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A meta-analysis of maturation-related variation in adolescent boy athletes' adaptations to short-term resistance training

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ABSTRACT

This meta-analysis investigated the maturation-related pattern of adaptations to resistance training in boy athletes. We included studies examining the effects of 4–16-week resistance training programmes in healthy boy athletes aged 10–18 years. Pooled estimates of effect size for change in strength across all studies ($n = 19$) were calculated using the inverse-variance random effects model for meta-analyses. Estimates were also calculated for groups based on likely biological maturity status ("before", "during" and "after" peak height velocity). Using the standardised mean difference, resistance training increased strength across all groups (effect size = 0.98, [CI: 0.70–1.27]). Strength gains were larger during (1.11 [0.67–1.54]) and after (1.01 [0.56–1.46]) peak height velocity than before (0.5 [–0.06–1.07]). Adaptations to resistance training are greater in adolescent boys during or after peak height velocity. These findings should help coaches to optimise the timing of training programmes that are designed to improve strength in boy athletes.

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KEYWORDS

Youth; sport; athlete; trainability; development

Introduction

Maximal strength is defined as the maximum force or torque that can be exerted by skeletal muscles in a given movement (Knuttgen & Komi, 2003) or action. High muscular strength is an integral element of sport performance for young athletes (Lloyd et al., 2014; Sander, Keiner, Wirth, & Schmidtbleicher, 2013) and resistance training is an effective way to enhance this quality (Chelly et al., 2009; Christou et al., 2006). However, there is variation in how children and adolescents of different biological maturity status adapt to the demands of resistance training (Meylan, Cronin, Oliver, Hopkins, & Contreras, 2014).

A recent meta-analytical review (Behringer, Vom Heede, Yue, & Mester, 2010) reported that resistance training was effective for increasing strength in general population youths, with a combined weighted effect size of 1.1 (0.9–1.3). Later, Behringer, Vom Heede, Matthews, and Mester (2011) conducted a meta-analysis on the effects of training on motor skills of running, jumping and throwing, and identified that younger participants and non-athletes had greatest improvement after resistance exercise. More recently, Harries, Lubans, and Callister (2012) focused exclusively on resistance training in youth athletes and identified a mean difference in vertical jump performance (cm) of 3.0 (1.6–4.5). This reinforced an earlier review that demonstrated similar results (Payne, Morrow, Johnson, & Dalton, 1997). Most recently, Lesinski, Prieske, and Granacher (2016) conducted a meta-analysis on the dose-response and programming variables of resistance training in youths, finding small to medium effect sizes across various physical qualities.

Despite these studies, when combined, the meta-analytical literature on resistance training with respect to biological

maturation in youths is undermined by several key limitations. Researchers have tended not to explicitly address mediating effects of biological maturity on adaptations to resistance training. Those that have implicitly addressed the issue (Behringer et al., 2011, 2010; Lesinski et al., 2016) have treated it only as a categorical moderator variable with boys and girls analysed in the same subgroups, making any conclusions largely redundant. Boys experience different maturational changes to girls (Marceau, Ram, Houts, Grimm, & Susman, 2011) and these changes give rise to differentials in performance throughout biological maturation (Ford et al., 2011). In addition, the inclusion of trials of long duration, in some cases in excess of one year (Behringer et al., 2011, 2010; Lesinski et al., 2016), distorts any maturation-related conclusions as participants can undergo substantial biological changes throughout the study period. Furthermore, the grouping of training methods, such as plyometric and traditional resistance training, to make inferences about a single outcome measure (Lesinski et al., 2016) is erroneous given the independent nature of training adaptations to different exercise modalities (Vissing et al., 2008), and the principle of training specificity (Gamble, 2006). On this, the principle of specificity is also often ignored for outcome measures with many reviewers including studies that reported no measure of muscular strength. These factors are important for practitioners to consider when research informs the prescription of resistance training.

In youths, the optimal long-term timing of resistance training is not well described. Adaptations to resistance training vary according to biological maturation (Behringer et al., 2010; Malina, 2006), and this type of activity seems less effective in increasing the strength of young athletes when performed before peak height velocity (PHV) (Meylan et al., 2014). This

review builds on previous analyses by focusing specifically on boy athletes and adopts a novel approach to characterise the pattern and specificity of adaptations to resistance training throughout biological maturation. Biological maturity and training status are important considerations in the prescription of this type of exercise. Accordingly, this study seeks to account for shortcomings in a way that is relevant to practitioners. No meta-analysis has adopted this multidimensional perspective.

Methods

Experimental approach to the problem

This study was approved by the University of Essex Ethics Committee. The review was carried out in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses statement (Liberati et al., 2009). The review used similar techniques to that of a recent review (Moran et al., *in press*). A comprehensive literature search was conducted before the results were analysed using a random-effects model.

Literature search

The search process is shown in Figure 1. With no date restrictions, an extensive search of the PubMed, Google Scholar, Sport Discus, Medline, CINAHL and Science Direct databases was conducted. Words used either as individual search terms or in conjunction with each other included “strength”, “power”, “weightlifting”, “resistance”, “training”, “exercise”, “paediatric”, “youth”, “young”, “children”, “adolescence”, “athletes”, “sport”, “volume”, “intensity”, “fitness”, “high”, “load”, “rest”, “sets” and “repetitions”. Only articles published in peer-reviewed journals were selected. Study selection involved a review of all seemingly relevant article titles and

was followed by an evaluation of article abstracts and, then, full published articles. After this, article reference lists were searched.

Specific criteria determined studies’ eligibility for inclusion. Studies must have included healthy sport-playing boys. Ages must have been stated for all within-study groups and participants must have been no younger than the mean age of 10 and no older than the mean age of 18 years: the adolescent growth spurt occurs at the age of approximately 11 years in boys (Malina, 1999) but can be preceded by several markers of sexual maturation, such as pubic hair and genitalia development at approximately the age of 10 years (Sun et al., 2002). By age 18 years, full adult stature is usually attained (de Onis et al., 2007; Sherar, Mirwald, Baxter-Jones, & Thomis, 2005). Studies must also have included a resistance training programme that conformed to descriptions used in previous reviews: exercise that “requires the musculature to contract (*sic.*) against an opposing force generated by some type of resistance” (Behringer et al., 2010) and “resistance training using body-weight or additional external weights” (Rumpf, Cronin, Pinder, Oliver, & Hughes, 2012). Programmes must have been between 4 and 16 weeks in duration and authors must have provided means and standard deviations for a measure of muscular strength for before and after the intervention.

Resistance training can improve strength in six weeks (Faigenbaum et al., 2007); therefore, a minimum training programme duration of 4 weeks was chosen to capture short-term effects. Biological maturation has a substantial impact on physical performance over an extended period of time (Beunen & Malina, 1988; Yagüe, La Fuente, & Manuel, 1998). To minimise this impact on our estimates, an upper limit programme duration of 16 weeks was imposed to distinguish between the effects of training and advancing maturation.

The physical characteristics of groups are in Table 1 and the study characteristics are in Table 2. A total of 19 studies provided enough information to be included.

Maturity status

To gauge the maturity status of the study participants, the classifications of previous reviewers (Moran et al., *in press*; Rumpf et al., 2012) were used (10–12.99 years = “before” PHV, 13–15.99 years = “during” PHV, 16–18 years = “after” PHV). Studies of resistance training in boys are undermined by an absence of controls for the biological maturity status of trial participants. This justified the use of the current method as the “interval of maximal growth” occurs between the ages of 13 and 15 years in boys (Malina, 2011; Malina, Bouchard, & Bar-Or, 2004), and we define this as “during” PHV. Indeed, PHV

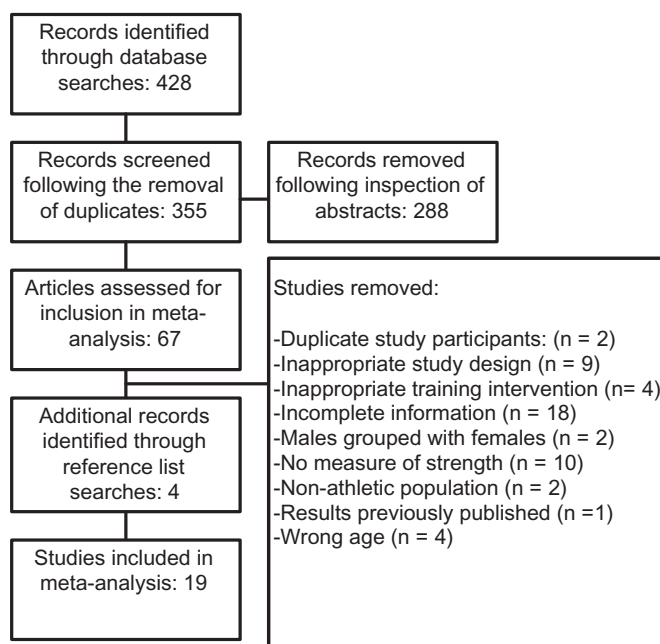


Figure 1. Flow chart for inclusion and exclusion of studies.

Table 1. Descriptive data for participants from resistance training studies included in meta-analysis.

	All	Before PHV	During PHV	After PHV
Group	n = 496	n = 57	n = 279	n = 160
Age (years)	15.1 ± 2.0	11.1 ± 1.1	14.9 ± 1.2	16.9 ± 1.0
Stature (cm)	170.7 ± 14.4	145.4 ± 8.4	173.2 ± 9.9	176.2 ± 12.7
Mass (kg)	65.2 ± 16.0	38.3 ± 11.2	60.4 ± 21.5	74.5 ± 9.8

Before PHV: 10–12.99-year-olds; during PHV: 13–15.99-year-olds; after PHV: 16–18-year-olds.

Table 2. Characteristics of the reviewed studies and their participants.

Reference	Age (years)	Maturation relative to PHV		Mass (kg)	Sport	Group	Group identifier	Number of participants	Resistance training experience (years)	Training frequency (per week)	Number of weeks	Mean total sessions	Test
		Before	During										
Chaouachi et al. (2014)	11 (1)	Before	During	145.5 (8.1)	Judo and Wrestling	Olympic-style weightlifting	OWL	17		2	12	24	Isokinetic leg strength at 60 degrees per second (kg)
Chaouachi et al. (2014)	11 (1)	Before	During	145.1 (8.8)	Judo and Wrestling	Resistance training	Trad. RT	16		2	12	24	
Meylan et al. (2014)	12.4 (0.7)	Before	During	152 (4.7)	Sports Academy	Pre-PHV	Pre	10		2	8	16	1RM Leg Press (kg)
Rumpf et al. (2015)	10.4 (0.8)	Before	During	141 (7.93)	Various	Pre-PHV	PHV	14		2.66	6	16	Peak Horizontal Force (N)
Behringer et al. (2013)	15.1 (1.8)	During	During	175.8 (12.9)	Tennis	Resistance training	RG	13		2	8	16	10RM Leg Press (kg)
Behringer et al. (2013)	15.5 (0.9)	During	During	177.1 (8.2)	Tennis	Plyometric training	PG	10		2	8	16	
Channell and Barfield (2008)	15.7 (1.23)	During	During	175.51	American Football	Olympic Lifting	OT	11	1.87 (0.81)	3	8	24	1RM Squat (kg)
Channell and Barfield (2008)	15.6 (0.6)	During	During	180.59	American Football	Powerlifting	PT	10	1.87 (0.81)	3	8	24	
Christou et al. (2006)	13.8 (0.4)	During	During	162 (3.8)	Soccer	Strength-soccer	STR	9		2	16	32	1RM Leg Press (kg)
Gabbett, Johns, and Riemann (2008)	14.1 (0.2)	During	During	169.5 (2.1)	Rugby League	Under 15	Under 15	14	0	3	10	30	20 second Chin Ups Test (Chin Ups)
Gorostiaga, Izquierdo, Iturralde, Ruesta, and Ibáñez (1999)	15.1 (0.7)	During	During	173.1 (5.3)	Handball	Strength training	ST	9		2	6	12	1RM Leg Press (kg)
Ignjatovic, Radovanovic, Stankovic, Marković, and Kocic (2011)	15.7 (0.8)	During	During	183.6 (6.1)	Basketball	Experimental	E	23	0	2	12	24	1RM Bench Press (60% intensity) (N)
Meylan et al. (2014)	13.6 (0.6)	During	During	165 (5.8)	Sports Academy	Mid-PHV	Mid	11		2	8	16	1RM Leg Press (kg)
Meylan et al. (2014)	14.3 (0.7)	During	During	174 (4.2)	Sports Academy	Post-PHV	Post	12		2	8	16	
Rumpf et al. (2015)	15.2 (1.6)	During	During	173 (5.32)	Various	Mid-/post-PHV	Mid-/post-PHV	18		2.66	6	16	Peak Horizontal Force (N)
Sarabia et al. (2015)	15.4 (0.8)	During	During	171.9 (4.1)	Tennis	Experimental	EG	11	0	2	6	12	Parallel half-squat (N)
Szymanski, Szymanski, Molloy, and Pascoe (2004)	15.3 (1.2)	During	During	176.6 (7.8)	Baseball	Strength	Group 1	23		3	12	36	1RM Parallel Squat (kg)
Szymanski et al. (2004)	15.4 (1.1)	During	During	179 (5)	Baseball	Strength and wrist training	Group 2	20		3	12	36	
Szymanski, Szymanski, Bradford, Schade, and Pascoe (2007)	15.3 (1.2)	During	During	178.4 (7.8)	Baseball	Strength	Group 1	24		3	12	36	1RM Parallel Squat (kg)
Szymanski et al. (2007)	15.4 (1.1)	During	During	176.4 (5)	Baseball	Strength and medicine ball training	Group 2	25		3	12	36	
Takai et al. (2013)	13.6 (0.6)	During	During	158.00	Various	Training	Training	36		5.625	8	45	Maximal Knee Extension Strength (kg)
Campos Vázquez et al. (2015)	18 (0.9)	After	After	177.9 (4.8)	Soccer	Squat	SG	10		2	8	16	Mean Velocity in Full Squat - 77.5kg (m/s)
Chelly et al. (2009)	17 (0.3)	After	After	173 (3)	Soccer	Resistance training	RTG	11	0	2	8	16	1RM Half Squat (kg)
Coutts, Murphy, and Dascombe (2004)	16.6 (1.2)	After	After	168 (6.4)	Rugby League	Unsupervised training	UNSUP	21		3	12	36	3RM Squat (kg)
Courtts et al. (2004)	16.8 (1)	After	After	170 (5.4)	Rugby League	Supervised	SUP	21		3	12	36	
Gabbett et al. (2008)	16.9 (0.3)	After	After	179.7 (1.3)	Rugby League	Under 18	Under 18	21	0	3	10	30	20 second Chin Ups Test (Chin Ups)

(Continued)

Table 2. (Continued).

Reference	Age (years)	Maturation relative to PHV	Stature (cm)	Mass (kg)	Sport	Group	Group identifier	Number of participants	Resistance training experience (years)	Training frequency (per week)	Number of weeks	Mean total sessions	Test
Harries, Lubans, and Callister (2016)	16.8 (1)	After	180.4 (3.3)	88.7 (18.2)	Rugby Union	Linear periodised	LP	8	0.5	2	12	24	1RM Box Squat (kg)
Harries et al. (2016)	17 (1.1)	After	181.3 (7)	82.4 (12.6)	Rugby Union	Daily undulating periodised	DUP	8	0.5	2	12	24	
Kotzamanidis, Chatzopoulos, Michalidis, Papaioakou, and Patikas (2005)	17 (1.1)	After	178 (35)	73.50	Soccer	Combined training	COM	12		2.3	13	29.9	1RM Half Squat (kg)
Kotzamanidis et al. (2005)	17.1 (1.1)	After	175 (25)	72.50	Soccer	Strength training	STR	11		2.3	13	29.9	
Prieske et al. (2016)	16.6 (1.1)	After	182 (0.05)	72.5 (6.3)	Soccer	Stable surface core	CSTS	19		2.4	9	21.6	Trunk Flexion Isometric Force (N)
Prieske et al. (2016)	16.6 (1)	After	179 (0.07)	69.4 (7.2)	Soccer	Unstable surface core	CSTU	18		2.3	9	20.7	

occurs approximately at the age of 14 in a North American and European population (Malina et al., 2004; Rumpf et al., 2012) and though sport-playing boys tend to mature slightly earlier than their non-sport playing peers (Malina, 2011), several longitudinal studies have estimated that PHV of young athletes occurs at this time (Bell, 1993; Philippaerts et al., 2006; Šprynarová, 1987). At or about the age of 14 years is a critical period for training-related physiological development in boys (Deprez et al., 2015). PHV typically occurs one year before this (Tanner, Whitehouse, & Takaishi, 1966) while up to 94% of full adult stature is usually attained by age 15 years (Malina, Cumming, Morano, Barron, & Miller, 2005; Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004). This is the period of greatest diversity in biological maturity amongst boys, with differences typically reducing beyond 16 years (Malina, Rogol, Cumming, Coelho, & Figueiredo, 2015). We classify this as “after” PHV.

Data extraction

Data extraction was undertaken by two reviewers (JM and JC). The data in Figure 2 and Table 2 was collected by JM before JC verified its accuracy and the eligibility of studies for inclusion.

Where data were incompletely or unclearly reported, JM contacted study authors for clarification. Where more than one relevant performance test was carried out, effect sizes were calculated by selecting the most relevant measure of muscular strength “based on theory or a logically defensible rationale” (Turner & Bernard, 2006). To account for the specificity of the training adaptation, we did not consider surrogate measures such as a vertical jump, as in a previous meta-analysis (Harries et al., 2012). Where possible, a maximal squat, or similar, was chosen because of that exercise’s validity in measuring strength, its specificity to athletic movements and muscle actions, the large amount of muscle mass it recruits and its common prescription in exercise training programmes (Hoffman, 2006).

Statistical analysis

The meta-analysis was carried out using the RevMan (Review Manager Version 5.3) software. The inverse-variance random-effects model for meta-analyses was chosen because it assigns a proportionate weight to studies based on the magnitude of their respective standard errors (Deeks, Higgins, & Altman, 2008) and permits analysis while controlling for heterogeneity across trials (Kontopantelis, Springate, & Reeves, 2013). As researchers used different outcome measures to assess muscular strength, effects are represented by the standardised mean difference between pre- and post-intervention measures in training groups only (Sedgwick & Marston, 2013), and are presented alongside 95% confidence intervals. Effect sizes were evaluated according to Hopkins, Marshall, Batterham, and Hanin (2009), i.e., <0.2 = trivial; 0.2–0.59 = small, 0.6–1.19 = moderate, 1.2–1.99 = large, 2.0–3.99 = very large and ≥4.0 = extremely large.

Study heterogeneity was confirmed via the I^2 statistic. This represents the proportion of “the total variation in estimated effects across studies that is due to heterogeneity rather than

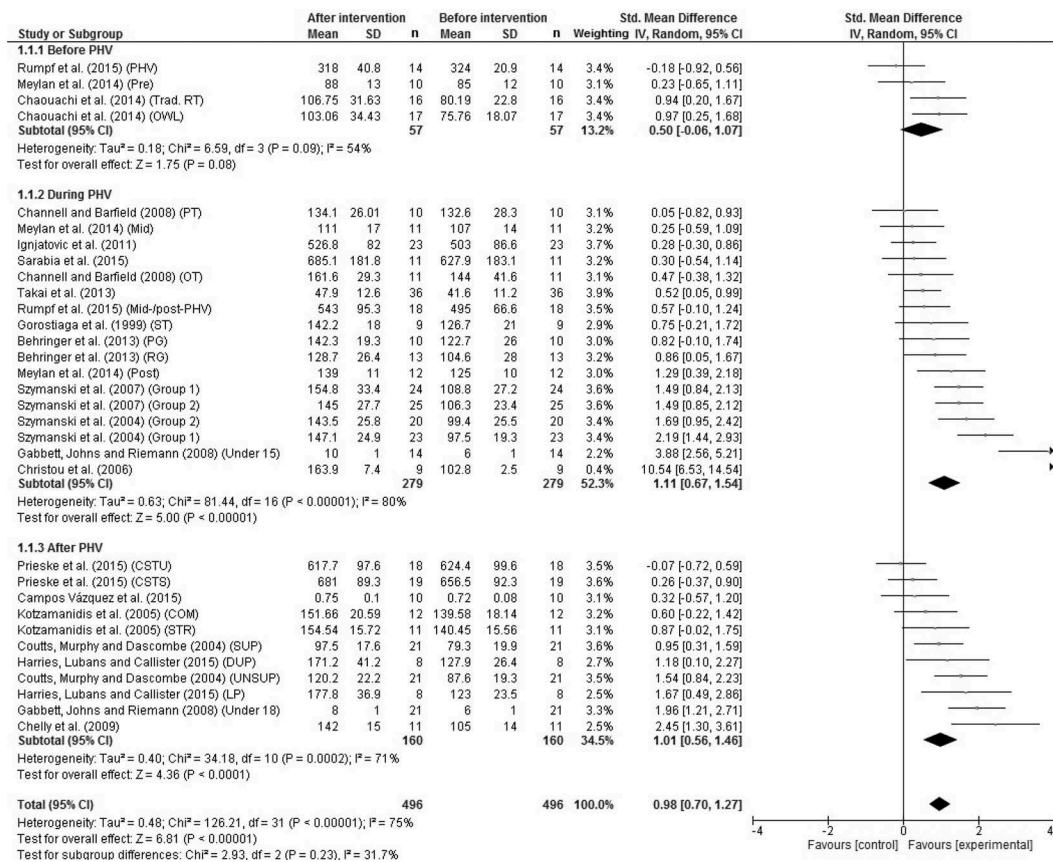


Figure 2. Forest plot of strength change in each maturation group with 95% confidence intervals. OWL: Olympic-style weightlifting, Trad. RT: resistance training, Pre: pre-PHV, PHV: pre-peak height velocity, PG: plyometric training, RG: resistance-training, OT: Olympic lifting, PT: powerlifting, ST: strength training, Mid: mid-PHV, Post: post-PHV, mid-/post-PHV: mid-/post-peak height velocity, SUP: supervised, UNSUP: unsupervised, DUP: daily undulating periodised, LP: linear periodised, COM: combined Training, STR: strength training, CSTS: stable surface core, CSTU: unstable surface core.

to chance" (Liberati et al., 2009). Higgins, Thompson, Deeks, and Altman (2003) stated that low, moderate and high heterogeneity correspond to I^2 values of 25%, 50% and 75%, respectively; however, these thresholds are considered tentative.

A risk of bias quality scale was not used. The Cochrane Collaboration discourages the use of such scales, stating that they are not supported by empirical evidence and can be inaccurate (Higgins, Altman, & Sterne, 2011). Studies of physical training have methodological constraints that can lead to lower scores relating to bias (Bolger, Kenny, Lyons, & Harrison, 2015). This can undermine the blinding of participants, trainers and assessors. Previous meta-analyses on resistance training in youths have reported low study quality and a medium to high risk of bias (Behringer et al., 2010; Harries et al., 2012).

Analysis of moderator variables

To identify other sources of heterogeneity, moderator variables were determined and assessed (Sandercock, Bromley, & Brodie, 2005). A summary of these can be seen in Table 3. Analysed with a random-effects model, moderator variables were selected based on differences in training programme configuration that could influence outcome measures (Wernbom, Augustsson, & Thomee, 2007). Programme duration and mean total training sessions were selected because longer training programmes could lead to sustained

performance improvements (Kraemer & Ratamess, 2004). Mean weekly training frequency was selected as this could have an impact on the magnitude of adaptation to training (Ross & Leveritt, 2001). All programme variables were grouped using a median split.

Results

Primary effects

The pooled mean estimate for all groups ($n = 3$) showed an increase in muscular strength (0.98 [0.70–1.27], $Z = 6.81$ [$P < 0.001$]). The overall estimate was moderate but there was heterogeneity among studies ($I^2 = 75\%$ [$P < 0.001$]).

Effects across and in maturity groups

In the "before" PHV group, the effect size for change in strength was small ($ES = 0.50$ [–0.06–1.07], $Z = 1.75$ [$P = 0.08$]). The "during" PHV group demonstrated a moderate increase in strength ($ES = 1.11$ [0.67–1.54], $Z = 5.00$ [$P < 0.001$]). This effect size was the largest of the three groups but the estimate was highly heterogeneous ($I^2 = 80\%$ [$P < 0.001$]). The "after" PHV group estimate was also moderate ($ES = 1.01$ [0.56–1.46], $Z = 4.36$ [$P < 0.001$]) and highly heterogeneous ($I^2 = 71\%$ [$P < 0.001$]).

Table 3. Effects of moderator variables on effect size for change in strength.

Moderator variable	Subgroup	Effect size (95% C.I.)	N	P	Between-group I^2	Between-group P	Within-group I^2	Within-group P
Programme duration	> 9.5 weeks	1.48 (1.06–1.9)	16	<0.001	93.7%	<0.001	77%	<0.001
	< 9.5 weeks	0.48 (0.24–0.73)	16	<0.001				
Mean total sessions	>24.5 sessions	1.63 (1.10–2.15)	12	<0.001	92.1%	<0.001	82%	<0.001
	< 24.5 sessions	0.59 (0.35–0.83)	20	<0.001				
Mean weekly training frequency (sessions)	>2.5 sessions	1.22 (0.76–1.68)	13	<0.001	55.5%	0.13	81%	<0.001
	< 2.5 sessions	0.78 (0.45–1.12)	19	<0.001				

Heterogeneity between maturity groups was moderate ($I^2 = 31.7\%$ [$P = 0.23$]).

Effect of moderator variables

Subgroup analysis indicated that programme duration accounted for a large proportion of the between-group heterogeneity ($I^2 = 93.7\%$, $P < 0.001$) with longer (>9.5 weeks) programmes producing greatest gains in strength (ES = 1.48 [1.06–1.9], $Z = 6.89$ [$P < 0.001$]). Total training sessions were also a source of between-study heterogeneity ($I^2 = 92.1\%$, $P < 0.001$). Studies reported that more than 24.5 training sessions produced the largest mean estimate (ES = 1.63 [1.10–2.15], $Z = 6.11$ [$P < 0.001$]). Training frequency explained a moderate proportion of between-group heterogeneity ($I^2 = 55.5\%$, $P = 0.13$). Mean estimates remained heterogeneous in all subgroups and heterogeneity was less in subgroups with smaller effect sizes, shorter programmes, fewer training sessions and less frequent training.

Discussion

This meta-analysis investigated the maturation-related pattern of adaptations to resistance training in boy athletes. Based on our results, it is concluded that strength, though trainable in boys, is sensitive to maturity status. Several controlled trials (Behringer, Neuerburg, Matthews, & Mester, 2013; Chaouachi, Othman, Hammami, Drinkwater, & Behm, 2014; Chelly et al., 2009) demonstrated that resistance training is moderately to largely effective in sport-playing boys with the diversity of age profiles in these studies suggesting that enhancements in strength occur regardless of biological maturity status. Throughout childhood and adolescence, factors that have been cited in support of this are broadly attributed to morphological and neurological changes (Behm, Faigenbaum, Falk, & Klentrou, 2008). Morphological adaptations include changes in muscle fibre size and composition, changes in myosin heavy chain, greater tendon stiffness and increases in the angle of muscle pennation. Neurological adaptations include increased activation of motor units, enhanced inter-muscular coordination and neuromuscular learning (Behm et al., 2008). Ultimately, as demonstrated by the primary effects, these mechanisms can lead to increases in strength in boys of any age, although the increases vary throughout growth and maturation (Lloyd et al., 2012).

The Long-Term Athlete Development Model (Balyi, Way, & Higgs, 2013) describes sensitive periods of adaptation when boys are more responsive to certain types of training. Indeed,

an increase in growth hormones and androgens during puberty could indicate a maturational threshold that signals peak growth of several indicators of performance (Malina et al., 2015; McNarry, Mackintosh, & Stoedefalke, 2014). This could signal the onset of heightened sensitivity to the demands of resistance training. However, the lack of empirical evidence to support the claims of the Long-Term Athlete Development Model has drawn criticism (Ford et al., 2011). Despite this, there is evidence (Lloyd, Oliver, Hughes, & Williams, 2011; Meylan et al., 2014; Rumpf et al., 2015) that specific periods of heightened adaptation do exist. The results of this meta-analysis seem to support these studies (Lloyd et al., 2011; Meylan et al., 2014) and could have implications for the way resistance training is planned for boy athletes.

Resistance training before PHV

The small effect size for strength gains before PHV indicates that resistance training is less effective in younger athletes. The “before” PHV athletes completed programmes of a similar length to the “during” and “after” PHV groups but were exposed to fewer total training sessions (approximately 20%) (Table 4). Preadolescent boys can increase muscular strength but because their hormonal profile is not conducive to increasing muscle mass (Faigenbaum et al., 2009), their potential for building strength is less than in older boys. Reflecting the pattern of strength development in the current review, a previous meta-analysis examining general-population boys and girls identified that younger participants had smaller increases in muscular strength (Behringer et al., 2010). Two intervention studies (Meylan et al., 2014; Rumpf et al., 2015) that measured biological maturity status (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002) reported similarly small (or negative) effect sizes before PHV (0.23 [–0.65–1.11] and –0.18 [–0.92–0.56]) than during and after PHV (1.29 [0.39–2.18] and 0.57 [–0.10–1.24]).

Together, these results could have occurred because of several factors. Lower concentrations of androgens and growth factors in younger athletes could mean that morphological changes that arise from resistance training were less

Table 4. Mean training programme characteristics.

Group	All	Before PHV	During PHV	After PHV
Training frequency (per week)	2.5 ± 0.7	2.2 ± 0.33	2.7 ± 0.9	2.4 ± 0.4
Number of weeks	9.9 ± 2.6	9.5 ± 3.0	9.4 ± 2.8	10.7 ± 2.0
Total sessions	24.7 ± 8.8	20.0 ± 4.6	25.1 ± 10.3	25.8 ± 7.0

Before PHV: 10–12.99-year-olds; during PHV: 13–15.99-year-olds; after PHV: 16–18-year-olds.

likely to occur. Biological maturity status is heavily influenced by these hormones that are associated with increased strength (Hansen, Bangsbo, Twisk, & Klausen, 1999) and impulse development in boys (Baldari et al., 2009).

Muscle hypertrophy can enhance muscular strength (Zatsiorsky & Kraemer, 2006). However, as preadolescents' ability to increase muscular size is less, they could be more dependent on neural mechanisms (Payne et al., 1997) to become stronger. For example, tendon cross-sectional area remained unchanged after resistance training of the plantar flexors in children, despite an increase in tendon stiffness of 29% (Waugh, Korff, Fath, & Blazeovich, 2014). In addition, maximal strength in upper and lower body muscle actions increased by 35% and 22%, respectively, in boys aged 9–11 years (Ramsay et al., 1990). These adaptations were independent of increases in muscular size despite a 30% improvement in the twitch torque of the knee extensor and elbow flexor muscles.

Given the above, Meylan et al. (2014) suggested that impulsive muscular actions could be optimally developed before PHV because of increased fascicle length and faster development of the central nervous system. Accordingly, a preferential emphasis on training with an impulsive component is warranted (Lloyd et al., 2011; Meylan et al., 2014) alongside a programme of fundamental movement skills training (Lloyd & Oliver, 2012). However, this should not be completely at the expense of resistance training as this is considered a prerequisite for effective impulsive performance (Stone et al., 2003).

Despite smaller effect sizes seen before PHV, resistance training should still be considered an important part of any sport preparation programme for younger children as it could be particularly effective in offsetting injury risk (Myer et al., 2011) because of enhanced tendon stiffness (Waugh et al., 2014). On this, a diversity of physical activities forms the basis for more intense activities later in life (Bergeron et al., 2015). A wide-ranging programme such as that of Faigenbaum et al. (2011) incorporates elements of basic strength exercises and neuromuscular coordination and addresses fundamental movement skills in prepubertal boys in a developmentally appropriate way.

The results seen before PHV are not suitable to generalise about the magnitude of adaptation to resistance training at that time of maturation because of the small body of research that examines the modality in athletes between the ages of 10 and 13 years. Additional controlled intervention studies are needed to improve descriptions of adaptations of athletes in that age range to resistance training.

Resistance training during and after PHV

Larger effect sizes seen in the more mature groups mirror results reported by the few studies in this meta-analysis that saw boys of differing maturity status presented with an identical resistance training stimulus (Meylan et al., 2014; Rumpf et al., 2012). Resistance training could be more effective during and after the time of the growth and strength spurts (De Ste Croix, 2007) as these are denoted by increases in muscle mass because of rising concentrations of anabolic hormones (Rogol, Roemmich, & Clark, 2002). PHV coincides with the

greatest gain of relative strength in boys (Viru et al., 1999) and is followed by peak body-mass velocity that is characterised by gains in bone and skeletal muscle tissues (Malina et al., 2004, 2015). At this time, muscle mass grows at its greatest rate, and hypertrophic gains are associated with enhanced force production capability (Zatsiorsky & Kraemer, 2006).

As resistance training is more effective during and after PHV, it could be beneficial to conduct a higher volume of exercise during these times, after appropriate foundational training at a younger age. However, it is important to consider that PHV can also coincide with higher susceptibility to traumatic and over-use injuries because of joint stiffness, impaired motor coordination and a differential in the ratio of limb growth to muscle strength (van der Sluis et al., 2014). This means that coaches must be cautious when programming resistance training as any increased trainability can coincide with a greater vulnerability to injury that can also persist after PHV (van der Sluis et al., 2014). Regardless of the magnitude of trainability, it is important that the training age of the athlete is taken into account when making programming decisions as increased training intensity and volume during and after PHV might not be advisable for inexperienced athletes (Lloyd et al., 2012).

The slightly lower effect size seen after PHV could be because of greater training experience and, thus, a lower ceiling of adaptation attributable to the accumulation of more training over greater durations (Deschenes & Kraemer, 2002; Hawley, 2008; Peterson, Rhea, & Alvar, 2004). Further research could identify if there is a difference in the size of adaptations among boys of similar training ages, but of different biological ages.

Effects of moderator variables

In meta-analysis, examination of potential moderator variables can gauge the influence of effect size modifiers, such as training intensity and duration, on primary effects (Ryan, 2014). The moderator variables of programme duration and mean total sessions had high heterogeneity. Mean weekly training frequency was a source of moderate heterogeneity. As anticipated, programmes of longer duration and more training sessions had greater effect. Also, a higher mean training frequency per week was more effective than a lower mean training frequency per week. High heterogeneity after subgroup analysis implies that moderators of the primary effect had not been identified meaning that other factors could account for training adaptations (Sandercock et al., 2005). This implies a synergy between programming variables and other factors, such as biological maturity, in determining the magnitude of adaptation to resistance training. Less variation among maturity groups than moderator variables was an anticipated outcome because of the highly variable nature of training programmes across studies. However, high heterogeneity in maturity groups could also be evidence of differing mechanisms of physiological adaptation to training. This could be particularly applicable when effect sizes of maturity groups are similar despite high heterogeneity, as can be observed in the “during” and “after” PHV groups.

Limitations

A lack of uniformity in how training programmes were prescribed could contribute to high heterogeneity. Additionally, the method of calculating effect sizes whereby baseline and post-training measures of muscular strength were compared only in intervention groups means that it is more difficult to differentiate between the effects of training and advancing maturation. On this, a subanalysis of the minority of studies that did include a comparable control group showed an effect size of 0.7 (0.2–1.2). This could reveal the proportion of strength gains that arise from training as opposed to those attributed to maturation.

The classifications used to account for biological maturity are related to chronological age and so can account for only some of the developmental diversity that is seen across groups. Relationships between physical performance and chronological age have been demonstrated (Deprez et al., 2015; Mendez-Villanueva et al., 2011; Valente-dos-Santos et al., 2014), implying that biologically mediated changes in physical performance can be captured via the used method. In relation to our subgroup analysis, we have dichotomised continuous data through median split and this could result in residual confounding and reduced statistical power (Altman & Royston, 2006; Sandercock, Alibrahima & Bellamy, 2016).

Conclusions

Our results show that resistance training is more effective during and after PHV in boy athletes and this means such exercise should be strategically programmed at this time. A practical measure of biological maturity, such as that put forward by Mirwald et al. (2002), can assist practitioners in assessing maturation status so that training can be prescribed in optimal doses at appropriate times.

Practitioners are advised to increase the intensity and volume of resistance training during and after PHV when adaptations are greater (Meylan et al., 2014). However, an athlete's training history and greater likelihood of sustaining injuries during PHV must also be carefully considered. Accordingly, a practitioner should ultimately make programming decisions based on movement proficiency and ability to display correct technique (Lloyd et al., 2012). Indeed, this approach should be prioritised across all youths, regardless of sex or maturity status. Before PHV, it could be beneficial to develop impulsive or neural qualities (Lloyd & Oliver, 2012; Lloyd et al., 2011) as specific types of training can vary in their effectiveness at different times throughout maturation (Moran et al., *in press*). A well-rounded integrative neuromuscular training programme could be an effective way to address foundational strength and movement skills before PHV (Faigenbaum et al., 2011) and prior to more advanced and voluminous training in later years. To summarise, this meta-analysis could assist coaches in determining the optimal time to programme resistance training as boys grow and mature in the long term. Its results can be considered complementary to those of other reviews (Behringer et al., 2010; Lesinski et al., 2016) which can help to determine appropriate programming variables for specific training session prescription.

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