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INFLUENCE OF MATURATION STAGE ON AGILITY PERFORMANCE GAINS AFTER PLYOMETRIC TRAINING: A SYSTEMATIC REVIEW AND META-ANALYSIS

Running head: COD Ability after Plyometric Training

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ABSTRACT

Although plyometric training (PT) improves change of direction (COD) ability, the influence of age on COD gains after PT is unclear. Therefore, the aim of this systematic review was to identify the age-related pattern of improvement in COD ability after PT in youths. A computerized search within six databases was performed, selecting studied based on specific inclusion criteria: experimental trials published in English-language journals, PT focused on the lower body, COD ability measurements reported before and after training, and male participants aged 10-to-18 years old. Sixteen articles with a total of 30 effect sizes (ESs) in the experimental groups and 13 ESs in the control groups were included. For the analyses, subjects were catagorized into three age groups: 10 to 12.9 years of age (PRE), 13 to 15.9 years of age (MID) and 16 to 18 years of age (POST). Independent of age, PT improved COD ability in youths (ES = 0.86, time gains [TG = -0.61]). However, a tendency toward greater COD ability gains was observed in older subjects (MID, ES = 0.95; POST, ES = 0.99) compared to younger subjects (PRE, ES = 0.68). Pearson product-moment correlation (r) indicated that 2-weekly sessions of PT induced meaningful COD ability gains (for ES, r = 0.436; for time gains, r = -0.624). A positive relationship was found between training intensity and ES (r = 0.493). In conclusion, PT improves COD ability in youths, with meaningfully greater effects in older youths. Two PT sessions per week with 1400 jumps for 7 weeks at moderate intensity seems to be an adequate dose.

KEY WORDS: maturity; leg power; quickness; stretch-shortening cycle; agility.

INTRODUCTION

Agility is a motor ability that is important to success in sports. It is defined as a high-speed action that involves a rapid change of direction (COD) in response to a stimulus (34). Effective agility performance is dependent on several factors and inputs including physical (strength and conditioning), cognitive (motor learning) and technical (biomechanics) elements (34). COD ability refers to a movement where no immediate reaction to a stimulus is required. Therefore, the COD ability is pre-planned, and is influenced by strength, jump and sprint performance (37). Due to the strong association between these physical demands (i.e., strength, sprint and jump performance) and COD ability (3, 34), it seems that an improvement in these variables may enhance COD ability.

Plyometric training (PT) is a popular training method to enhance strength (33), power (30), sprint performance (31) and COD ability (23, 26, 35). It commonly includes quick and powerful movements involving the muscle stretch-shortening cycle (SSC) (12). The SSC entails the storage of elastic energy during the initial stretch which contributes to a potentiation of force during the subsequent shortening of the muscle (12). The ability of athletes to use the SSC may positively affect sprint (31), strength (33), jump (30) and COD ability (3).

In a recent review of research on adult athletes (3) recommended 2 to 3 d/wk of PT for 6 to 8 weeks with moderate-to-high intensity was recommended to induce meaningful gains in COD ability (ES = 0.96). Plyometric training also may have positive effects on COD ability, in youths (2, 6, 7, 9, 10, 17, 21-27, 32, 35, 36). For example, Ramirez-Campillo et al. (24) examined the effects of seven weeks (2 d/wk) of depth jump PT on COD ability (i.e., L-run) in soccer players with a mean age of 10 years and found meaningful improvements (ES = 1.03, -0.4 sec). Recently, Hammami et al. (10) investigated the effects of eight weeks (2 d/wk) of hurdle and depth jump PT on repeated COD ability in soccer players with a mean age of 15 years and reported meaningful improvements (ES = 0.66, -1.5 sec). With regard to training at different ages, it appears that maturation plays an important role in performance gains in response to training. Lloyd et al. (13) reported that youths between 10 to 11 years of age showed accelerated SSC development, a phenomenon that continued near the time of peak height velocity (PHV). However, the effects of intervention studies incorporating PT on COD ability in subjects in different age groups are unclear (16). Although, the effects of PT on COD ability in youth athletes from 10 to 12.9 (PRE PHV), 13 to 15.9 (MID PHV) and 16 to 18 (POST PHV) years of age have been reported (2, 6, 7, 9, 10, 17, 21-27, 32, 35, 36), comparisons across these age groups are scarce. Therefore, the purpose of this systematic review and meta-analysis was (1) to describe the effects of PT on COD ability and (2) to compare the effects of PT on COD ability in PRE, MID and POST PHV youths.

METHODS

Experimental Approach to the Problem

In the present study, the meta-analysis was performed in different steps, grounded in previous recommendations (3, 20).

Literature Search

This meta-analytical review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) statement (19). Literature searches of PubMed, Google Scholar, MEDLINE, SPORTDiscus, Science Direct and Web of Science databases were conducted in June 2016. Additionally, manual searches were performed in journals that are relevant to sports science as well as references lists obtained from gathered articles. The search terms included "agility", "agility performance", "agility times", "change of direction", "plyometric training", "plyometrics", "neuromuscular training", "explosive training", "power training", "jump training", "stretch shortening cycle", "youth", "young", adolescent, "maturation", "pubertal", "trainability", "children", "pediatric", and "age". After eliminating duplicates, the search results were screened by two investigators against the inclusion criteria. Following subsequent screening, 16 articles were obtained for inclusion in the final meta-analysis. Figure 1 presents the steps taken to eliminate inappropriate studies for a variety of reasons.

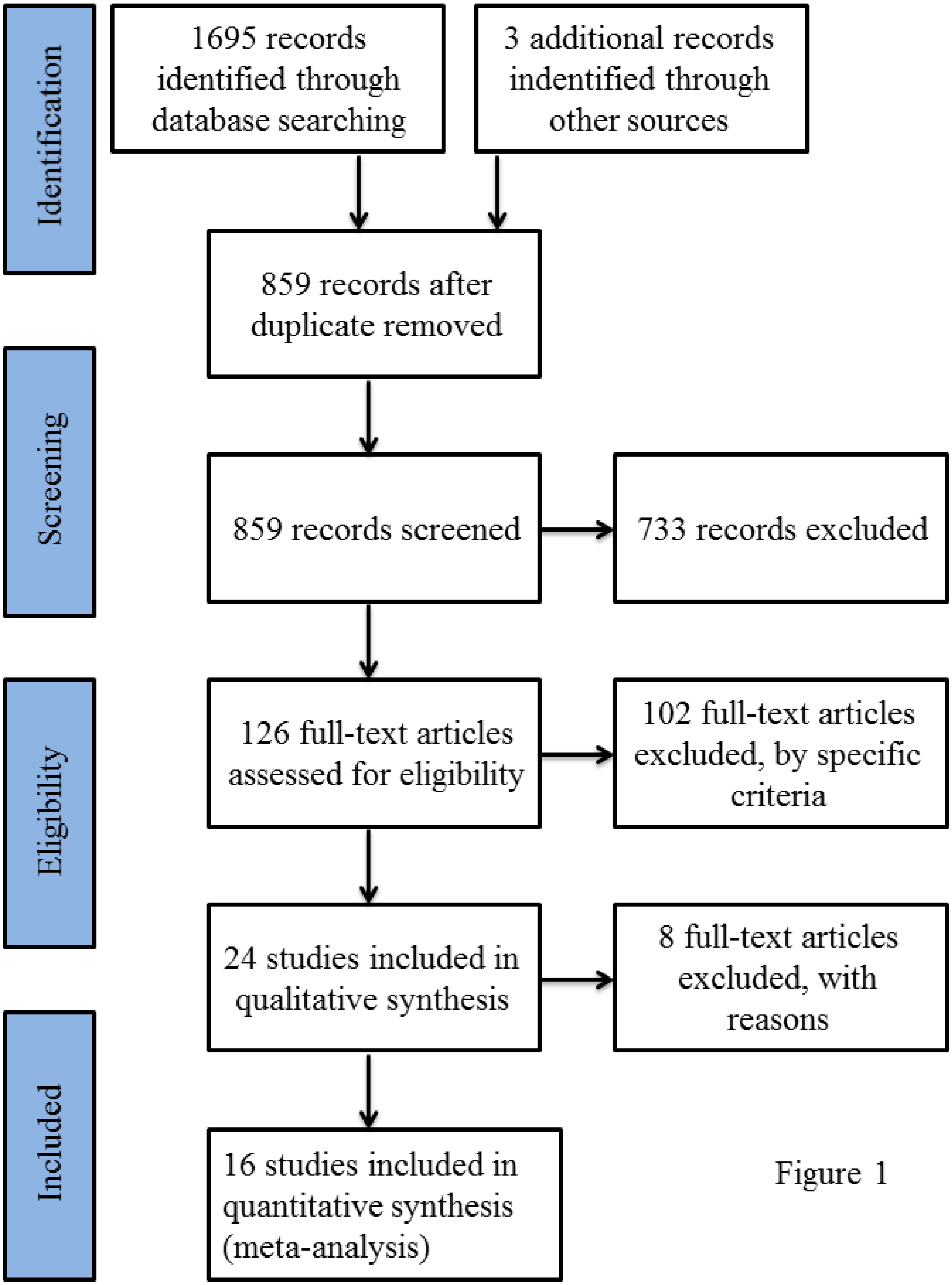

Figure 1. Procedures to include studies in the review.

The inclusion criteria for studies in this review were as follows (5); 1) experimental trials published in English-language refereed journals with full-text availability; 2) healthy participants; 3) interventions that only used PT focused on lower limb exercises; 4) the inclusion of pre- and post-intervention measurements of COD ability and 5) male participants aged 10-to-18 years-old.

Data Extraction

The studies were read and coded by two of the researchers with a focus on the following variables: descriptive information (age, body mass, height and group size); sport activity (physically active, soccer, rugby, basketball, tennis, and none); type of PT intervention (aquatic PT, land PT, mat PT, grass PT, sand PT, vertical PT, horizontal PT, bilateral PT, unilateral PT, progressive PT, and non-progressive PT); type of plyometric drill (depth jump [DJ], countermovement jump, vertical jump, standing long jump, hurdle jump, and mixed model [combination of different plyometric drills]); frequency of weekly sessions, program duration, outcome measurements of COD ability (i.e., T test [TT], Illinois agility test [IAT], shuttle run (SR), 505, L-run, 10×5-m, 10-m, and zigzag), and findings (i.e., magnitude of COD ability changes). Moreover, the studies were separated into three age-range categories: PRE, MID and POST PHV, according to previous recommendations (13, 20). Details about the coding of studies are presented in Table 1

Table 1. Summary of characteristics of studies included in the meta-analysis.

Author	Year	Group	n	Age (y)	Height (cm)	Weight (kg)	Sport activity	Type of treatment	Type of exercise	TD	TF	Type of tests	ES	TG	INT	NTJ	R	IR
10-to-12.99 years																		
Ramirez-Campillo et al. b	2014	Exp	13	10.4	141	37	Soccer	LPT	DJ	7	2	L-Run	1.03	-0.4	H	840	30	48
Ramirez-Campillo et al. b	2014	Exp	14	10.4	141	37.2	Soccer	LPT	DJ	7	2	L-Run	0.87	-0.3	H	840	60	48
Ramirez-Campillo et al. b	2014	Exp	12	10.3	142	38	Soccer	LPT	DJ	7	2	L-Run	1.04	-0.4	H	840	120	48
Ramirez-Campillo et al. b	2014	Con	14	10.1	143	39	Soccer	-	-	-	-	L-Run	0.4	-0.1	-	-	-	-
Sohnlein et al.	2014	Con	10	12.3	154.2	40.8	Soccer	-	-	-	-	HAR	0.31	-0.18	-	-	-	-
Ramirez-Campillo et al. a	2015	Exp	12	11	146	43.5	Soccer	BPT	Mix	6	2	10-m	0.42	-0.3	M	2160	-	-
Ramirez-Campillo et al. a	2015	Exp	16	11.6	147	45	Soccer	UPT	Mix	6	2	10-m	0.80	-0.5	M	2160	-	-
Ramirez-Campillo et al. a	2015	Exp	12	11.6	144	42.2	Soccer	U+BPT	Mix	6	2	10-m	0.66	-0.5	M	2160	-	-
Ramirez-Campillo et al. a	2015	Con	14	11.2	143	41.8	Soccer	-	-	-	-	10-m	-0.06	0.2	-	-	-	-
Ramirez-Campillo et al. b	2015	Exp	8	12.8	160	53.9	Soccer	PPT	Mix	6	2	TT	0.82	-0.85	M	1800	60	48
Ramirez-Campillo et al. e	2015	Exp	10	11.6	144	40	Soccer	VPT	Mix	6	2	10-m	0.43	-0.4	M	1610	60	48
Ramirez-Campillo et al. e	2015	Exp	10	11.4	150	44.6	Soccer	HPT	Mix	6	2	10-m	0.21	-0.32	M	1610	60	48
Ramirez-Campillo et al. e	2015	Exp	10	11.2	141	40.1	Soccer	V+HPT	Mix	6	2	10-m	0.7	-0.55	M	1610	60	48
Ramirez-Campillo et al.	2015	Con	10	11.4	146	42.2	Soccer	-	-	-	-	10-m	-0.1	0.02	-	-	-	-
Fernandez-Fernandez et al.	2016	Exp	24	12.5	156.6	44.2	Tennis	LPT	Mix	8	2	505	0.58	-0.1	M	1160	90	48
Fernandez-Fernandez et al.	2016	Con	27	12.5	156.6	44.2	Tennis	-	-	-	-	505	-0.05	0.01	-	-	-	-
13-to-15.99 years																		
Meylan & Malatesta	2009	Exp	14	13.3	159	48.6	Soccer	GPT	Mix	8	2	10-m	2.8	-0.45	L	-	90	-
Meylan & Malatesta	2009	Con	11	13.1	163	47.8	Soccer	-	-	-	-	10-m	-0.5	0.16	-	-	-	-
Ramirez-Campillo et al. a	2014	Exp	38	13.2	154	47.9	Soccer	GPT	DJ	7	2	IAT	0.26	-0.7	H	-	90	48
Ramirez-Campillo et al. a	2014	Con	38	13.2	153	47.4	Soccer	-	-	-	-	IAT	-0.25	0.4	-	-	-	-
Chaouchi et al.	2014	Exp	14	13.7	161.5	45.9	Non athlete	LPT	Mix	8	3	SR	1.21	-0.56	L	780	-	48
Chaouchi et al.	2014	Con	14	13.5	158.1	46.6	Non athlete	-	-	-	-	SR	-0.28	0.11	-	-	-	-
Sohnlein et al.	2014	Exp	12	13	162.4	51	Soccer	LPT	Mix	16	2	HAR	0.89	-0.71	M	-	-	72
Ramirez-Campillo et al. b	2015	Exp	8	13	161	53.8	Soccer	NPPT	Mix	6	2	TT	0.43	-0.7	M	1440	60	48
Ramirez-Campillo et al. b	2015	Con	8	13	159	53.2	Soccer	-	-	-	-	TT	0.58	-0.74	-	-	-	-
Ramirez-Campillo et al. c	2015	Exp	54	14.2	158	50.3	Soccer	LPT	Mix	6	2	10×5	0.57	-0.72	H	1200	120	24
Ramirez-Campillo et al. c	2015	Exp	57	14.1	159	51.8	Soccer	LPT	Mix	6	2	10×5	0.63	-0.75	H	1200	120	48
Ramirez-Campillo et al. c	2015	Con	55	14	160	52.1	Soccer	-	-	-	-	10×5	-0.28	0.5	-	-	-	-
Saez de Villarreal et al.	2015	Exp	13	15.3	168	57.1	Soccer	GPT	Mix	9	2	10-m	1.1	-0.38	M	2240	-	72
Saez de Villarreal et al.	2015	Con	13	14.9	165.2	54.4	Soccer	-	-	-	-	10-m	-0.1	0.02	-	-	-	-
Hammami et al.	2016	Exp	15	15.7	176	59	Soccer	LPT	Hurdle+DJ	8	2	RCOD	0.66	-1.5	H	722	-	48
Hammami et al	2016	Con	13	15.8	169	58	Soccer	-	-	-	-	RCOD	-0.78	1.31	-	-	-	-
16-to-18 years																		
Thomas et al.	2009	Exp	6	17.1	177.2	68.5	Soccer	LPT	DJ	6	2	505	1.3	-0.5	H	-	-	-
Thomas et al.	2009	Exp	6	17.3	177.9	68.7	Soccer	LPT	CMJ	6	2	505	1.5	-0.61	H	-	-	-
Arazi et al.	2012	Exp	6	18	182.4	67.5	Basketball	MPT	Mix	8	3	TT	1.4	-1.28	M	1188	60	48
Arazi et al.	2012	Exp	6	18	182.4	67.5	Basketball	MPT	Mix	8	3	IAT	1.6	-1.15	M	1188	60	48
Arazi et al.	2012	Exp	6	18	180.2	75.6	Basketball	APT	Mix	8	3	TT	1.3	-1.89	M	1188	60	48
Arazi et al.	2012	Exp	6	18	180.2	75.6	Basketball	APT	Mix	8	3	IAT	1.5	-1.09	M	1188	60	48
Ramirez-Campillo et al.	2013	Exp	9	16.8	-	-	Non athlete	MPT	DJ	7	2	IAT	0.57	-0.3	L	780	90	48
Ramirez-Campillo et al.	2013	Exp	8	16.8	-	-	Non athlete	LPT	DJ	7	2	IAT	0.4	-0.2	L	780	90	48
Ramirez-Campillo et al.	2013	Exp	7	16.8	-	-	Non athlete	MPT	DJ	7	2	IAT	0.33	-0.45	M	1860	90	48
Ramirez-Campillo et al.	2013	Con	5	16.8	-	-	Non athlete	-	-	-	-	IAT	0	0	-	-	-	-
de Hoyo et al.	2016	Exp	9	18	177.4	72.3	Soccer	LPT	Mix	8	2	zigzag	0.02	-0.01	M	-	-	48

Exp = experimental; Con = control; APT = aquatic plyometric training, LPT = land PT, MPT = mat PT, GPT = grass PT, SPT = sand PT, U=unilateral, B=bilateral, PPT=progressive PT, NPPT=no PPT, VPT=vertical PT, HPT=horizontal PT; ES = effect size; TG = time gains (sec); DJ = depth jump, hurdle jump; CMJ = countermovement jump; Mix = mixed; TT = T-test; IAT= Illinois agility test; SR = shuttle run; HAR = hurdle agility run; RCOD = repeated change of direction; TD = training duration; TF = training frequency; INT = intensity; L = low; M = moderate; H = high R = rest between sets; IR = rest between exercise sessions.

For each COD ability test, the effect size (ES) was calculated using Hedges and Olkin´s *g* (11), with the following formula (1): $g = (M_{post} – M_{pre}) / SD_{pooled}$, where M_{post} is the mean at post-test, M_{pre} is the mean at pre-test, and SD_{pooled} is the pooled of the measurements (2) as recommended previously (3, 30, 31, 33):

$$SD_{pooled} = \frac{(M_{post} - M_{pre})}{\sqrt{((n_1 - 1) \cdot SD_1^2 + (n_2 - 1) \cdot SD_2^2) / (n_1 + n_2 - 2)}}$$

ES was the standardized value that indicated the magnitude of training effects between groups or experimental conditions in a study. It has been suggested (3, 11) that ES should be corrected for the magnitude of the sample size of each study. Therefore, correction was performed using the following formula (3): $1-3 / (4m-9)$, where $m = n - 1$, as proposed by Hedges and Olkin (11).

Statistical Analyses

Data are presented as the means ± standard deviations (SDs). To determine the effects of PT on COD ability, the ES and TG are reported. To compare the magnitude of improvements across groups an analysis of variance (ANOVA) was used (3, 30, 31, 33). Pearson product moment correlation coefficient (r) was used to determine the relationship between COD ability ESs and time gain (TG) with training variables. The significant level of each test, α, was set at $p \leq 0.05$. Threshold values for assessing the magnitudes of the ESs were ≤ 0.35, 0.36-0.80, 0.81-1.50 and > 2.0 for trivial, small, moderate and large respectively (3, 28).

RESULTS

Subjects' basal characteristics (mean ± SD) are presented in Table 2.

Table 2. Subjects' basal characteristics (mean ± SD).

	PRE		MID		POST		All	
	Exp (n = 141)	Con (n = 75)	Exp (n = 225)	Con (n = 154)	Exp (n = 65)	Con (n = 9)	Exp (n = 435)	Con (n = 234)
Age (y)	11.3 ± 0.8	11.5 ± 1.0	13.9 ± 1.0	13.9 ± 1.05	17.4 ± 0.56	16.8 ± 0.0	14.1 ± 2.7	13.2 ± 1.8
Weight (kg)	42.3 ± 4.8	41.6 ± 1.9	51.6 ± 4.3	51.3 ± 4.3	70.8 ± 3.6	0.0 ± 0.0	52.8 ± 12.3	47.3 ± 6
Height (cm)	146.6 ± 6.4	148.5 ± 6.4	162.5 ± 6.3	161 ± 5.2	179.6 ± 2.2	0.0 ± 0.0	160.4 ± 14.5	155.8 ± 8.4

Exp: experimental; Con: control; PRE, MID and POST: youth athletes from 10 to 12.9, 13 to 15.9, and 16 to 18 years-old, respectively.

The effects of PT on COD ability ESs in PRE, MID and POST age groups are presented in Figure 2.

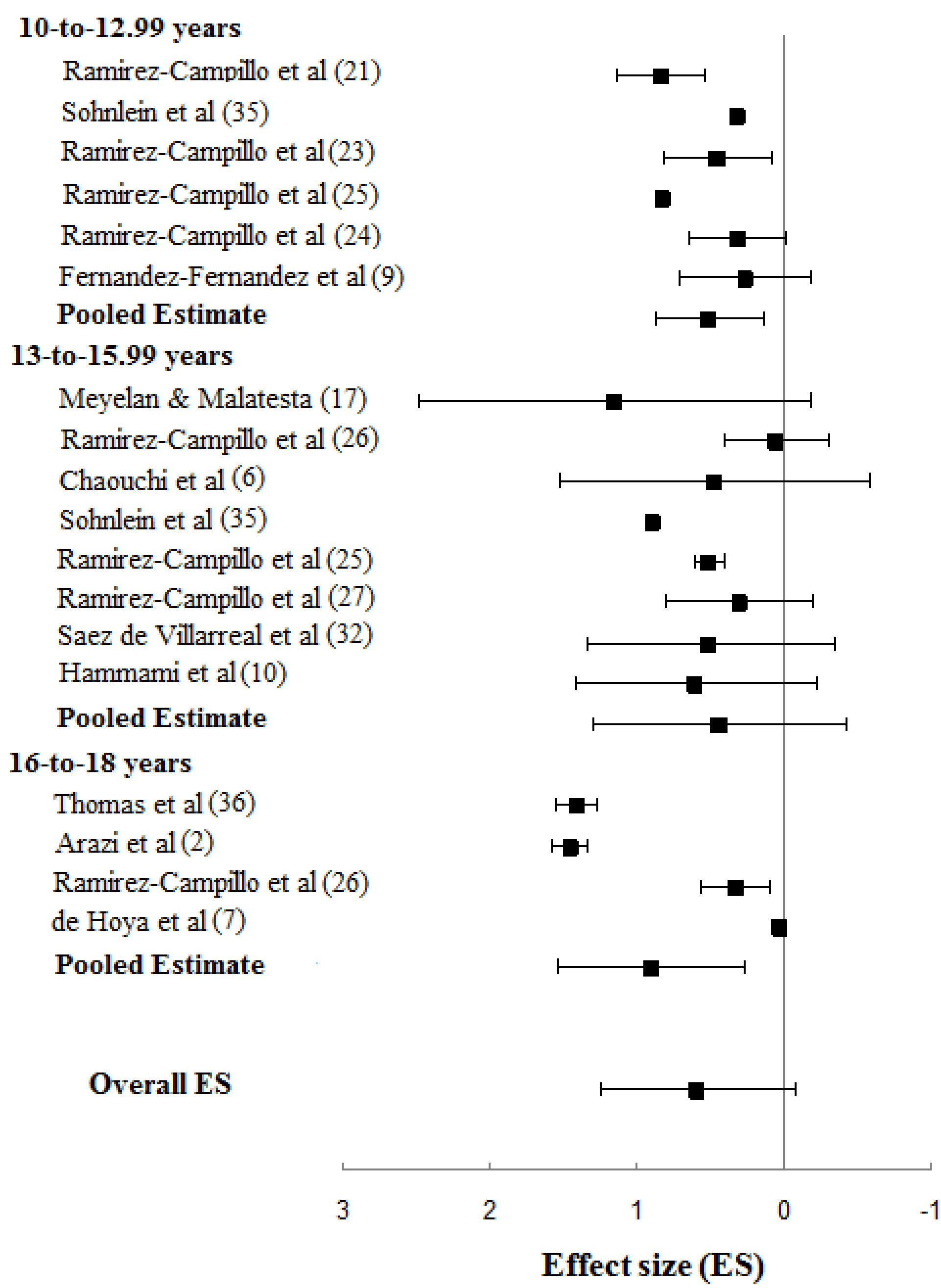

Figure 2. Plyometric trining effects (ES) on change of direction ability in different age groups.

When the PRE, MID and POST age groups were combined (All), the experimental groups showed greater ($p < 0.05$) improvements in COD ability (ES = 0.86; TG = -0.61 sec) compared to the control groups (ES = -0.07; TG = 0.13 sec). Similarly, in each age group greater ($p < 0.05$) improvements in COD ability were observed in the experimental groups compared to the control groups ($p < 0.05$) (Table 3). However, experimental PRE, MID and POST age groups did not show differences in ES ($p = 0.41$) or TG ($p = 0.11$) after PT (Figure 3).

Table 3. Effects of plyometric training on change of direction ability.

Sub-group		Experimental	Control	Within groups	Between groups
PRE	ES	0.68 ± 0.26	0.12 ± 0.22*	F = 17.526, P = 0.001	ES
	TG	-0.40 ± 0.22	-0.01 ± 0.14*	F = 12.237, P = 0.004	F = 0.918, P = 0.411
MID	ES	0.95 ± 0.75	-0.23 ± 0.41*	F = 13.591, P = 0.002	
	TG	-0.71 ± 0.32	0.26± 0.63*	F = 16.386, P = 0.001	TG
POST	ES	0.99 ± 0.59	0.0 ± 0.0*	F = 12.533, P = 0.000	F = 2.344, P = 0.115
	TG	-0.74 ± 0.58	0.0 ± 0.0*	F = 14.475, P = 0.000	

PRE, MID and POST: youth athletes from 10 to 12.9, 13 to 15.9, and 16 to 18 years-old, respectively; Effect size (ES) and time gains (TG) data are expressed as mean ± standard deviation. *Significant differences with Experimental group ($p \leq 0.05$)

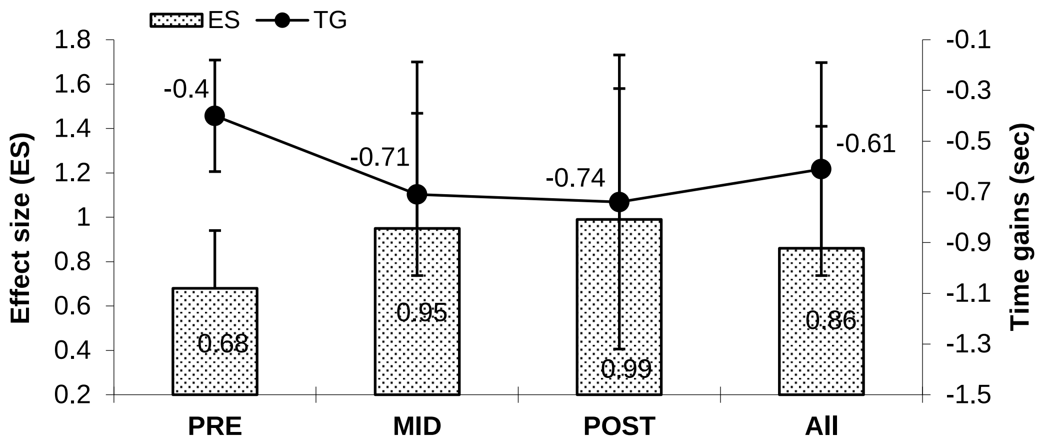

Figure 3. Effects of plyometric training on change of direction ability in youth athletes from 10 to 12.9 (PRE), 13 to 15.9 (MID) and 16 to 18 (POST) years-old. ES and time gains (TG) data are expressed as mean ± standard deviation.

Results of the ANOVA indicated that no significant differences existed between any of the training variables between across groups, except training frequency (POST vs. PRE, p = 0.041) (Table 4).

Table 4. Training program characteristics and analysis between groups (mean ± SD).

	PRE	MID	POST	All	F	p-value
Training frequency (sessions/week)	2	2.1 ± 0.3	2.4 ± 0.5	2.1 ± 0.3	3.603	**0.041**
Training duration (weeks)	6.4 ± 0.6	8.2 ± 3.1	7.0 ± 1.0	7.1 ± 1.9	2.324	0.117
Intensity of plyometric exercise*	2.2 ± 0.4	2.2 ± 0.8	2.0 ± 0.6	2.1 ± 0.6	0.494	0.616
Number of total jump (repetition)	1526 ± 534	1264 ± 551	1167 ± 361	1356 ± 501	1.263	0.303
Rest between sets (sec)	67.5 ± 26.5	90 ± 24.5	72.8 ± 16.0	74.2 ± 23.1	1.322	0.294
Rest between training sessions (hour)	48.0 ± 0.0	51.0 ± 15.3	48.0 ± 0.0	49.0 ± 8.6	0.304	0.741

*1= low, 2 = moderate, 3 = high

There were no relationships between training duration (weeks) (r = 0.118 and r = -0.74), training frequency (sessions/week) (r = 0.436 and r = -0.624), number of total jump (repetitions) (r = -0.304 and r = -0.010), rest between sets (s) (r = -0.030 and r = -0.105) and rest between exercise sessions (hours) (r = 0.064 and r = -0.180) with COD ability ESs and TG, respectively (Table 5). A relationship was observed both between training frequency (sessions/weeks) and COD ability ES gains (r = 0.436) and TG (r = -0.624) and between intensity of plyometric exercise (r = 0.493) and COD ability ES gains.

Table 5. Correlation between effect size and time gains with training variables in all subjects

	INT	NTJ	TD	TF	R	IR
ES	r = 0.493	r = -0.304	r = 0.118	r = 0.436	r = -0.30	r = 0.064
	p = 0.006	p = 0.148	p = 0.536	**p = 0.016**	p = 0.903	p = 0.765
TG	r = 0.058	r = -0.010	r = -0.74	r = -0.624	r = -0.105	r = -0.180
	p = 0.762	p = 0.963	p = 0.697	**p = 0.001**	p = 0.669	p = 0.400

ES = effect size; TG = time gain; INT = intensity; NTJ = number of total jump; TD = training duration; TF = training frequency; R = rest between sets; IR = rest between exercise sessions.

DISCUSSION

The purpose of this systematic review and meta-analysis was to describe the effects of PT on COD ability and to compare the effects of PT on COD ability in PRE, MID and POST PHV youths. The main results of this study were that PT enhances COD ability in youths and two training sessions per week applied for seven weeks with moderate intensity seems to be affective dose (ES = 0.86). Moreover, performing a total-program volume of ~ 1400 jumps, with 75 sec and 48 hours of rest between plyometric exercises and training sessions, respectively, could be meaningful programing to enhance COD ability in youths. When age groups were compared, no significant differences were found across the PRE, MID and POST PHV groups in COD ability gains. However, older youths (MID and POST) showed a meaningful tendency toward greater adaptive responses to PT compared to younger youths (PRE).

Regarding the effect of PT on COD ability in youths, PT improved COD ability in PRE, MID and POST youths compared to controls (Table 3), which is consistent with the findings of previous researchers (3, 10, 23, 26, 35). In youth team-sport athletes, improvements in COD ability might be transferred to key explosive competitive actions (24, 25, 36). Potential mechanisms underpinning the improvements in COD ability after PT might be related to neuromuscular adaptations (1, 2), such as enhanced motor unit recruitment and firing frequencies (2). These physiological changes may lead to a greater rate of force development and power output and, consequently, COD ability improvement after PT (34, 36). In addition, PT may reduce ground contact times through an increase in muscular force output and movement efficiency, which positively affects COD ability (38). Moreover, PT may improve the eccentric strength of the thigh muscles, a prevalent component in COD during the deceleration phase of impulsive movements (34), which may involve a rapid switch from eccentric to concentric muscle action in the leg extensor muscles.

Regarding the effects of age on PT-induced changes in COD ability, older youths (MID and POST) showed a meaningful tendency toward greater COD ability changes in responses to PT compared to younger youths (PRE), although it was not statistically significant. It might be that older youths express greater plasticity after PT in muscle size, transition from type I to type II muscle fibers, muscle contractile ability, fascicle angle, motor unit recruitment, inter-muscular coordination, stretch-reflex excitability, utilization of the SSC properties and neural drive to agonist muscles (15). However, further studies are needed to clarify which of these potential underlying physiological mechanisms may help to explain the results observed in this systematic review and meta-analysis more effectively.

In the PRE (i.e., 10 to 12.9 years of age) group, greater improvement in COD ability was observed after PT in the experimental group compared to the control group (ES = 0.68 vs. 0.12, TG = -0.4 vs. -0.01, respectively). This finding is aligned with those of previous research on PRE athletes (9, 23, 24, 25). This consistency is probably due to the inclusion of similar training program variables across studies (3).

In the two older groups in this meta-analysis, the experimental groups showed greater improvement in COD ability compared to the control groups (Table 3). This result is consistent with those of previous research on MID (6, 17, 26, 27, 32) and POST athletes (2, 22, 36). The improvement in COD ability in the MID (ES = 0.95) and POST (ES = 0.99) groups was not statistically significantly greater than in the PRE (ES = 0.68) group. However, a difference in improvement of -0.31 to -0.34 sec (Figure 3) could be meaningful in a competitive athletic context (2, 6, 7, 9, 10, 17, 21-27, 32, 35, 36). Therefore, coaches working with MID and POST athletes should aim for PT interventions to take advantage of their increased effect on COD ability improvement in this age group. It may be possible that the fastest period of growth that typically occurs at

MID allows for greater increases in total, trunk and leg length; bodyweight; muscle mass and muscle length, which permits increased tolerance to greater plyometric drills intensity (8) and therefore, PT-induced changes. These growth-related adaptations may be retained in older age (POST). Overall, the results of this study showed minimal differences between the MID and POST groups in COD ability improvement (ES = 0.95 vs. 0.99) after PT. It seems that the marked differences between age groups in COD ability improvements after PT occur between the PRE and MID groups, and the elevation of anabolic hormone concentrations that occur with increased age may attenuate adaptation differences (14, 29). However, it appears that adaptive responses to PT are dependent upon maturation status. Additional studies are necessary to clarify the maturation-related PT effects on COD ability gains.

Moreover, other potential mechanisms that lead to further enhancements in COD after PT for the MID and POST groups could be due to maturation-related development of the central nervous system and increases in fascicle length (18). Another possible explanation involves the elevation of anabolic hormone concentrations during maturation and their effects during the MID and POST maturation phases. Hormone-related hypertrophy of type II muscle fibers as well as the growth spurt-related increases in muscle coordination and motor unit activation greatly influence COD ability (14, 18, 29). Moreover, COD ability gains after PT might relate to improvements in muscle strength and power (34).

Some potential limitations are perceived for this review: i) PT interventions differed across studies (i.e., type of plyometric exercise used, number of exercises performed, number of jumps during training sessions, type of testing and training duration); ii) as research in the area is lacking regarding measures of subjects' maturity status, the categories used were based on chronological age; iii) an small number of studies and ESs were available. Therefore, caution should be used when generalize the results of this study.

In conclusion, PT significantly improve COD ability in youth subjects (ES = 0.86, TG = -0.61 sec). In comparison of age groups, older youths showed more adaptive responses to PT in COD ability gains. Therefore, adaptations in COD ability after PT are related to age. To achieve COD ability gains, it seems that 2 training sessions per week with 1400 jumps for 7 weeks at moderate intensity could be a meaningful dose.

PRACTICAL APPLICATIONS

Plyometric training can be recommended as an effective training modality for improving agility or COD performance; yet, the positive effects of plyometric training is in relation to several factors including training program design, training level, the specific sport activity, familiarity with plyometric training, program duration, and training volume or intensity (3). One of the important variables is age or maturation status of subjects. Regarding the results of this meta-analysis improvements in COD ability performance may be more trainable in the MID and POST stage of maturation with periods of acceleration in physiological adaptation. On the other word, adaptation of COD ability following PT is in relation to maturation status of subjects. These conclusions are essential and should be taken into account by strength and conditioning professionals in the field of youth athletes who adaptive responses to PT for COD ability performance is greater in mature athletes and overall PT improves COD ability in youths and two PT sessions/week seems to be an adequate dose.

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