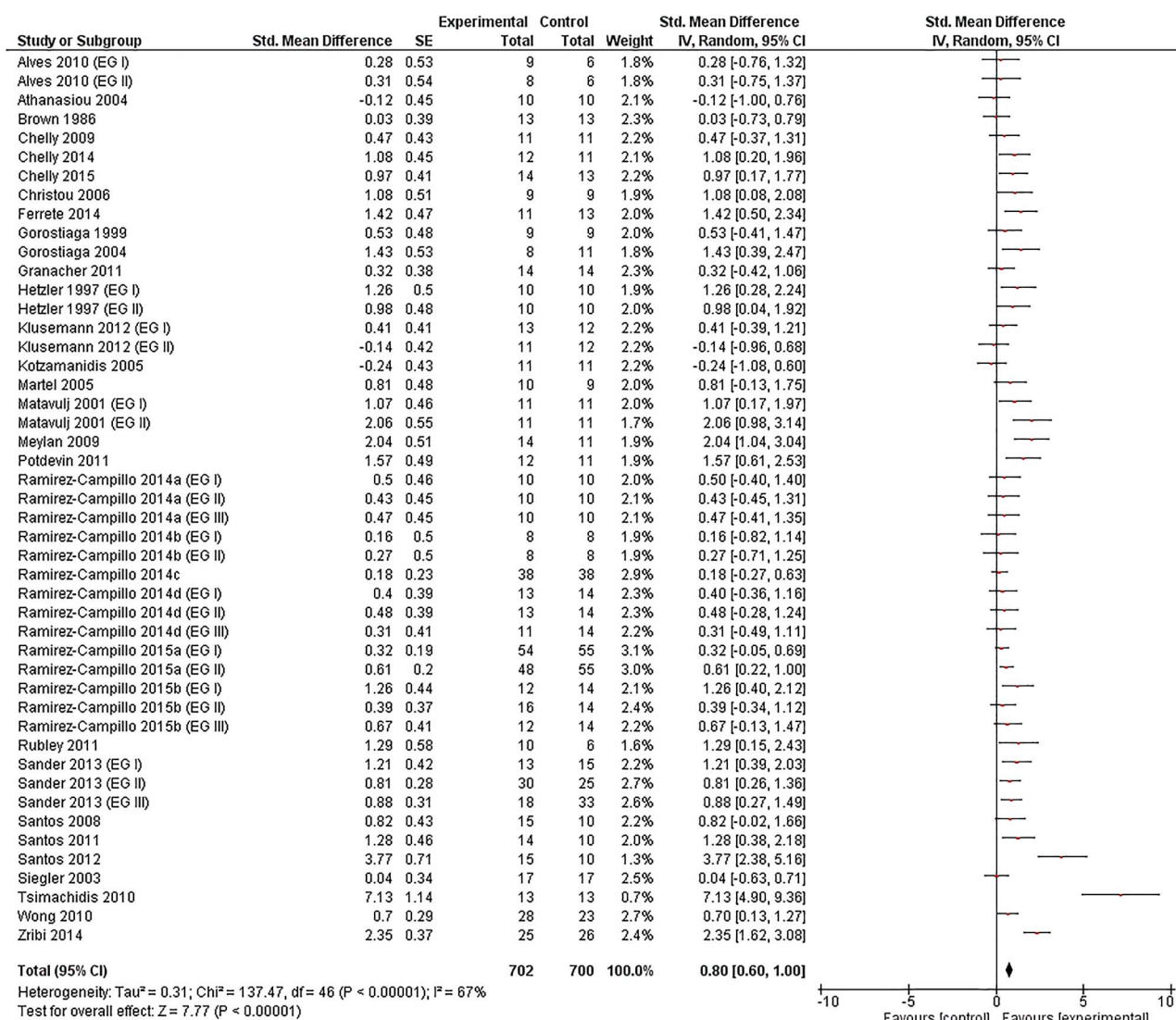


Figure 3 Effects of resistance training (experimental) versus active control on measures of vertical jump performance (IV, inverse variance).

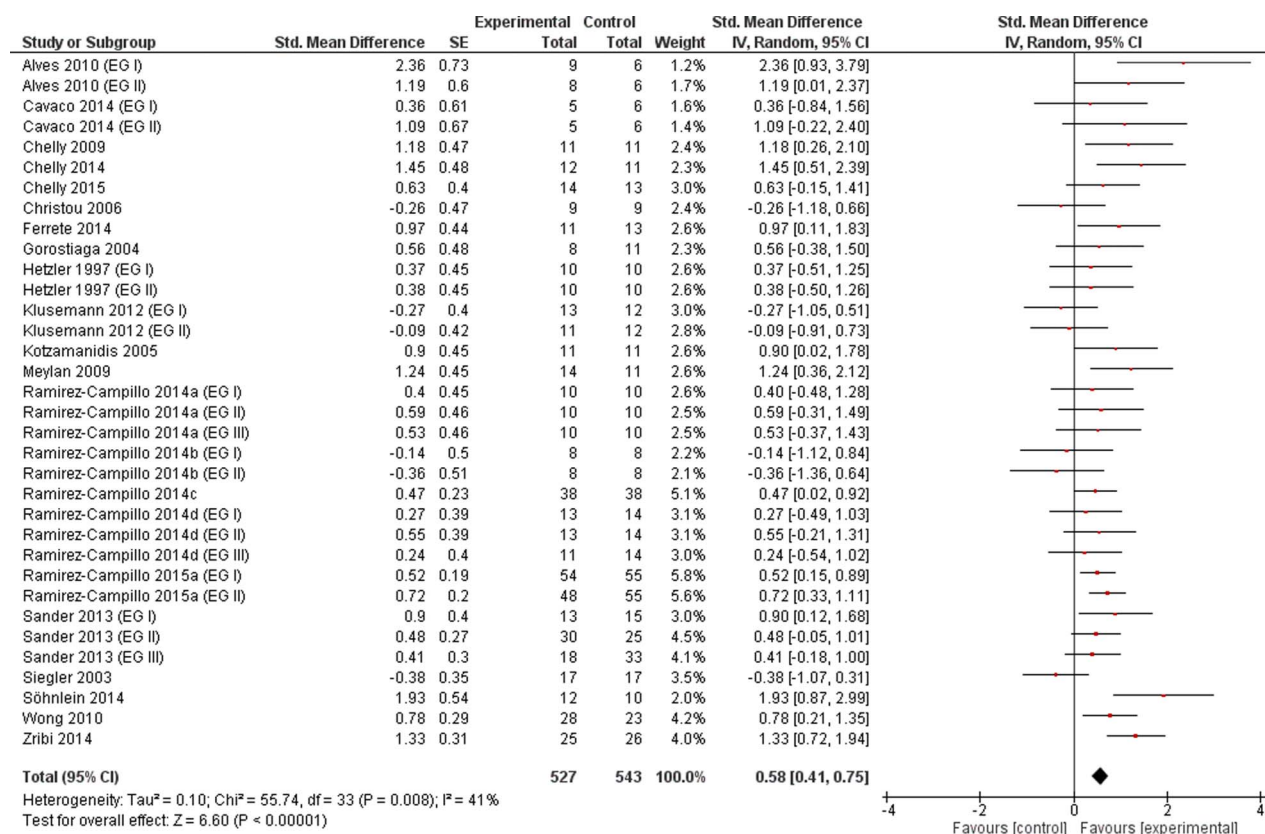


Figure 4 Effects of resistance training (experimental) versus active control on measures of linear sprint performance (IV, inverse variance).

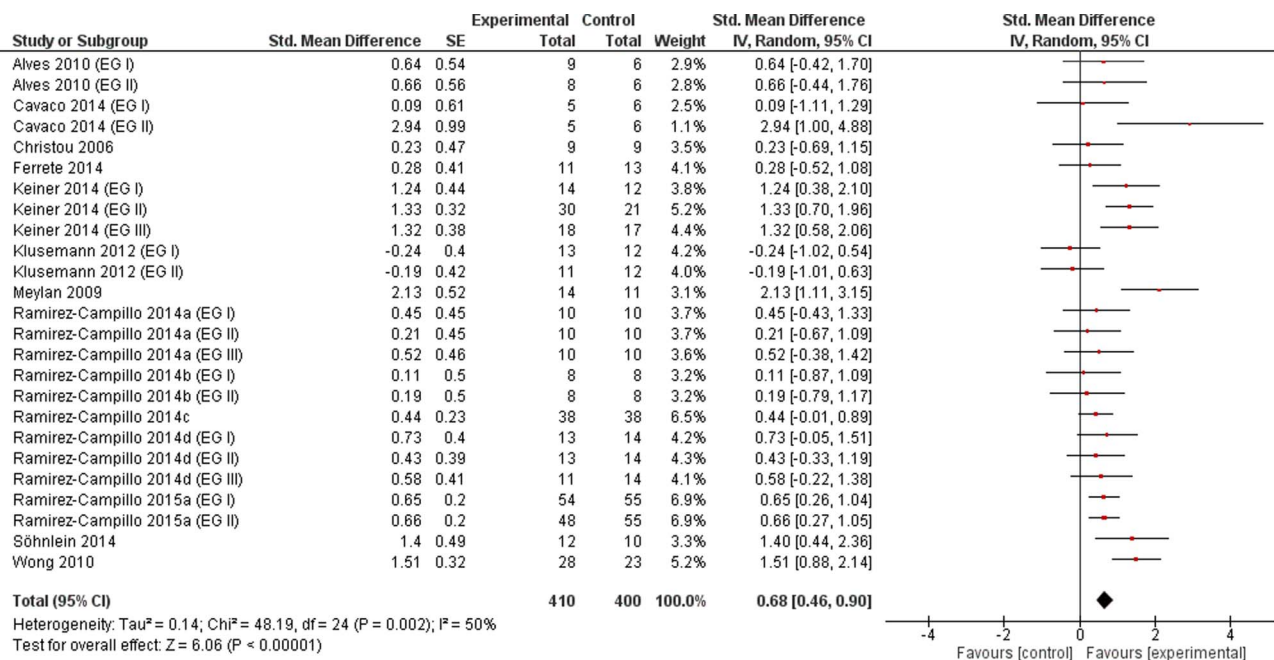


Figure 5 Effects of resistance training (experimental) versus active control on agility (IV, inverse variance).

Training volume (number of sets per exercise)

There was a significant difference with regard to the effects of conventional RT on muscle strength ($p < 0.01$), and a tendency towards significance for measures of vertical jump performance ($p = 0.06$; figure 10). Five sets per exercise resulted in more pronounced improvements in muscle strength ($SMD_{wm} = 2.76$)

compared with fewer sets. Three sets per exercise tended to be more effective in improving vertical jump performance ($SMD_{wm} = 1.19$), as compared with four or five sets per exercise.

For plyometric training, there was a tendency towards larger training-related effects on measures of muscle strength ($p = 0.09$), linear sprint performance ($p = 0.07$), as well as sport-specific

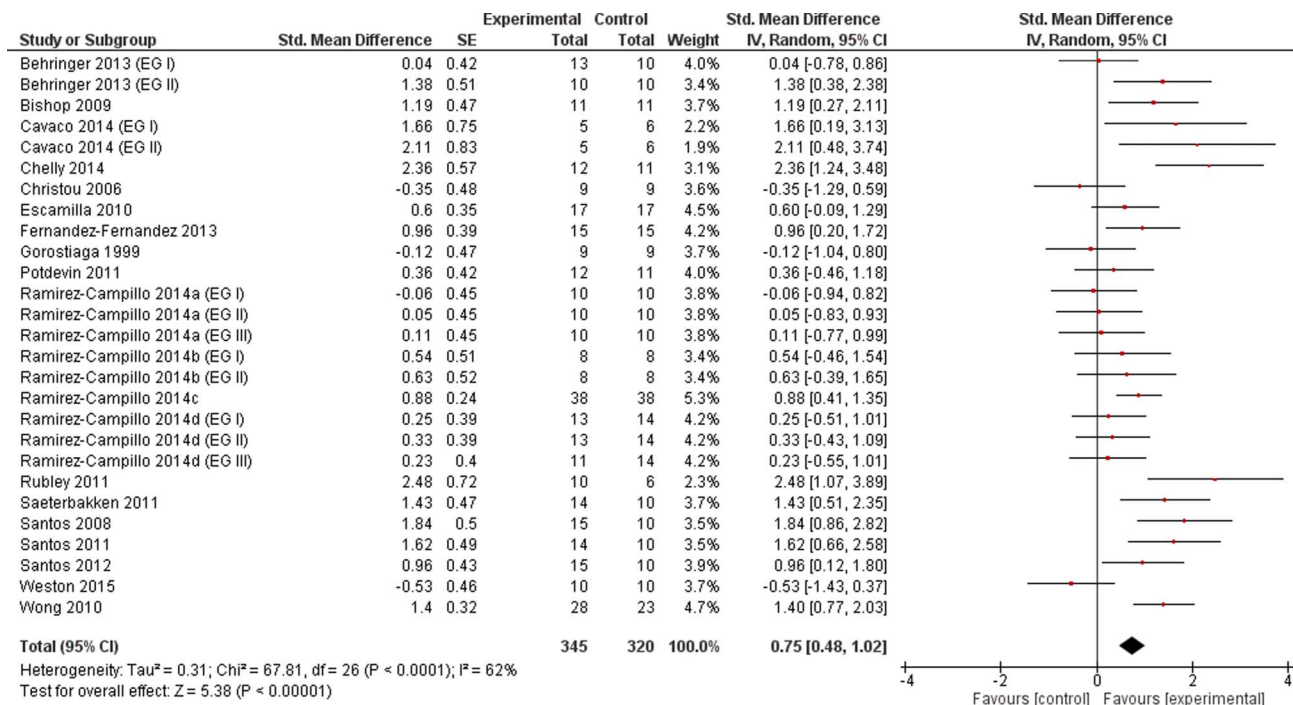


Figure 6 Effects of resistance training (experimental) versus active control on proxies of sport-specific performance (IV, inverse variance).

performance ($p=0.05$) depending on the number of sets per exercise. Four sets per exercise revealed the largest effects for measures of muscle strength ($SMD_{wm}=0.79$) and sport-specific performance ($SMD_{wm}=1.84$), while three or four sets appear to be most effective for improving linear sprint performance ($SMD_{wm}=0.95$).

Training volume (number of repetitions per set)

There was a significant difference in terms of the effects of conventional RT on measures of muscle strength ($p<0.05$; figure 11). Six to eight repetitions per set produced the largest effects on muscle strength ($SMD_{wm}=2.42$). For plyometric training, there was a tendency towards significance for proxies of sport-specific performance ($p=0.05$). Six to 8 repetitions per set were less effective ($SMD_{wm}=0.15$), while 3–5 and 9–12 repetitions per set produced similar effects ($SMD_{wm}=0.89$ and 0.93).

Rest between sets

There was a significant difference for the effects of conventional RT on measures of muscle strength ($p<0.05$; figure 12). Three to 4 min of rest between sets resulted in more pronounced improvements in measures of muscle strength ($SMD_{wm}=2.09$), as compared with shorter durations of rest.

DISCUSSION

This systematic review with meta-analysis examined the general effects as well as the age, sex, sport and training type-specific impact of RT on proxies of physical performance in healthy young athletes. In addition, dose-response relationships of RT parameters were independently computed. The main findings were: (1) RT has moderate effects on muscle strength as well as on vertical jump performance, and small effects on linear sprint, agility and sport-specific performance in young athletes, (2) the effects of RT were moderated by the variables sex and RT type, (3) most effective conventional

RT programmes to improve measures of muscle strength in healthy young athletes comprised training periods of more than 23 weeks, 5 sets per exercise, 6–8 repetition per set, a training intensity of 80–89% of the 1 RM, and 3–4 min of rest between sets.

Effects of RT on physical performance in youth athletes

In general, RT is an effective way to improve proxies of physical performance in youth athletes, and our findings support recently published literature.^{4 17 72 73} We found that the main effects of RT on measures of muscle strength and vertical jump performance were moderate in magnitude, with small effects for secondary outcomes, including linear sprint performance, agility and sport-specific performance (eg, throwing velocity). The lower RT effects on secondary outcomes might be explained by the complex nature of these qualities, with various determinants contributing to the performance level. For instance, agility depends on perceptual factors and decision-making as well as on changes in direction of speed, which is again influenced by movement technique, leg muscle quality and straight sprinting speed.⁷⁴ Thus, muscle strength appears to be only one of several factors contributing to agility.

We recommend the incorporation of RT as an important part of youth athletes' regular training routine to enhance muscle strength and jump performance.

How age, sex, sport and training type moderate RT effects

Age-specific effects of RT in youth athletes

Biological maturity is related to chronological age, and has a major impact on physical performance in youth athletes.⁷⁵ However, unlike age, growth and maturation are not linear factors.^{76 77} There is often a discrepancy between chronological age and biological maturity among youth athletes.^{4 16 78}

We found no significant differences in effect sizes for any proxy of physical performance between prepubertal and postpubertal athletes. Similarly, we did not find significant differences

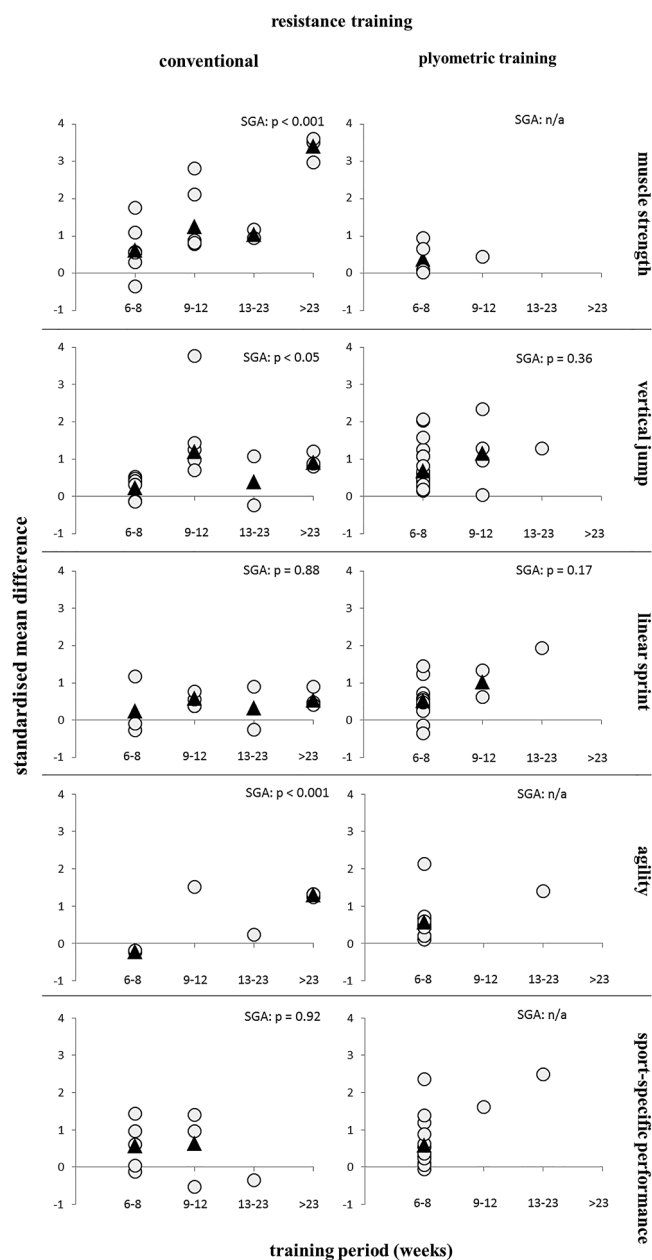


Figure 7 Dose–response relationships of the parameter ‘training period’ on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference.

for the effects of RT on any physical performance measure with respect to the moderator variable ‘chronological age’ (table 4). Merely, a tendency ($p=0.05$) towards higher sport-specific performance gains following RT in adolescents, compared with children, was identified.

Although a minimum age has been defined at which children are mentally and physically ready to comply with coaching instructions,⁴ our subgroup analyses regarding biological and chronological age suggest that youth athletes may benefit to the same extent from RT, irrespective of age. However, it is important to note that most studies did not report the biological maturity status of the participants. Therefore, more research is

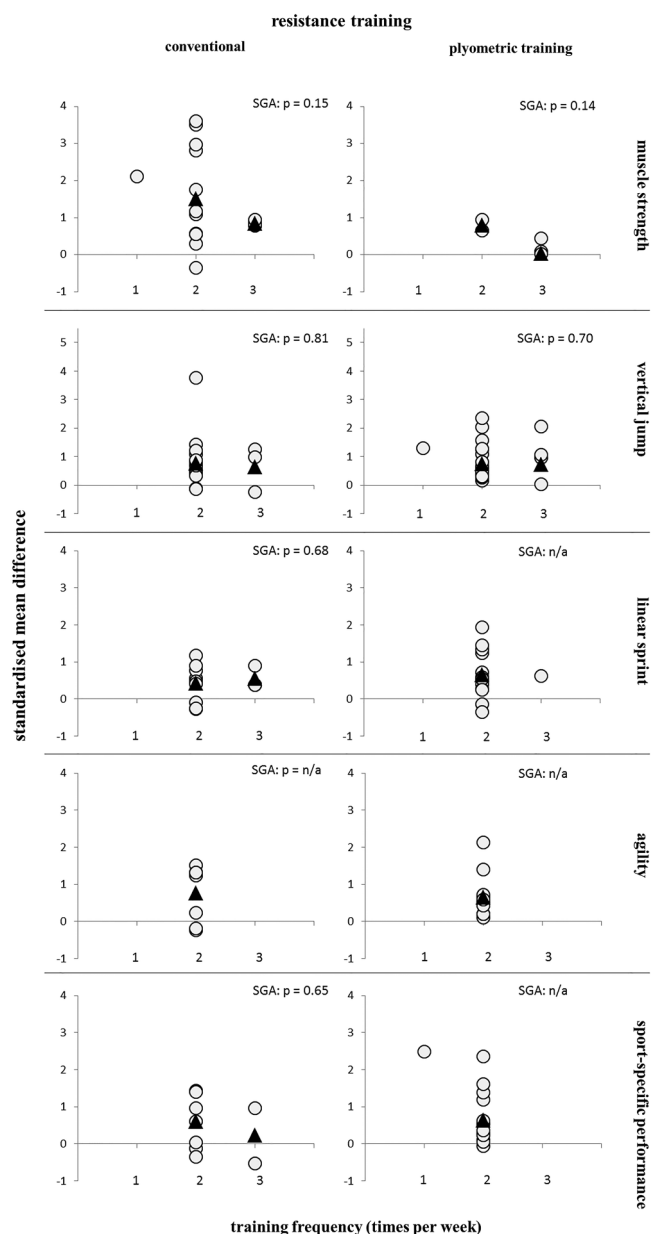


Figure 8 Dose–response relationships of the parameter ‘training frequency’ on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference.

needed to elucidate biological age-specific RT effects on physical performance in youth athletes and to verify our preliminary findings.

Sex-specific effects of RT in youth athletes

Previous research on the effects of RT on proxies of physical performance in youth athletes has primarily focused on boys. However, findings from male youth athletes can only partially be transferred to female youth athletes because the physiology of boys and girls (eg, hormonal status during puberty) varies. We found that male and female youth athletes show similar RT-related gains in muscle strength and vertical jump performance, but girls had significantly larger training-induced

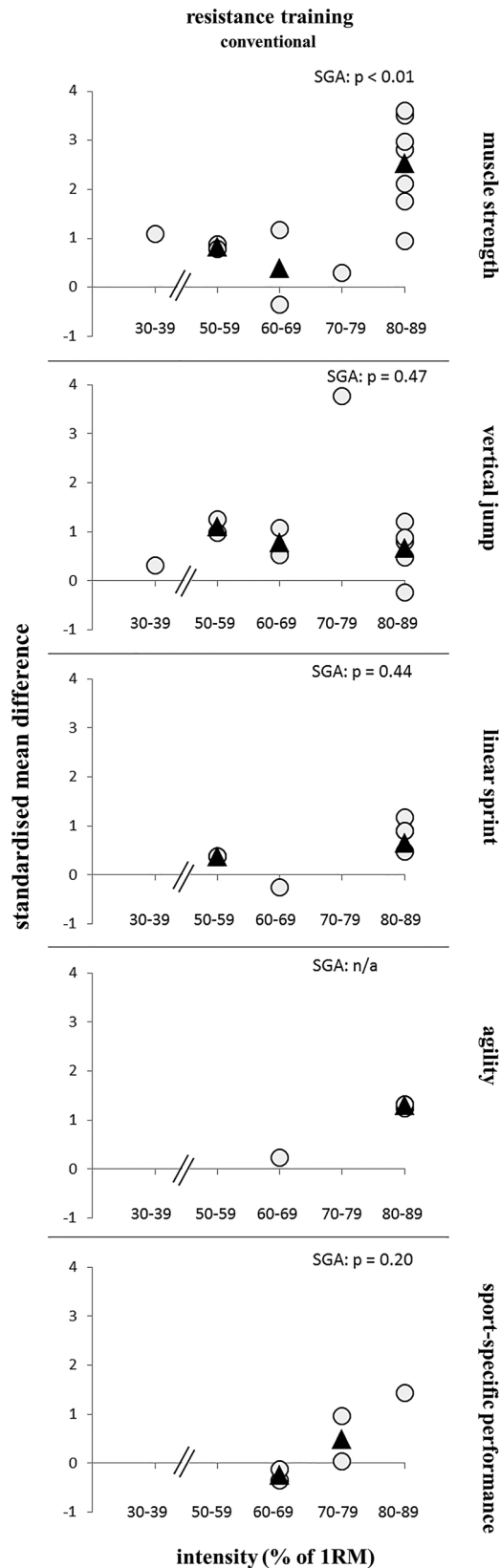


Figure 9 Dose-response relationships of the parameter 'training intensity' on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference; RM, repetition maximum.

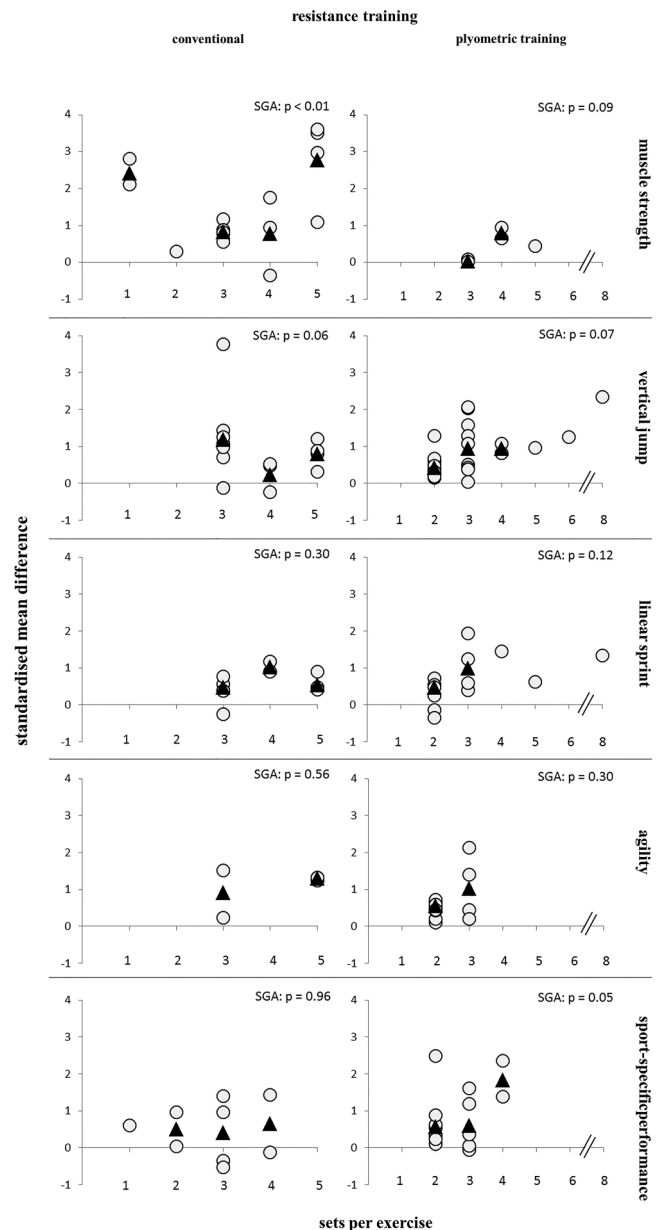


Figure 10 Dose-response relationships of the parameter 'sets per exercise' on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference.

improvements in sport-specific performance ($SMD_{wm}=1.81$) compared with boys ($SMD_{wm}=0.72$). This suggests preliminary evidence that the RT trainability of female adolescent athletes may be at least similar or even higher compared with males. Given that girls' and boys' physiology changes differently with age and maturation,^{76 77} sex-specific effects of RT in youth athletes should be investigated with respect to biological maturity. Owing to an insufficient number of studies that examined female youth athletes and reported their biological maturity status, we were not able to include 'biological maturity' as a moderator variable in our subgroup analyses. We consider our sex-specific findings preliminary because these are based on five

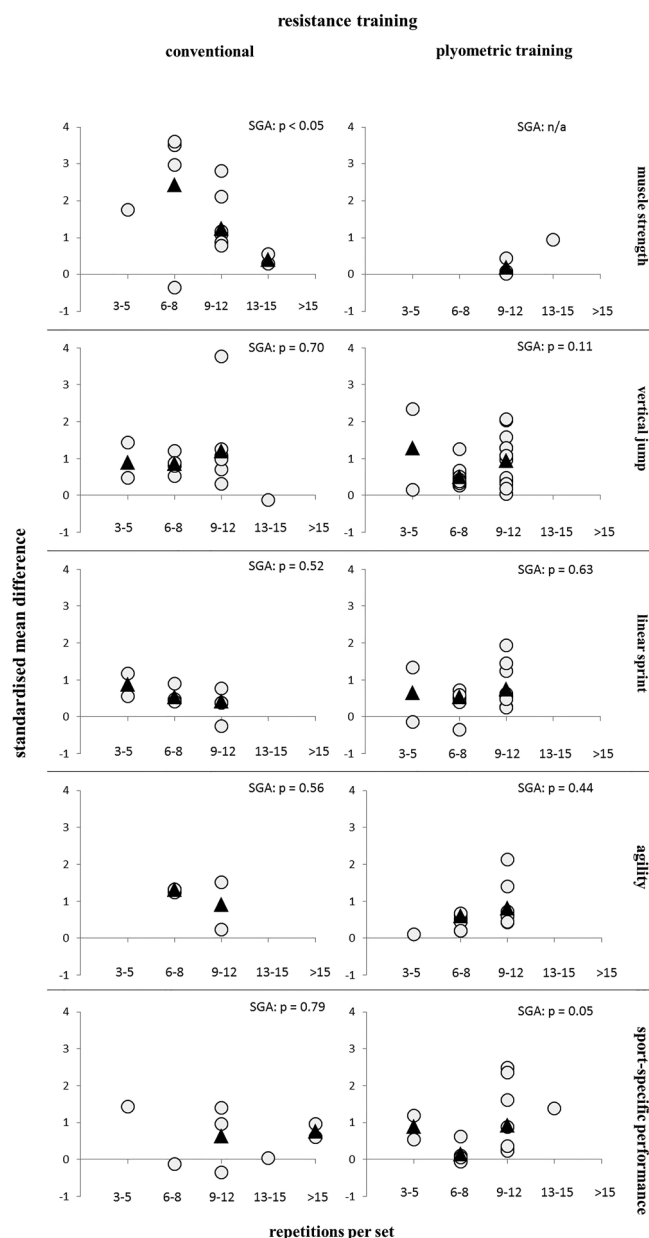


Figure 11 Dose–response relationships of the parameter ‘repetitions per set’ on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference.

studies only investigating female youth athletes. More research is needed to elucidate sex-specific RT effects on physical performance in youth athletes and to verify our preliminary findings.

Sport-specific effects of RT in youth athletes

The effects of RT in elite adult athletes may be specifically moderated by the respective athlete profile of the sport performed.^{79–80} Whether this is also the case in youth athletes remains unresolved. Given that most included studies ($n=38$) investigated young athletes competing in team sports, our analyses with regard to the moderator variable ‘sport’ was limited and did not reveal any significant differences between sports

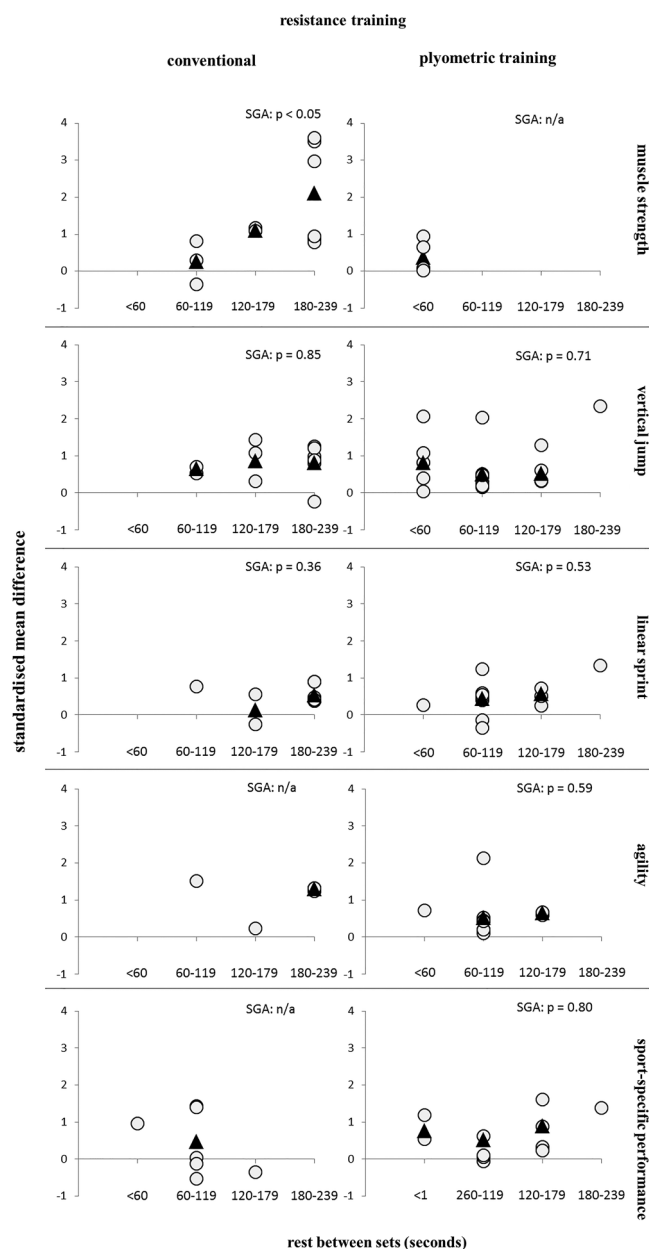


Figure 12 Dose–response relationships of the parameter ‘rest between sets’ on measures of muscle strength, vertical jump and linear sprint performance, agility, and sport-specific performance. Each filled grey circle illustrates between-subject SMD per single study with active control. Filled black triangles represent weighted mean SMD of all studies. NA, not applicable; SGA, subgroup analyses; SMD, standardised mean difference.

disciplines (table 4). Therefore, further research has to be conducted to examine if youth athletes respond differently to RT programmes as per the sport practiced.

Training type-specific effects of RT in youth athletes

Various types of RT have been reported (eg, machine-based RT, free weight RT and functional RT). Each of these types has specific benefits and limitations.^{20–73} Machine-based RT may represent a safe environment for young athletes when supervision cannot be ensured, whereas supervised RT using free weights allows full range of motion that better mimics sports-specific movements.^{20–73} We found that RT programmes using free

weights were most effective to enhance muscular strength and agility. In addition, complex training produced the largest effect sizes if the goal was to improve sport-specific performance. Therefore, the choice of RT types should be variable and based on the exercise goal (eg, enhancing muscle strength or sport-specific performance).

Dose–response relationships of RT in youth athletes

Planning and designing RT programmes is a complex process that requires sophisticated manipulation of different training parameters. Owing to a lack of evidence-based information on dose–response relationships following RT in youth athletes, it is quite common for established and effective RT protocols for healthy untrained children and adolescents to be transferred to youth athletes. However, this may hinder to fully recruit the adaptative potential of young athletes because the optimal dose to elicit the desired effect appears to be different in trained compared with untrained youth.¹³ Owing to the observed limitations regarding female youth athletes and biological maturation status in the present meta-analysis, the dose–response relationships of RT in youth athletes were determined irrespective of sex and maturity.

In general, the specific configuration of RT parameters determines the underlying training stimulus and thus, the desired physiological adaptations. However, significant effects were predominantly identified for conventional RT parameters for measures of muscle strength. Therefore, it appears that gains in muscular strength may be more sensitive to the applied training parameters of the conventional RT programmes, as compared with the secondary performance outcomes (eg, linear sprint performance, agility, sport-specific performance).

Training period

The effects of short-term (<24 weeks) RT peaked almost consistently with training periods of 9–12 weeks for both conventional RT and plyometric training. However, our subgroup analyses indicated significant differences only for conventional RT for measures of muscle strength and vertical jump performance. Nevertheless, with regard to strength gains, long-term (≥ 24 weeks) conventional RT was more effective in youth athletes ($SMD_{wm}=3.40$), as compared with short-term conventional RT ($SMD_{wm}=0.61$ – 1.24). Thus, it can be postulated that conventional RT programmes should be incorporated on a regular basis in long-term athlete development.⁶⁶ Given that continuous performance improvements are difficult to achieve particularly over long time periods, properly varying RT programmes may avert training plateaus, maximise performance gains and reduce the likelihood of overtraining.

Regular basketball practice during a detraining/reduced training period was sufficient to maintain previously achieved muscular power gains due to its predominantly power-type training drills.⁸¹ Therefore, it is reasonable to hypothesise that regular training can maintain RT-based gains in muscular strength for several weeks if similar physical demands are addressed during regular training. Coaches may reduce the time spent on RT for several weeks without impairing previously achieved strength gains during competition periods when the training must emphasise motor skills and competition demands.

Training frequency

The phase of periodisation, projected exercise loads and the dose of additional physical training (ie, overall amount of physical stress) may influence training frequency.²¹ In order to avoid overtraining and achieve maximal benefits of RT, it is important

to allow the body sufficient time to recover from each RT session. However, if the rest between RT sessions is too long, adaptive processes from previous RT sessions may get lost.

Most studies performed RT two or three times per week (figure 8), and there was no significant difference between the observed training frequencies. To our knowledge, there is no study available that directly compared the effects of two RT sessions per week as opposed to three sessions for youth athletes. Although a reduced RT frequency of one session per week may be sufficient to maintain muscle strength gains following RT for several weeks,^{41 82} training twice per week might be preferred to achieve further gains in muscle strength in youth athletes.

Training volume and training intensity

Both volume and intensity have to be considered when prescribing RT to maximise physiological adaptations and minimise injury risk.⁴ Different configurations of training volume and intensity result in different forms of physiological stress, which in turn induce different neural and muscular adaptations.⁷¹

Owing to the large methodological variety in dealing with training intensity during plyometric training, we were not able to consistently quantify the dose–response relationship for training intensity with regard to plyometric training.

Conventional RT programmes using average training intensities of 80–89% of the 1 RM were most beneficial in terms of improving muscle strength in youth athletes. These findings are in accordance with the position stand of the American College of Sports Medicine for strength training in adults.⁸³ The largest effect sizes for muscle strength gains in adults, trained individuals and athletes were achieved at 80–85% of the 1 RM.^{8 12} However, it should be noted that the individual percentage of 1 RM is a stress rather than a strain factor. Several studies have indicated that a given number of repetitions cannot be associated with a specific percentage rate of the 1 RM.^{78 84} Thus, to individualise RT, future studies should focus on finding a valid strain-based method to quantify RT intensity effectively.

In terms of the number of sets per conventional RT exercise, our data show similar effect size magnitudes when comparing single-set ($SMD_{wm}=2.41$) versus multiple-set conventional RT programmes (5 sets: $SMD_{wm}=2.76$). The primary benefit of a single-set conventional RT is time efficiency. Nevertheless, since our results for single-set conventional RT are based on two intervention groups from one study, this finding has to be interpreted with caution. Although there was no study that directly compared the effects of single-set versus multiple-set conventional RT in youth athletes, there is evidence from adult athletes that single-set conventional RT may be appropriate during the initial phase of RT,⁸⁵ whereas multiple-set conventional RT programmes should be used to promote further gains in muscle strength, especially in athletes.⁸⁶ Therefore, multiple-set conventional RT may be necessary to elicit sufficient training stimuli during long-term youth athlete development.

Regarding the applied plyometric training, 3 (for vertical jump) or 4 sets per exercise (for muscle strength, sport-specific performance) as well as 3–5 or 9–12 repetitions per set (for vertical jump, sport-specific performance) might be beneficial for youth athletes' physical performance. However, the movement quality of plyometric exercises is more important than the total session volume.⁸⁷ Therefore, we recommend the use of thresholds for performance variables, such as ground contact time or performance indices, to determine individualised training volume.⁸⁷

Rest between sets

The duration of rest between sets and repetitions depends on parameters like training intensity and volume. The rest interval significantly affects the biochemical responses following RT.⁷¹ Owing to an insufficient number of studies that reported the duration of rest between repetitions, we focused on dose-response relationships for rest between sets. Long rest periods (ie, 3–4 min of rest between sets) were most effective for improving muscle strength following conventional RT in youth athletes. This is most likely because long rest periods allow athletes to withstand higher volumes and intensities during training.

Limitations of this meta-analysis

A major limitation is that we could not provide insights into the interactions between the reported training parameters. Our analyses are based on a variety of studies using different combinations of training parameters magnitudes (eg, training frequency, number of sets, intensity). It remains unclear if performance gains would still be maximal if, according to the present dose-response relationships, the optimum of each parameter was implemented in RT programmes.⁸¹ Thus, further research is necessary to find an analytical method to provide insights into the interactions between the investigated training parameters. The modelling of training variables might help to address this limitation. Holding a set of RT variables constant while changing the effects of one specific variable could determine the unique effects of each training variable.

Further limitations of this systematic review and meta-analysis are the high risk of bias of the included studies (only 4 out of 43 studies reached a PEDro score of ≥ 6), the considerable heterogeneity between studies (ie, $I^2=41\text{--}81\%$), and the uneven distribution of SMDs calculated for the respective training parameters. In addition, the scale for determining the magnitude of effect sizes³² is not specific for RT research in children and adolescents. Another limitation is that almost all studies failed to report RT parameters which had got recent research attention (eg, temporal distribution of muscle action modes per repetition).⁷¹ Further, studies used traditional stress-based (ie, RM) instead of recent strain-based (eg, OMNI resistance exercise scale of perceived exertion⁸⁸) methods to quantify RT intensity.⁸⁹ We were not able to aggregate the effects of moderator variables, such as sex and maturation, for the dose-response relationships due to an insufficient number of studies that specifically addressed these issues.

SUMMARY

RT was effective for improving proxies of physical performance in youth athletes. The magnitudes of RT effects were moderate in terms of measures of muscle strength and vertical jump performance, and small with regard to measures of linear sprint, agility and sports-specific performance in youth athletes. Sex and RT type appeared to moderate these effects. However, most studies were at high risk of bias and therefore, the results should be interpreted cautiously.

A training period of more than 23 weeks, 5 sets per exercise, 6–8 repetitions per set, a training intensity of 80–89% of 1 RM, and 3–4 min rest between sets were most effective for conventional RT programmes to improve muscle strength in youth athletes. However, these evidence-based findings should be adapted individually by considering individual abilities, skills and goals. Specifically, youth coaches should not use high RT intensities

before the youth athlete developed technical skills to adequately perform the RT exercises.

What is already known on this topic?

- ▶ Resistance training is safe for children and adolescents if appropriately prescribed and supervised.
- ▶ Several meta-analyses have already shown that resistance training has the potential to improve muscle strength and motor skills (eg, jump performance) in healthy, untrained children and adolescents.

What this study adds

- ▶ This is the first systematic review and meta-analysis to examine age, sex, sport and training type-specific effects of resistance training on physical performance measures in youth athletes.
- ▶ The effect of resistance training was moderated by sex and resistance training type. Girls had greater training-related sport-specific performance gains compared with boys, and resistance training programmes with free weights were most effective for increasing muscle strength.
- ▶ Dose-response relationships for key training parameters indicate that youth coaches should aim for resistance training programmes with fewer repetitions and higher intensities to improve physical performance measures.

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Contributors ML, OP and UG performed systematic literature search and wrote the paper. ML and OP analysed the data.

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Competing interests None declared.

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