ORIGINAL RESEARCH

Pediatric Exercise Science, 2011, 23, 186-206

Effects of Strength Training on Motor Performance Skills in Children and Adolescents: A Meta-Analysis

Michael Behringer and Andreas vom Heede
German Sport University Cologne

Maria Matthews
East Stroudsburg University

Joachim Mester
German Sport University Cologne

The recent literature delineates resistance training in children and adolescents to be effective and safe. However, only little is known about the transfer of achieved strength gains to athletic performance. The present meta-analysis revealed a combined mean effect size for motor skill types jumping, running, and throwing of 0.52 (95% CI: 0.33–0.71). Effect sizes for each of aforementioned skill types separately were 0.54 (95% CI: 0.34–0.74), 0.53 (95% CI: 0.23–0.83), and 0.99 (95% CI: 0.19–1.79) respectively. Furthermore, it could be shown that younger subjects and nonathletes showed higher gains in motor performance following resistance training than their counterparts and that specific resistance training regimes were not advantageous over traditional resistance training programs. Finally, a positive dose response relationship for "intensity" could be found in subgroups using traditional training regimens. These results emphasize that resistance training provides an effective way for enhancing motor performance in children and adolescents.

Numerous studies spanning the last 50 years have shown resistance training to be an effective and safe way for enhancing muscle strength in children and adolescents[1], if appropriately prescribed and supervised. Reviewing those studies by meta-analytical procedures, four meta-studies revealed that a variety of different resistance training programs can result in significant increases in muscle strength in children and adolescents (3,13,29,54). Furthermore resistance training has been shown to be associated with several health-related benefits such as increased bone mineral density, improved body composition and enhanced mental health and well-being (20).

Behringer, vom Heede, and Mester are with the Institute of Training Science and Sport Informatics, German Sport University Cologne, Cologne, Germany. Matthews is with East Stroudsburg University, East Stroudsburg, PA.

In contrast only little is known about the effect of resistance training on youth sports performance, due to a small number of conducted studies in that field (4,8,10,32,35). This situation might be explained by the multivariate characteristic of the athletic performance that makes it difficult to identify the impact of single influencing factors, such as resistance training. Consequently it seems reasonable to limit the scope to fundamental sport skills (e.g., jumping, running, throwing) which affect the performance in nearly all types of sports. But contrary to expectations, previously published studies have failed to detect a definite link between skeletal muscle strength and aforementioned skills (24,27,30). In this context, Milliken and coworkers (51) found only weak correlation coefficients between lower body muscular strength and vertical ($r = .09$) or long jump ($r = .18$) performance. Therefore it remains unclear, whether improvements in muscle strength resulting from resistance training will lead to a higher sport specific performance in childhood and youth. In addition, it remains to be determined how much specificity in resistance training is needed.

For this reason the primary aim of the present meta-analysis was (a) to evaluate the broader question, whether resistance training can be an effective method for improving different types of motor performance skills in children and adolescents and secondary, (b) to identify subject- and program- related parameters which might have an impact on the effectiveness of the training intervention. Such moderator analysis might reveal a closer insight on how sports-related resistance training programs should be designed. Currently available sport specific exercise prescriptions and guidelines are still simply based on anatomical requirement profiles of different sports disciplines (44)—i.e., strengthening all muscles that are predominantly needed in a given sport.

Methods

Data Sources

Systematic computerised searches of the following databases from their inception to the end of August 2009 were undertaken: Medline (1966), PubMed (1966), Sport Discus (1975), ERIC (1966), Web of science (1945) and Evidence Based Medicine Reviews Multifile (1917). In addition hand searching of key journals and reference lists was performed. To avoid an oversampling of statistically significant studies that are preferentially published in English language (19) and peer reviewed journals, German studies and studies from the gray literature[2] were included in the present meta-analysis. The following subject headings, key words and text words, in English and German respectively, were included: children, adolescents, youth, athletes; resistance, strength, weight, power; training, exercise and sport and motor performance. When data were missing from the original document, authors were contacted to provide additional information.

Study Selection and Quality Assessment

Inclusion criteria were: (i) the study design must have included a traditional resistance and/or plyometric[3] training intervention; (ii) the effects of resistance and/or plyometric training on motor performance skills must have been examined and reported in means and standard deviations for the treatment (TG) and control group (CG) for pre- and posttests; (iii) the age of participants had to be 18 years or less; (iiii) research must have been conducted on healthy male or female subjects. Overweight children were considered to meet this criterion unless any indispositions were reported.

Presented motor performance skills have been grouped into three different skill types: jumping, running, and throwing. The first group consisted of vertical jumps and long jumps, whereas the second consisted of shuttle runs and sprints. The third cluster consisted of medicine ball puts / throws.

Two independent investigators assessed the methodological quality of the selected studies by use of the PEDro scale (53). Any discrepancies were resolved by a third investigator. Methodological quality was not an inclusion criterion. The quality of evidence was assessed with the Strength of Recommendation Taxonomy (18).

Meta Analysis Procedure

It is necessary to combine data from multiple studies, to increase the precision of treatment effect estimates. The appropriate statistical method for this approach, the meta-analysis, was first introduced by Glass 1976 (34). In contrast to narrative reviews the meta-analysis provides the opportunity to quantify the results of various studies to a standard metric called effect size (ES) that allows comparisons by the use of statistical methods.

The effect size for prepost-test designs in this study was computed as the difference between the standardized mean change for the treatment and control groups divided by the pooled pretest standard deviation proposed by Hedges and Olkin (39):

$$ES = c\frac{\left(\mu_{Tpost} - \mu_{Tpre}\right) - \left(\mu_{Cpost} - \mu_{Cpre}\right)}{SD_{pooled}}$$

where μ_{Tpre} and μ_{Cpre} are the mean pretest scores and μ_{Tpost} and μ_{Cpost} are the mean posttest scores of the training (T) and control group (C), respectively. The population variance was estimated by the pooled estimate of variance:

$$SD_{pooled} = \sqrt{\frac{\left(n_T - 1\right)SD^2_T + \left(n_C - 1\right)SD^2_C}{n_T + n_C - 2}}$$

where n_T and n_C are the numbers of participants and SD is the pretest standard deviation of each group (52). As effect sizes of small samples tend to be positively biased and therewith overestimated, a virtually unbiased estimate was calculated by using a correction factor(38):

$$c = 1\frac{3}{4\left(n_T + n_C - 2\right) - 1}$$

Based on the fact that the studies were drawn from different populations and therefore many variables may have an impact on the treatment effect, the random effects model was used for the meta-analysis procedure. Under this model it is assumed that there is a distribution of true effects, rather than there is one true effect size $(ES)_{\text{true}}$ and the combined effect represents the mean of the population of true effects (6). In this model statistical variability caused by sampling error (*var* (*ES*)) and substantive variability (τ^2) is incorporated:

$$ES = ES_{true} + \text{var}(ES) + \tau^2$$

For assessing the proportion of the observed variance that reflects real differences in effect size due to heterogeneity rather than sampling error, the I^2-Index was examined.

In cases where studies used a single control group and more than one treatment group, the data of the control group should not be used to compute more than one ES, as the information of this ESs would not be independent. To ensure that control participants of trials with multiple treatment groups and only one control group were not counted more than once, the control group participant number was divided out equally among comparisons (15).

Statistical Analysis

The impact of categorical moderator variables was assessed by subgroup meta-analyses and z-tests, whereas meta-regressions and Pearson (r) correlation tests were used to examine the relationships between ESs and continuous variables. The hypothesized categorical moderator variables were: sex (male vs. female), maturity (prepubertal vs. intra/postpubertal), training type (auxotonic vs. isokinetic vs. isometric), and resistance type (machine vs. free weights vs. mixed). For quantitative independent variables the duration of intervention, the age of participants, the training frequency per week, the number of sets, the number of repetitions, and the mean intensity (average percent of 1RM used throughout the training) were tested. When continuous moderator variables were listed as ranges and no raw data were available to calculate a mean, data were excluded from statistical analyses. Statistical significance was set to *p* £ 0,05 for all analyses. A funnel graph was plotted to determine whether publication bias existed. Z-test, meta-regression and production of all graphics were performed using Statistica version 7.1 (StatSoft, Inc., Tulsa, USA).

Results

The searches provided 152 studies as potential relevant, spanning the period of 1949–2009. After excluding 103 studies in the initial assessment, 49 Studies were retained for further evaluation. Of these, only 34 met the inclusion criteria for meta-analysis. According to the fact that some studies examined the effects of resistance training in different subgroups, the 34 studies represented a total of 51 combined effect sizes, based on 124 outcomes. The PEDro scores of the included 34 studies ranged from 2/10–7/10 (4.56 ± 0.99).

The number of participants in the included studies was 1432 (T: 845; C: 587). There was a distinct sex imbalance, with a total of 1019 male (T: 593; C: 398) and 413 female subjects (T: 214; C: 169), respectively. Sex distribution was not presented for two subgroups of one study, with a total of 28 male and 30 female participants. Although some studies presented demographic data as ranges, the estimated mean age of all analyzed subjects was 13.2 years (*SD*: 3.12). Only one-third (n = 476) of all children and adolescents were classified for maturational status. Of these, 85 subjects were categorized as prepubertal, 81 as pubertal, and 43 as postpubertal, respectively. For 228 subjects the maturational status was provided as a range of pre- to early pubertal stages (Tanner stage 1–2) while two subgroups consisted of 39 intra- to post pubertal subjects (Tanner 3–5).

The overall mean height of subjects was 151.2cm whereas the mean body weight was 60.0kg. 39.6% of subgroups were reported to be novice, while only 11.3% had previous strength training experience. For the remaining studies the respective training status was not documented. Eighteen (34.0%) out of 53 subgroups were classified as athletes.

The applied training programs showed an extensive variation in duration, frequency, intensity, volume (sets x repetitions), and type of exercise. The duration of the analyzed training interventions ranged from 6 to 68 weeks ($\bar{x}$ = 10.7 ± 8.8) with a mean training frequency of 2.6 ± 0.9 sessions per week and an average work-out duration of 41 ± 0.9 min.. In 17 cases, body weight was used as resistance type, whereas 16 subgroups used free weights or performed exercises on weight training machines. Although various combinations of sets and repetitions from single-set protocols with moderate loading to multiple set training regimens with near-maximal loading have been applied, the average auxotonic strength training program design consisted of 2–3 sets with 8–15 repetitions and loads between 60% and 80% of the 1RM on 4–8 exercises. Training loads were usually determined either by taking a specific percentage of the 1 RM or by performing a multiple-RM testing, e.g., 10RM. The average plyometric resistance training program consisted of 3–5 sets with 8–12 repetitions on 3–7 exercises, which roughly corresponds to 100 jumps per session. Detailed characteristics of the included studies, specifically participants and intervention design, are illustrated in Table 1.

To evaluate whether resistance training is generally suitable for improving motor performance in children and adolescents, a combined mean effect size was calculated for the motor skill types jumping, running, and throwing. This analysis revealed a pooled ES of 0.52 (95% CI: 0.33–0.71; see Figure 1). Since the heterogeneity index I^2 was equal to zero, a similar pooled estimate was found using a fixed-effect model (ES: 0.50; CI: 0.39–0.61). Both, fixed- and random-effect, were significantly greater than zero (p < .01). Subgroup analyses showed no significant differences in ESs between nonathletes and athletes. Moreover, there were no significant differences between traditional-, plyometric-, or mixed resistance training programs (all p > .05). In contrast, a significant negative correlation coefficient was found for age of subjects (r = -0.25; p < .05) with the magnitude of the ES. Further, for subgroups using traditional training regimens, meta-regressions disclosed a significant correlation coefficient for mean intensity expressed as a percentage of 1RM (r = .38; p < .05) with the magnitude of ES. Since no comparable standardized parameter was available for assessing the intensity of plyometric training programs, no such analysis was performed for those subgroups. Besides aforementioned, no other subject- or program design-parameter reached significance.

Table 1 Chronological Summary of Main Characteristics of All Studies Included in the Meta-Analysis

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Taddonio et al. 1966(58)	Male	16	14	Grade 5	M	16	5	15	BW	Trad	-	1x3–20	?	?
Taddonio et al. 1966(58)	Female	11	13	Grade 5	F	16	5	15	BW	Trad	-	1x3–20	?	?
Blattner & Noble, 1979(5)	Iso-kinetic	12	15	17	M	8	3	?	MA	Trad	-	3x10	?	1
Blattner & Noble, 1979(5)	Plyo-metric	11			M	8	3	?	BW	Plyo	30	3x10	?	1
Ford & Puckett 1983(32)	-	17	15	14–15	M	6	4	?	FW	Trad	-	-	?	4
Brown et al. 1986(7)	-	13	13	15,0 ±0,7	M	12	3	?	BW	Plyo	30	3x10	?	1
Weltman et al., 1986(62); Rians et al., 1987(55)	-	16	10	8,2	M	14	3	45	MA+BW	Trad	-	Max. Reps. in 30sec.	?	10
Diekmann & Letzelter, 1987(16)	Male	33	33	8–8,1	M	12	3	30–45	?	Trad	-	?	?	?
Diekmann & Letzelter, 1987(16)	Female	33	33	8–8,1	F	12	3	30–45	?	Trad	-	?	?	?
Duke & Ben Eliyahu, 1992(17)	-	5	5	16	M	6	2–3	?	BW	Plyo	300	1–6x1–40	?	16

(continued)

Table 1 (continued)

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Faigenbaum et al., 1993(27)	-	14	9	10,8	M+F	8	2	35	MA, BW	Trad	-	3x10–15	50–100% 10RM	7
Falk & Mor,1996(28)	-	14	15	6,4	M	12	2	40	BW	Trad		3x1–15	?	?
Holcomb et al., 1996(41)	Weight Training	12		16	M	8	3	?	MA	Trad	-	3x4–8	4–8RM	4
Holcomb et al., 1996(41)	CMJ	10	9	16	M	8	3	?	BW	Plyo	72	9x8	Max. Effort	4
Holcomb et al., 1996(41)	Plyo-metrics	10		16	M	8	3	?	BW	Plyo	72	9x8	Max. Effort	?
Holcomb et al., 1996(41)	Mod. Plyo-metrics	10		16	M	8	3	?	BW	Plyo	72	3x8	Max. Effort	3
Faigenbaum et al., 1996(26); Faigenbaum et al., 1997(26)	-	15	9	10,8	M+F	8	2	?	MA, BW	Trad	-	2–3x 6–20	6–20RM	7
Wagner et al., 1997(60,60)	Nonath-letic	20	20	17,5	M	6	2	?	BW	Plyo	60–80	2–5x 3–7	?	4
Wagner et al., 1997(60)	Athletic	20	20	17,5	M	6	2	?	BW	Plyo	60–80	2–5x 3–7	?	4

(continued)

Table 1 (continued)

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Hetzler et al., 1997(40)	Novice Training Group	10	10	13,8	M	12	3	?	MA, FW	Trad	-	3x10	50–100% 10RM	9
Hetzler et al., 1997(40)	Expe-rienced Training Group	10		13,2	M	12	3	?	MA, FW	Trad	-	3x10	50–100% 10RM	9
Lillegard et al., 1997(45)	Tanner 1–2 (male)	20	18	11,2	M	12	3	40	MA, FW	Trad	-	3x10	10RM	6
Lillegard et al., 1997(45)	Tanner 1–2 (female)	8	6	9,5	F	12	3	40	MA, FW	Trad	-	3x10	10RM	6
Lillegard et al., 1997(45)	Tanner 3–5 (male)	16	10	13,9	M	12	3	40	MA, FW	Trad	-	3x10	10RM	6
Lillegard et al., 1997(45)	Tanner 3–5 (female)	8	5	13,8	F	12	3	40	MA, FW	Trad	-	3x10	10RM	6
Cossor et al.,1999(12)	-	19	19	11,7	M	20	3	15	BW	Plyo	300–450	2x10–15	Low—Mod[b]	15
Gorostiaga et al., 1999(35)	-	9	9	15,1	M	6	2	40	MA	Trad	-	4x3–12	40–90% 1RM	5

(continued)

Table 1 (continued)

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Matavulj et al., 2001(50)	EG-50	11	11	15–16	M	6	3	?	BW	Plyo	30	3x10	Max Effort	1
Matavulj et al., 2001(48)	EG-100	11		15–16	M	6	3	?	BW	Plyo	30	3x10	Max Effort	1
Faigenbaum et al., 2002(25)	1x/ week	22	13	10,2	M+F	8	1	30–40	MA, BW	Trad	-	1x10–15	10–15RM	12
Faigenbaum et al., 2002(25)	2x/week	20		9,7	M+F	8	2	30–40	MA, BW	Trad	-	1x10–15	10–15RM	12
Flanagan et al.2002(30)	Machine	14	20	8,8	M+F	10	2	40	MA	Trad	-	1–3x8–15	10–15RM	8
Flanagan et al.2002(30)	Body Weight	24		8,6	M+F	10	2	40	BW	Trad	-	"varied"	"varied"	5
Siegler et al., 2003(57)	-	17	17	16,5	F	10	5	45	MA, BW	Mix	50[c]	3–5 Sets	?	9
MacKelvie et al., 2003(46)	-	32	43	9,9	F	68	5	1,5–2	BW	Plyo	50–100	1x10–20	3.5–5x BW	5
Gorostiaga et al.,2004(36)	-	10	11	17,2	M	11	2	40	FW, MA, BW	Mix	12–40[d]	2–5x3–8	?	5
Martel et al. 2005(49)	-	10	9	15	F	6	2	45	BW	Plyo	?	2–4x ?	Max Effort	7

(continued)

Table 1 (continued)

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Faigenbaum et al., 2005(24)	LoRep	19	12	10,4	M+F	8	2	30	MA, BW	Trad	-	1x15–20	15–20RM	9
	HiRep	12		10,4	M+F	8	2	30	MA, BW	Trad	-	1x6–10	6-10RM	9
Christou et al., 2006(10)	-	9	8	13,8	M	16	2	?	FW, MA, BW	Trad	-	2–3x8–15	55–85% 1RM	10
Athanasiou et al., 2006(1)	-	10	10	13–15	M	8	2	?	FW, MA, BW	Mix	0–100	3–8x4–20	?	14–15
Ingle et al., 2006(42)	-	33	21	12,3	M	12	3	60–75	FW	Mix	-	1–3x6–15	70–100%10RM	8
Faigenbaum et al., 2006(23)	-	69	49	15–16	M+F	6	2	10–15	FW	Trad	-	1–3x5–15	Lev. 1–6 of 6 Levels	15–40
Kotzamandis et al., 2006(43)	-	15	15	11,1	M	10	-	?	BW	Plyo	79	10x6–10	?	?
Vom Heede et al., 2007(59)	Elastic Band	24	16	10,6	M+F	8	2	45–90	FW	Trad	-	2–3x30	?	7
Vom Heede et al., 2007(59)	Speed Strength	20		10,6	M+F	8	2	45–90	BW, FW	Mix	120	3x10	?	7
Mikkola et al., 2007	-	13	12	16–18	M+F	8	2	30–60	FW, MA, BW	Mix	-	2–3x 6–10	?	6
Faigenbaum et al., 2007(22)	-	13	14	13,4	M	6	2	90	BW, FW	Plyo	82,5	1–3x6–12	Trad: 10–12 RM / Plyo: ?	10–12

(continued)

Table 1 *(continued)*

Study	Sub-group	N (T)	N (C)	Age [y][a]	Sex	St-dur [w]	S/w	S-dur [min]	R-type	T-type	No. of Jumps	Sets x reps or duration	Intensity [% of 1RM]	No. of exer-cises
Channell &Barfield, 2008(9)	Olympic	11	6	15,9	M	8	3	?	FW	Trad	-	3–5x 3–20	60–95%1RM	8
Channell &Barfield, 2008(9)	Tradi-tional	10			M	8	3	?	FW	Trad	-	3–5x 3–20	60-100%1RM	8
Santos & Janeira, 2008(56)	-	15	10	14,7	M	10	2	?	MA, BW	MIX	114	2–3x 5–12	10–12RM	6

[a] Age of participants expressed in years (if available)

[b] Exercise intensity were classified as low to moderate according to Chu (11)

[c] Data derived from (14)

[d]Training program included CMJs and VJs with eccentric actions performed at low velocity. Due to the lack of the stretch-shortening cycle (SSC), training type did not meet requirements of plyometric training.

BW = body weight; C = control group; E-dur = Exercise duration; F = female; FW = free weights; M = male; MA = machines; Mix = mixed programmes (strength training programmes that consist of a combination of plyometric and traditional training); Plyo = plyometric training (strength training programmes including stretch-shortening-cycle exercises); R-type = resistance type; Reps = repetitions; RM = repetition maximum (all listed RM-values refer to exercises of Trad training programmes exclusively); S = duration of one training session; St-dur = study duration; S/w = training sessions per week; T = treatment group; T-type = training type; Trad = traditional strength training (strength training programmes with all kind of resistance to muscle-contraction but without stretch-shortening-cycle).

Study	Subgroup	ES	Var	SE	Lower limit	Upper limit	Z value	p	Relative Weight
Taddonio et al. 1966	Male	0,07	0,07	0,27	-0,46	0,61	0,26	0,79	2,85
Taddonio et al. 1966	Female	0,14	0,07	0,27	-0,39	0,68	0,52	0,60	2,86
Blattner & Noble, 1979	Isokinetic	0,58	0,16	0,40	-0,20	1,35	1,46	0,14	2,32
Blattner & Noble, 1979	Plyometric	0,66	0,17	0,41	-0,14	1,46	1,62	0,11	2,27
Ford & Puckett 1983		0,15	0,13	0,35	-0,54	0,85	0,43	0,67	2,49
Brown et al. 1986		0,69	0,16	0,40	-0,10	1,48	1,72	0,09	2,28
Weltman et al., 1986		0,37	0,17	0,41	-0,43	1,17	0,91	0,36	2,26
Diekmann & Letzelter, 1987 (1)	Male	2,74	0,14	0,37	2,01	3,46	7,40	0,00	2,42
Diekmann & Letzelter, 1987 (1)	Female	3,13	0,14	0,37	2,41	3,85	8,51	0,00	2,43
Duke & Ben Eliyahu, 1992		0,39	0,41	0,64	-0,86	1,64	0,61	0,54	1,46
Faigenbaum et al., 1993		0,17	0,18	0,43	-0,67	1,01	0,41	0,68	2,18
Falk & Mor, 1996		0,76	0,14	0,38	0,02	1,51	2,01	0,04	2,39
Holcomb et al., 1996	CMJ	0,33	0,55	0,74	-1,13	1,78	0,44	0,66	1,21
Holcomb et al., 1996	Weight training	0,25	0,53	0,73	-1,17	1,68	0,35	0,73	1,24
Holcomb et al., 1996	Plyometrics	0,64	0,56	0,75	-0,82	2,11	0,86	0,39	1,19
Holcomb et al., 1996	Mod. Plyometrics	0,60	0,56	0,75	-0,87	2,07	0,80	0,42	1,20
Faigenbaum et al., 1996		0,64	0,19	0,43	-0,21	1,48	1,48	0,14	2,17
Lillegard et al., 1997	Tanner 1-2 male	0,50	0,11	0,33	-0,16	1,15	1,49	0,14	2,59
Lillegard et al., 1997	Tanner 1-2 female	0,48	0,30	0,55	-0,59	1,56	0,88	0,38	1,74
Lillegard et al., 1997	Tanner 3-5 male	0,36	0,17	0,41	-0,45	1,16	0,86	0,39	2,24
Lillegard et al., 1997	Tanner 3-5 female	0,33	0,33	0,58	-0,79	1,46	0,58	0,56	1,65
Hetzler et al., 1997	Novice	0,06	0,31	0,55	-1,03	1,14	0,10	0,92	1,72
Hetzler et al., 1997	Expirienced	-0,04	0,31	0,56	-1,13	1,06	-0,06	0,95	1,71
Wagner et al., 1997	Nonathletic	0,23	0,15	0,39	-0,53	0,99	0,59	0,56	2,34
Wagner et al., 1997	Athletic	0,28	0,15	0,39	-0,48	1,05	0,73	0,47	2,34
Cossor et al., 1999		-0,35	0,11	0,33	-0,99	0,29	-1,08	0,28	2,61
Gorostiaga et al., 1999		-0,07	0,22	0,47	-0,99	0,86	-0,14	0,89	2,01
Matavulj et al., 2001	EG-50	0,84	0,29	0,54	-0,22	1,91	1,55	0,12	1,76
Matavulj et al., 2001	EG-100	1,21	0,32	0,56	0,11	2,32	2,16	0,03	1,69
Faigenbaum et al., 2002	1x/ week	0,03	0,20	0,45	-0,84	0,91	0,08	0,94	2,11
Faigenbaum et al., 2002	2x/ week	0,26	0,21	0,45	-0,63	1,15	0,58	0,56	2,08
Flanagan et al. 2002	Machine trained	0,12	0,17	0,42	-0,70	0,93	0,28	0,78	2,23
Flanagan et al. 2002	Body weight	0,24	0,14	0,38	-0,50	0,99	0,64	0,52	2,38
Siegler et al., 2003		0,09	0,12	0,35	-0,58	0,77	0,27	0,79	2,53
MacKelvie et al. 2003		0,27	0,05	0,23	-0,19	0,73	1,16	0,25	3,03
Gorostiaga et al., 2004		0,39	0,20	0,45	-0,48	1,27	0,88	0,38	2,11
Martel et al. 2005		0,46	0,22	0,47	-0,45	1,37	0,99	0,32	2,03
Faigenbaum et al., 2005	LoRM	0,08	0,22	0,47	-0,84	1,00	0,17	0,86	2,02
Faigenbaum et al., 2005	HiRM	0,16	0,25	0,50	-0,82	1,14	0,32	0,75	1,90
Athanasiou et al., 2006		-0,07	0,20	0,45	-0,95	0,80	-0,16	0,87	2,10
Faigenbaum et al., 2006		0,52	0,04	0,19	0,15	0,89	2,75	0,01	3,21
Christou et al., 2006		2,00	0,40	0,63	0,76	3,24	3,17	0,00	1,48
Ingle et al. 2006		0,22	0,08	0,28	-0,33	0,77	0,78	0,44	2,82
Kotzamanidis et al., 2006		1,98	0,20	0,45	1,11	2,86	4,43	0,00	2,10
vom Heede et al., 2007	Elastic band	0,61	0,19	0,43	-0,24	1,46	1,40	0,16	2,15
vom Heede et al., 2007	Speed strength	0,55	0,17	0,42	-0,27	1,37	1,31	0,19	2,22
Mikkola et al., 2007		0,74	0,17	0,41	-0,07	1,55	1,79	0,07	2,24
Faigenbaum et al., 2007		0,33	0,15	0,39	-0,43	1,09	0,84	0,40	2,34
Channel & Barfield, 2008	Olympic	0,53	0,43	0,66	-0,76	1,82	0,81	0,42	1,41
Channel & Barfield, 2008	Traditional	0,28	0,44	0,66	-1,02	1,57	0,42	0,68	1,40
Santos & Janeira, 2008		0,89	0,15	0,38	0,13	1,64	2,31	0,02	2,36
Total (Random)		0,52	0,01	0,10	0,33	0,71	5,41	0,00	

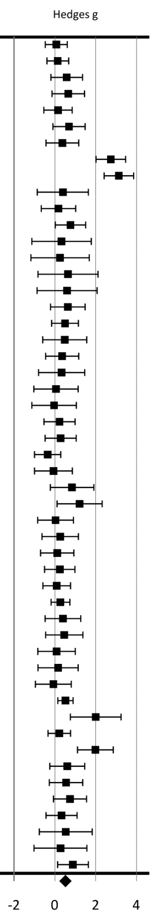

Figure 1 — Forest plot of meta-analysis showing the combined ES of each subgroup as well as the summary effect. ES = Effect size; Var = Variance; *SE* = Standard error 10

Analyzing each skill type in separate meta-analyses (see Tables 2 through 4) revealed that the greatest effect size occurred in throwing performance tests. The combined ES for this cluster was 0.99 (95% CI: 0.19–1.79). The effect sizes for the jumping- and sprinting-cluster was 0.54 (95% CI: 0.34–0.74) and 0.53 (95% CI: 0.23–0.83), respectively. All three ESs were significantly greater than zero ($p < .01$) but no significant differences were found between the selected skill types.

Discussion

The overall weighted ES of 0.52 (*SE*: 0.1) of this investigation demonstrates that structured resistance training programs significantly improve running-, jumping-, and throwing-performance in children and adolescents. Since motor performance

Table 2 Analysis for Categorical Moderator Variables Affecting the Combined Motor Performance Outcome

Independent variables	Z	p	ES	*SE*	N
Condition	1.24	0.24			
Non-Athlete			0.64	0.17	24
Athlete			0.40	0.12	18
Training Type					
Traditional vs. Plyometric	0.16	0.87			
Traditional vs. Mixed	0.93	0.35			
Plyometric vs. Mixed	0.77	0.35			
Plyometric			0.51	0.15	15
Traditional			0.54	0.15	29
Mixed			0.36	0.12	7

Table 3 Analysis for Continuous Moderator Variables of Subject Characteristics and Program Design Elements

Independent variables	$\bar{x}$	*SD*	n	r[a]	p
Age (years)	13.00	3.16	45	-0.25	0.02
Height (cm)	146.61	29.18	51	-0.15	0.13
Weight (kg)	65.18	24.87	51	-0.16	0.11
Duration (weeks)	10.73	8.76	51	-0.07	0.51
Mean intensity (% of 1RM)*	71.12	8.88	21	0.38	0.02
Frequency (Sessions / week)	2.63	0.85	50	-0.05	0.60
Number of Sets	3.19	1.92	37	0.12	0.33
Number of Repetitions	11.02	4.14	28	-0.04	0.80

[a] r = Correlation coefficient

Table 4 Analysis for Motor Performance Skill Groups

Motor Performance Skills	Z	p	ES	*SE*	N
Groups					
Throwing vs. Running	0.69	0.49			
Throwing vs. Jumping	0.69	0.49			
Jumping vs. Running	0.04	0.97			
Throwing			0.99	0.41	11
Jumping			0.54	0.10	50
Running			0.53	0.15	23

Note: The values listed in this table refer to three separately performed meta-analyses for each of the analyzed skill types. Therefore the total number of effect sizes differs from that listed in Table 1, where only one combined ES is listed for every subgroup.

skills are known to be essential components in different types of sports, it can be assumed that there is a positive transfer of resistance training effects to sport specific performance in young athletes. This is in concordance with the recently published position statement of the National Strength and Conditioning Association, which concludes that resistance training is an effective method for improving sports performance (21).

Separate analysis of each motor performance group revealed that the greatest effect size occurred in throwing performance (ES: 0.99, 95% CI: 0.19–1.79) followed by jumping- (ES: 0.54, 95% CI: 0.34–0.74) and sprinting-performance (ES: 0.53, 95% CI: 0.23–0.83). However, besides being statistically insignificant, the observed differences might be the result of an insufficient number of studies (n = 8) assessing the effect of resistance training on throwing performance in children and adolescents. Therefore, some caution is warranted regarding the estimated effect size of this specific motor performance cluster.

The heterogeneity of effects in this meta-analysis was very low ($I^2 = 0.00$), indicating that all of the observed variation in findings is spurious and that the included studies examined the same effect. This is supported by the outcome of the sensitivity analysis performed using a fixed effects model, which revealed a similar weighted mean effect size and comparable confidence intervals (ES: 0.50; CI: 0.39–0.61). Nevertheless, since all studies included in this meta-analysis were drawn from discrete populations and varied training regimes were applied, we do not assume one common (true) effect size. In accordance to the recent literature (6), the computational model of random effects was used.

Both, functional (e.g., changes in motor unit coordination) and structural adaptations (e.g., muscular hypertrophy) might explain the observed changes in motor performance. However, higher gains were found in children compared with adolescent subjects. Since there is little evidence of hypertrophy in children, it is generally assumed that training-induced strength gains in younger subjects are more related to neural adaptations than to hypertrophic factors (21). These neural adaptations include changes in motor unit coordination, firing and recruitment—factors that are known to be essential for movement optimization (i.e., eliminating unnecessary and counterproductive muscular movements). Since the most significant neural adaptations occur at the beginning of resistance training interventions and hypertrophy, as aforementioned, plays a subordinate role, we would expect the results of long-term interventions to be similar to that of mid- and short term programs. This is supported by the performed meta-regression for study duration that did not reach significance, indicating that gains in motor performance skills are likely to be achieved during early stages of intervention. However, the lack of significance for duration could also be explained by a low baseline skill level.

One might speculate that participants with previous strength training experience show blunted results due to a ceiling effect in motor learning. Studies that attempt to dissect the relative importance of training experience on gains in motor performance skills in children and adolescents are scant and produced conflicting results (40,60). Although not statistically significant ($p = .24$), we found higher ESs for nonathletes (ES: 0.64, *SE*: 0.17) compared with athletes (ES: 0.40, *SE*: 0.12), suggesting that greater initial enhancements of motor performance skills might be found in untrained subjects. This trend may be the result of greater learning effects in terms of aforementioned neural adaptations in subjects being short on coordinative experience.

The same argument might apply to the observed age dependency of training effects: Analysis for continuous moderator variables revealed a significant negative correlation coefficient for age of participants with the magnitude of the ES, indicating that resistance training is more beneficial in younger subjects. According to recently published data of neuromagnetic imaging, this could be an effect of a reduced motor cortical inhibition in immature subjects, promoting neural plasticity and consequently motor learning in children (33). This assumption is supported by Walther et al., who concluded that a reduced GABAeric inhibition can be found in children due to immaturity of inhibitory intracortical pathways (GABAergic interneurons) and that this may facilitate neuronal plasticity and motor learning in children (61). These suggestions are in concordance with the results presented by Lillegard et al. (45), who studied the impact of various maturity levels on changes in motor performance following a 12 week resistance training program. Highest effect sizes were found in pre- and early pubertal boys (ES: 0.5, *SE*: 0.33) and girls (ES: 0.48, *SE*: 0.3) followed by pubertal and postpubertal male (ES: 0.36, *SE*: 0.41) and female (ES: 0.33, *SE*: 0.58) adolescents, respectively. However, to which extent maturational changes of the central neurologic system (CNS) contribute to improvements of motor performance skills following resistance training remain uncertain.

In the present meta-analysis, a significant positive correlation was found between gains in motor performance skills (expressed in ESs) and the mean intensity (% of 1RM) of the applied training stimulus, in studies using traditional resistance training regimes. It remains unclear, if the observed correlation is a result of enhanced functional adaptations, or if increased exercise intensity is more conducive to the generation of structural changes (muscular hypertrophy). Nevertheless, this dose response relationship for intensity (ES = -0,8149 + 0,0164*x) is essential to the prescription of proper doses of training stimuli and should be taken into account by conditioning professionals, when prescribing training for children and adolescents. That is, the "minimal threshold" for children and adolescent to elicit desired effects in motor performance skills would be around 50% of the individual 1RM. Even though, this threshold is likely to be different between trained and untrained subjects, no such statement can be derived from the available data, since only a minority of subgroups had previous strength training experience. Therefore, to figure out if different training intensities are necessary to evoke comparable training effects in trained and untrained subjects, further research needs to be conducted. However, to reduce the risk of injury, it is generally recommended that children and adolescents should use light weights for all exercises until a proper technique is learned (21). Thereafter, the amount of weight lifted during exercises should be gradually increased to allow for more intense workouts depending on individual training objectives (2).

Program design parameters describing the volume of the applied training stimulus, i.e., number of repetitions, number of sets, and training sessions per week, were not significantly correlated with changes of the selected motor performance skills. Due to the fact that these parameters might be interrelated (e.g., number of sets and number of repetitions), and/or they are homogeneous across the analyzed studies (e.g., number of training sessions per week), the absence of significance should be interpreted with caution. Therefore, further research regarding these moderators is needed.

Nevertheless, similar concerns like aforementioned precautions for gradually increasing intensity to reduce the risk of injury should be taken into account for training volume, when planning resistance training programs for children and adolescents. That is, training volume needs to be increased carefully with regards to the individual stress tolerance of each child to avoid overuse symptoms and/or acute injuries.

Although it seems reasonable to achieve higher gains in motor performance skills by implementing exercises (e.g., plyometrics) that are specific to the test in contraction type, movement velocity and movement pattern of skills tested (37), no such difference in ESs could be derived from the present data. That is, plyometric training programs and traditional training regimes revealed comparable results. Currently it is assumed that the greatest gains on motor performance skills can be expected from training regimes that combine traditional resistance training elements with plyometric training content (22). This finding is commonly explained by the synergistic attributes of both training types. Even though we observed the highest effect sizes from studies that combined plyometric- with traditional resistance training protocols and both training types alone produced somewhat lower effects, the differences between those training types did not reach significance in the present meta-analysis.

Like all meta-analyses, the present intervention is limited by the quality of the included studies. According to the Strength of Recommendation Taxonomy (18), we awarded the current evidence a level of 2[4] and a grade of B[5], as the result of limited quality (see PEDro score below) and some inconsistent findings of the available studies. The PEDro score for the 34 articles averaged 4.56/10 ± 0.99 with a range from 2/10–7/10. This score is commonly considered to describe a fair methodological quality of studies (31). However, it should be taken into account that within resistance training studies almost always, by its very nature, it is impossible to blind the trainer or the participants to the intervention applied. Therefore, the revealed PEDro score should be interpreted with caution.

Another potential limitation of the present meta-analysis is related to the observed publication bias. The funnel plot[6] analysis revealed an asymmetrical appearance with a gap at the upper right- and the bottom left side of the graph, indicating that intervention effects of smaller studies (i.e., with a lower number of subjects) tend to be greater in comparison with those estimated in larger studies. This phenomenon, well known as "small-study effects", is usually assumed to be a result of publication bias. There is a higher probability for publication of a small study if it represents significant results, and is therefore more likely to be included in a meta-analysis. However, the observed asymmetry might be the result of study factors other than publication bias, such as low methodological quality in smaller studies that often yields in an overestimation of treatment effects. Further, it should be taken into account that small and less precise studies are weighted less in the meta-analysis procedure and that the funnel plot does not display the aforementioned virtually unbiased estimated ES. Therefore, the impact of publication bias on the observed overall effect might be somewhat lower than expected from funnel plot analysis.

Statistical tests for detecting funnel plot asymmetry such as Begg's rank correlation test and Egger's linear regression test were not performed in the present analysis, as they were reported to suffer from low statistical power (6).

Conclusion

To our knowledge, the present investigation is the first meta-analysis that provides a robust estimation of the effect of resistance training on selected motor performance skills in children and adolescents based on a statistically meaningful sample size. Although improvements in motor performance have been found previously, the vast majority of available studies lack statistical power due to small sample sizes. From our data it can be stated that resistance training is an effective method for enhancing selected motor performance skills (i.e., jumping, running, and throwing) during childhood and youth.

Furthermore, the results of this meta-analysis provide valuable information concerning the importance of certain subject- and program design parameters. In this context, it is evident that age of participants was negatively correlated to training induced improvements of motor skills (expressed in combined effect sizes), indicating that younger subjects obtained the greatest enhancements in aforementioned skills. Since a similar trend was identified in athletes and nonathletes, we assume that this might be a ceiling effect of functional adaptations in experienced subjects. That is, novices such as children and nonathletes experience greater adaptations in motor performance due to higher learning effects, or that the applied intensity did not sufficiently overload the musculature of experienced subjects who were more conditioned. This would underline the need for load progression over time.

Finally, subgroup analysis for program design parameters revealed a significant positive association between mean intensity of traditional training programs and gains in selected motor performance skills. This should be taken into account by conditioning professionals, when prescribing training for children and adolescents.

Due to the fact that the vast majority of participants were not classified for maturational age and only some data are available on female subjects, further research is still required in this important field of study.

Notes

1. The term "children" in this text refers to subjects being in middle childhood that starts at the age of eight and ends with the onset of puberty (47). The term "adolescents" refers to all intra- and postpubertal subjects up to the age of 18.

2. In this text, gray literature refers to studies that were not formally published in peer reviewed journals

3. "Plyometric training" in this text refers to all exercises that consist of a direct succession of eccentric contractions just before the concentric phase to take advantage of the elastic rebound tendency of muscle tissue, usually known as "stretch shortening cycle". For simplicity, the remaining training modalities that lack a "stretch shortening cycle" are called "traditional resistance training" throughout this text.

4. Study quality level 2 = limited quality patient oriented evidence (18).

5. Strength of recommendation grade B = Recommendation based on inconsistent or limited-quality patient-oriented evidence (18).

6. Not shown in this manuscript.

Acknowledgments

a) No funding was provided for the preparation of the paper. b) There are no relevant conflicts of interest for all authors. c) All persons who made substantial contributions to the work met the criteria for authorship.

References

1. Athanasiou, N., T. Evangelos, and S. Konstantos. Entwicklung und Trainierbarkeit der Kraft bei Basketballspielern im vorpubertären Alter (Development and trainability of muscle strength in prepubertal basketball players). *Leistungssport.* 36:48–52, 2006.
2. Behm, D.G., A.D. Faigenbaum, B. Falk, and P. Klentrou. Canadian Society for Exercise Physiology position paper: resistance training in children and adolescents. *Appl. Physiol. Nutr. Metab.* 33:547–561, 2008.
3. Behringer, M., H.A. Vom, Z. Yue, and J. Mester. Effects of resistance training in children and adolescents: a meta-analysis. *Pediatrics.* 126:e1199–e1210, 2010.
4. Blanksby, B., and J. Gregor. Anthropometric, strength and physiological changes in male and female swimmers with progressive resistance training. *Aust. J Sports Sci.* 1:3–6, 1981.
5. Blattner, S.E., and L. Noble. Relative Effects of Isokinetic and Plyometric Training on Vertical Jumping Performance. *Res. Q.* 50:583–588, 1979.
6. Borenstein, M., L.V. Hedges, J.P.T. Higgins, and H.R. Rothstein. *Introduction to Meta-Analysis*, (1. ed.). Chichester: John Wiley & Sons, Ltd, 2009.
7. Brown, M.E., J.L. Mayhew, and L.W. Boleach. Effect of Plyometric Training on Vertical Jump Performance in High-School Basketball Players. *J Sports Med Phys Fitness.* 26:1–4, 1986.
8. Bulgakova, N.Z., A.R. Vorontsov, and T.G. Fomichenko. Improving the technical prepardness of young swimmers by using strength training. *Sov Sports Rev.* 25:102–104, 1990.
9. Channell, B.T., and J.P. Barfield. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *J. Strength Cond. Res.* 22:1522–1527, 2008.
10. Christou, M., I. Smilios, K. Sotiropoulos, K. Volaklis, T. Pilianidis, and S.P. Tokmakidis. Effects of resistance training on the physical capacities of adolescent soccer players. *J. Strength Cond. Res.* 20:783–791, 2006.
11. Chu, D.A. *Jumping Into Plyometrics*, (1. ed.). Champaign: Leisure Press, 1992.
12. Cossor, J.M., B.A. Blanksby, and B.C. Elliott. The influence of plyometric training on the freestyle tumble turn. *J. Sci. Med. Sport.* 2:106–116, 1999.
13. De Oliveira, A.R., and J.D. Gallagher. Strength Training in Children: A Meta-Analysis [abstract]. *Pediatr. Exerc. Sci.* 7:108–1995, XXX.
14. de Villarreal, E.S., E. Kellis, W.J. Kraemer, and M. Izquierdo. Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *J. Strength Cond. Res.* 23:495–506, 2009.
15. Deeks, J.J., J.P.T. Higgins, and D.G. Altman. Analysing and presenting results. In: *Cochrane Handbook for Systematic Reviews of Inventions,* J.P.T. Higgins and S. Green (Eds.). Chichester, UK: John Wiley & Sons Ltd, 2006.
16. Diekmann, W., and M. Letzelter. Stabilität und Wiederholbarkeit von Trainingszuwachs durch Schnellkrafttraining im Grundschulalter (Stability and reproducibility of strength training induced improvements during elemantary school age). *Sportwissenschaft.* 17:280–293, 1987.

17. Duke, S., and D. BenEliyahu. Plyometrics: Optimizing athletic performance through the development of power as assessed by vertical leap ability: An observational study. *Chirop. Sports Med.* 6:10–15, 1992.
18. Ebell, M.H., J. Siwek, B.D. Weiss, et al. Strength of recommendation taxonomy (SORT): a patient-centered approach to grading evidence in the medical literature. *Am. Fam. Physician.* 69:548–556, 2004.
19. Egger, M., T. Zellweger-Zahner, M. Schneider, C. Junker, C. Lengeler, and G. Antes. Language bias in randomised controlled trials published in English and German. *Lancet.* 350:326–329, 1997.
20. Faigenbaum, A. Resistance training for children and adolescents: Are there health outcomes? *Am. J. Lifestyle Med.* 1:190–200, 2007.
21. Faigenbaum, A.D., W.J. Kraemer, C.J. Blimkie, et al. Youth resistance training: Updated position statement paper from the national strength and conditioning association. *J. Strength Cond. Res.* 23:S1–S20, 2009.
22. Faigenbaum, A.D., J.E. McFarland, F.B. Keiper, et al. Effects of a short-term plyometric and resistance training program on fitness performance in boys age 12 to 15 years. *J Sports Sci Med.* 6:519–525, 2007.
23. Faigenbaum, A.D., and P. Mediate. Effects of medicine ball training on fitness performance of high-school physical education students. *Phys. Educ.* 63:160–167, 2006.
24. Faigenbaum, A.D., L. Milliken, L. Moulton, and W.L. Westcott. Early muscular fitness adaptations in children in response to two different resistance training regimens. *Pediatr. Exerc. Sci.* 17:237–248, 2005.
25. Faigenbaum, A.D., L.A. Milliken, R.L. Loud, B.T. Burak, C.L. Doherty, and W.L. Westcott. Comparison of 1 and 2 days per week of strength training in children. *Res. Q. Exerc. Sport.* 73:416–424, 2002.
26. Faigenbaum, A.D., W.L. Westcott, and L. Micheli. The effects of strength training and detraining on children. *J. Strength Cond. Res.* 10:109–114, 1996.
27. Faigenbaum, A.D., L.D. Zaichkowsky, W.L. Westcott, L. Micheli, and J.M. Fernandez-Garcia. The effects of twice-a-week strenth training program on children. *Pediatr. Exerc. Sci.* XXX:339–346, 1993.
28. Falk, B., and G. Mor. The effects of resistance and martial arts training in 6 to 8 year old boys. *Pediatr. Exerc. Sci.* XXX:48–56, 1996.
29. Falk, B., and G. Tenenbaum. The effectiveness of resistance training in children. A meta-analysis. *Sports Med.* 22:176–186, 1996.
30. Flanagan, S.P., L.L. Laubach, G.M. De Marco, et al. Effects of two different strength training modes on motor performance in children. *Res. Q. Exerc. Sport.* 73:340–344, 2002.
31. Foley, N.C., R.W. Teasell, S.K. Bhogal, and M.R. Speechley. Stroke Rehabilitation Evidence-Based Review: methodology. *Top. Stroke Rehabil.* 10:1–7, 2003.
32. Ford, H.T., and J.R. Puckett. Comparative effects of prescribed weight-training and basketball programs on basketball skill test scores of ninth grade boys. *Percept. Mot. Skills.* 56:23–26, 1983.
33. Gaetz, W., M. Macdonald, D. Cheyne, and O.C. Snead. Neuromagnetic imaging of movement-related cortical oscillations in children and adults: age predicts post-movement beta rebound. *Neuroimage.* 51:792–807, 2010.
34. Glass, G.V. Primary, secondary, and meta-analysis of research. *Educ. Res.* 5:3–8, 1976.
35. Gorostiaga, E.M., M. Izquierdo, P. Iturralde, M. Ruesta, and J. Ibanez. Effects of heavy resistance training on maximal and explosive force production, endurance and serum hormones in adolescent handball players. *Eur. J. Appl. Physiol.* 80:485–493, 1999.
36. Gorostiaga, E.M., M. Izquierdo, M. Ruesta, J. Iribarren, J.J. Gonzalez-Badillo, and J. Ibanez. Strength training effects on physical performance and serum hormones in young soccer players. *Eur. J. Appl. Physiol.* 91:698–707, 2004.

37. Häkkinen, K., A. Mero, and H. Kauhanen. Specificity of endurance, sprint and strength training on physical performance capacity in young athletes. *J Sports Med Phys Fitness.* 29:27–35, 1989.
38. Hedges, L.V. Distribution theory for Glass's estimator of effect size and related estimators. *J. Educ. Stat.* 6:107–128, 1981.
39. Hedges, L.V., and I. Olkin. *Statistical methods for meta analysis*. Orlando, FL: Academic Press, 1985.
40. Hetzler, R.K., C. DeRenne, B.P. Burton, K.W. Ho, D.X. Chai, and G. Seichi. Effects of 12 weeks of strength training on anaerobic power in prepubescent male athletes. *J. Strength Cond. Res.* 11:174–181, 1997.
41. Holcomb, W.R., J.E. Lander, R.M. Rutland, and G.D. Wilson. The effectiveness of a modified plyometric program on power and the vertical jump. *J. Strength Cond. Res.* 10:109–114, 2009.
42. Ingle, L., M. Sleap, and K. Tolfrey. The effect of a complex training and detraining programme on selected strength and power variables in early pubertal boys. *J Sports Sci.* 24:987–997, 2006.
43. Kotzamanidis, C. Effect of plyometric training on running performance and vertical jumping in prepubertal boys. *J. Strength Cond. Res.* 20:441–445, 2006.
44. Kraemer, W.J., and S.J. Fleck. *Strength training for young athletes*, (2. ed.). Champaign: Human Kinetics, 2005.
45. Lillegard, W.A., E.W. Brown, D.J. Wilson, R. Henderson, and E. Lewis. Efficacy of strength training in prepubescent to early postpubescent males and females effects of gender and maturity. *Pediatr. Rehabil.* 1:147–157, 1997.
46. MacKelvie, K.J., K.M. Khan, M.A. Petit, P.A. Janssen, and H.A. McKay. A school-based exercise intervention elicits substantial bone health benefits: a 2-year randomized controlled trial in girls. *Pediatrics.* 112:e447–e2003, XXX.
47. Malina, R.M., C. Bouchard, and O. Bar-Or. *Growth, Maturation, and Physical Activity*, (2. ed.). Champaign: Human Kinetics, 2004.
48. Mareck, U., G. Sigmund, G. Opfermann, H. Geyer, and W. Schanzer. Identification of the aromatase inhibitor aminoglutethimide in urine by gas chromatography/mass spectrometry. *Rapid Commun. Mass Spectrom.* 16:2209–2214, 2002.
49. Martel, G.F., M.L. Harmer, J.M. Logan, and C.B. Parker. Aquatic plyometric training increases vertical jump in female volleyball players. *Med. Sci. Sports Exerc.* 37:1814–1819, 2005.
50. Matavulj, D., M. Kukolj, D. Ugarkovic, J. Tihanyi, and S. Jaric. Effects of plyometric training on jumping performance in junior basketball players. *J Sports Med Phys Fitness.* 41:159–164, 2001.
51. Milliken, L.A., A.D. Faigenbaum, R.L. Loud, and W.L. Westcott. Correlates of upper and lower body muscular strength in children. *J. Strength Cond. Res.* 22:1339–1346, 2008.
52. Morris, S.B. Estimating effect sizes from pretest-posttest-control group designs. *Organ. Res. Methods.* 11:364–386, 2008.
53. Olivo, S.A., L.G. Macedo, I.C. Gadotti, J. Fuentes, T. Stanton, and D.J. Magee. Scales to assess the quality of randomized controlled trials: a systematic review. *Phys. Ther.* 88:156–175, 2008.
54. Payne, V.G., J.R. Morrow, L. Johnson, and S.N. Dalton. Resistance training in children and youth: A meta-analysis. *Res. Q. Exerc. Sport.* 68:80–88, 1997.
55. Rians, C.B., A. Weltman, B.R. Cahill, C.A. Janney, S.R. Tippett, and F.I. Katch. Strength Training for Prepubescent Males - Is It Safe. *Am J Sports Med.* 15:483–489, 1987.
56. Santos, E.J., and M.A. Janeira. Effects of complex training on explosive strength in adolescent male basketball players. *J. Strength Cond. Res.* 22:903–909, 2008.

57. Siegler, J., S. Gaskill, and B. Ruby. Changes evaluated in soccer-specific power endurance either with or without a 10-week, in-season, intermittent, high-intensity training protocol. *J. Strength Cond. Res.* 17:379–387, 2003.
58. Taddonio, D.A. Effect of daily fifteen-minute periods of calisthenics upon the physical fitness of fifth-grade boys and girls. *Res. Q.* 37:276–281, 1966.
59. vom Heede, A., H. Kleinöder, and J. Mester. Kindgemäßes Krafttraining im Schulsport - Untersuchungsergebnisse (Strength training suitable for children in physical education - study results). *Haltung und Bewegung.* 27:11–19, 2007.
60. Wagner, D.R., and M.S. Kocak. A multivariate approach to assessing anaerobic power following a plyometric training program. *J. Strength Cond. Res.* 11:251–255, 1997.
61. Walther, M., S. Berweck, J. Schessl, et al. Maturation of inhibitory and excitatory motor cortex pathways in children. *Brain Dev.* 31:562–567, 2009.
62. Weltman, A., C. Janney, C.B. Rians, et al. The Effects of Hydraulic Resistance Strength Training in Pre-Pubertal Males. *Med. Sci. Sports Exerc.* 18:629–638, 1986.